High-Time Resolution “BLINK” GPU Imager for Low-Frequency Radio Telescopes

Gayatri Aniruddha - Milestone 3 (MPhil)
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International Centre for Radio Astronomy Research

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SKAO Regional Centre Australia

Pawsey

Curtin University

The University of Western Australia

Government of Western Australia
Department of the Premier and Cabinet
Office of Science

Contents

Imager will be a part of the larger GPU based pipeline searching for Fast Radio Bursts (FRBs)

PaCER project :
- Sponsored by PAWSEY, ICRAR and AUS-SRC

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Background

FRBs

FRB detections at low frequencies (< 350 MHz)

FRB search methods

Imaging & Gridding in Radio Astronomy

Motivation

Why do we need a new GPU imager?

Initial target instruments

Work done

Project 1: GPU imager

Project 2: Pilot FRB searches with EDA2

Part 1: Background + Motivation

Fast Radio Bursts (FRBs)

FRBs are ms duration radio pulses with Jy level flux densities, originating from even distant Universe

The first FRB: (Lorimer et. al, 2007)
- also called the 'Lorimer burst'

- was discovered in 2007

- while processing archival pulsar data from Murriyang (Parkes) radio telescope

This 30 Jy burst:
- had a duration of < 5 ms

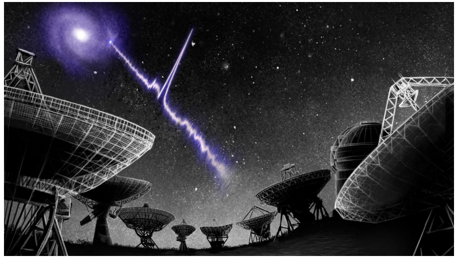
- was located approximately 3 degrees south of the center of the Small Magellanic Cloud (SMC)

Below: dynamic spectrum of the Lorimer burst
- FRB was detected at 1.4 GHz

- Dispersed pulses at higher frequencies arrive earlier than at low frequencies

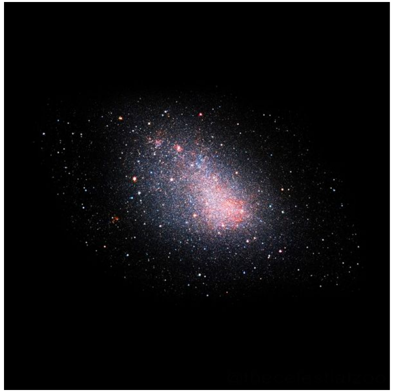
Delay in their arrival times is inversely dependent on their observing frequencies:

$$t_2 - t_1 = \frac{e^2}{2\pi m_e c}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right) DM$$

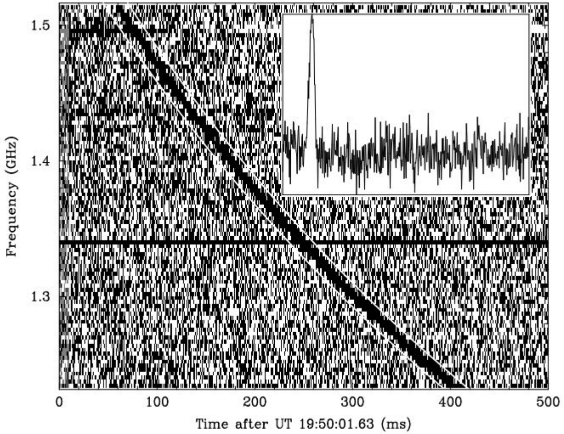


An artist's impression of an FRB.
Source:
https://earthsky.org/space/fast-radio-burst-121102-twisted-black-hole-supernova/

Parkes Radio Telescope in NSW, Australia.
Source : Wikipedia



Small Magellanic Cloud as photographed by an amateur astronomer. Source : Wikipedia



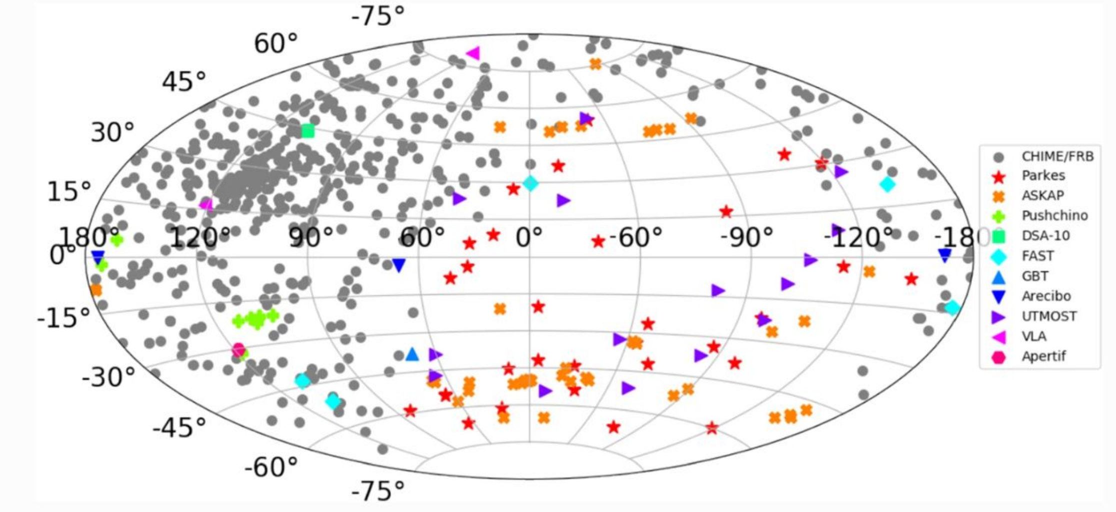
Lorimer Burst (Lorimer et al., 2007)

FRB detections

Since their initial discovery in 2007, this FRB population is growing rapidly

The current total number of FRB detections as of September 2023 ~ 756
(FRB Newsletter: Petroff & Chatterjee, September 2023)

Most FRB detections have been made by the Canadian Hydrogen Intensity Mapping Experiment (CHIME), operates in the frequency range of 400 - 800 MHz



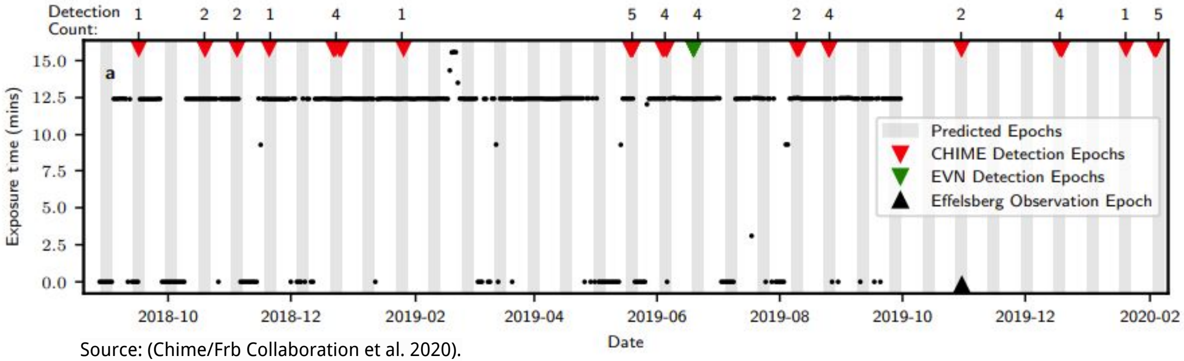
Distribution of known sample of FRBs in Galactic coordinates as of Jan 2022 (Petroff, 2022).

FRB detections

Most FRBs appear to be one-off (or apparently non-repeating) events

Some FRBs are known to repeat, where bursts are observed from such FRBs at irregular intervals
- Presently, there are 51 such sources known to repeat

Evidence of **periodic activity windows** from two of them:
1) FRB 121102 (~ 157 days)
   - Discovered by the Arecibo Radio Telescope
   - First FRB to be detected with a telescope other than Parkes
2) FRB 180916B (~ 16.35 days)



Source: (Chime/Frb Collaboration et al. 2020).

Activity window plot of FRB 180916B

- Grey shaded regions: activity was predicted

- Downward triangles: when bursts were observed by different telescopes (during the predicted ON periods)

- No bursts were observed during the OFF periods

FRB detections at low frequencies (< 350 MHz)

To date, FRBs have been detected at frequencies from 300 MHz, up to 8 GHz

There have been searches for FRB emission at low frequencies using:
- Low-Frequency Array (LOFAR, van Haarlem et al., 2013)
- Murchison Widefield Array (MWA, Tingay et al., 2013)
- Long Wavelength Array (LWA, Ellingson et al., 2009)

Hundreds of FRBs have been detected down to 400 MHz by the CHIME telescope

Only a handful of them have been detected at frequencies below 350 MHz

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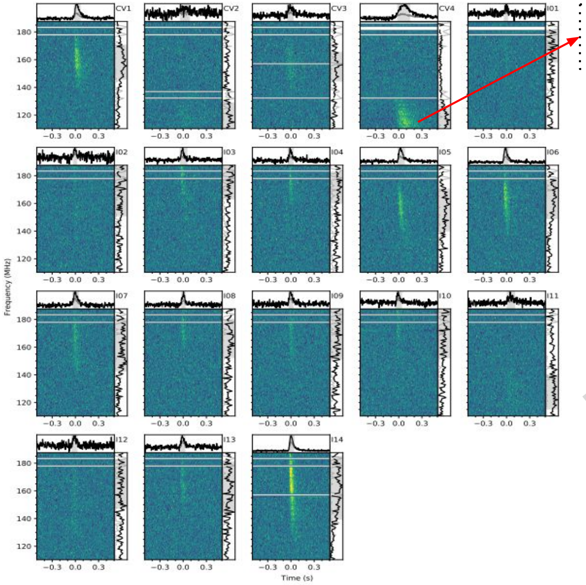

Some bursts observed down to 110 MHz

FRB 180916B: (one such FRB)
- Discovered by CHIME in 2018

- Observed to repeat regularly, ~ every 16.35 days
- Bursts are clustered into a period of 4 days, dormant period of 12 days

- Detections made by multiple telescopes around the world

- First low frequency detections were also detected with LOFAR

- Left: dynamic spectra of the 18 bursts observed with LOFAR
- By far the lowest-frequency detections of any FRB to date

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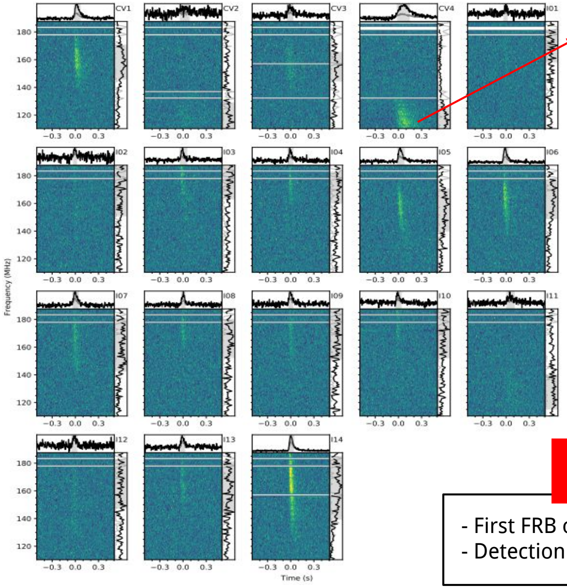

Some bursts observed down to 110 MHz

Milestone in the history of FRB detections!

- First FRB observed at low-frequencies (down to 110 MHz)
- Detection gave renewed hope for detections of low-frequency FRBs

FRB Search Methods

Tied-array beam-based:

FRB searches are similar to that of single pulse searches from pulsar observations

FRBs are searched in beamformed data

Computational cost : $O(N_a N^2_{px})$

Correlation-based imaging:

Correlation $\longrightarrow$ $O(0.5N_a(N_a-1))$

Gridding $\longrightarrow$ $O((N_a(N_a-1)N^2_{kern}))$

Dirty image $\longrightarrow$ $O((N^2_{px}\log_2(N^2_{px}))$

N_a = Number of antennas in the telescope
N_{px} = Number of pixels in the desired image size

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- Number of antennas
- Image size
- for MWA, EDA2

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Telescope	N_a	N_{px} X N_{px}	Beamforming cost	Imaging cost
MWA	128	1000 x 1000	~ 1.28×10^8	~ 1.993×10^7
EDA2	256	150 x 150	~ 5.76×10^6	~ 3.6×10^5

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N_a = Number of antennas in the telescope
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For these specifications, image-based methods seem to be a few times faster than tied-array beam based methods!

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New GPU Imager?

Existing imagers such as:
Common Astronomy Software Applications (**CASA**, CASA Team et al., 2022)
Multi-channel Image Reconstruction, Image Analysis, and Display (**MIRIAD**, Sault et al., 2011)
WSClean (Offringa et al., 2014)

Suitable for offline FRB searches

1) They involve an additional cost of converting the data:
- as they expect their input data in specific formats
- (either a CASA measurement set or UV FITS files)

2) Other than the image-domain-gridding mode (**IDG**, van der Tol et al., 2018) in WSClean,
- these imagers do not have an implementation on GPUs
- no imaging software, operating entirely on GPUs

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High Time Resolution GPU Imager:

Executed on GPUs:
1) Utilises the computational power of GPUs (which are becoming more powerful..)

2) GPUs are also **highly energy efficient** (10 times better than CPUs for complex problems)
- makes them a good alternative to CPUs
- to reduce the carbon footprint of HPC centres

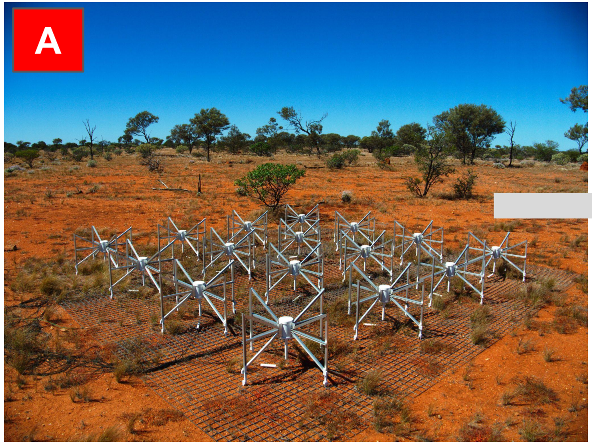
Keep data in the GPU memory from the beginning of the processing: - through correlation, gridding & imaging

1) To eliminate the time taken to convert input data into a specific file format (data conversion operations)

2) Minimise memory copy operations between GPU & standard CPU memory, which can also be time-consuming

Initial Target Instruments

Single Tile of MWA, Credits: CIRA Wiki



A) Murchison Widefield Array (MWA)
Wide low frequency operating range: 70 to 350 MHz

- Phase 1: Originally 128 tiles
16 dual-polarisation dipole antennas in every tile

- Phase 2: Additional 128 tiles
compact, extended configurations
(Baselines: 200m to 5 km)

Aerial view of EDA2, Image credits: Wayth et. al., 2021

B) Engineering Development Array 2 (EDA2)
- Prototype stations built for low-frequency Square Kilometre Array (SKA-Low)

- 256 dual-polarisation dipole antennas, distributed over max. 35 m

In the future, this software will also become publicly available for other telescopes!

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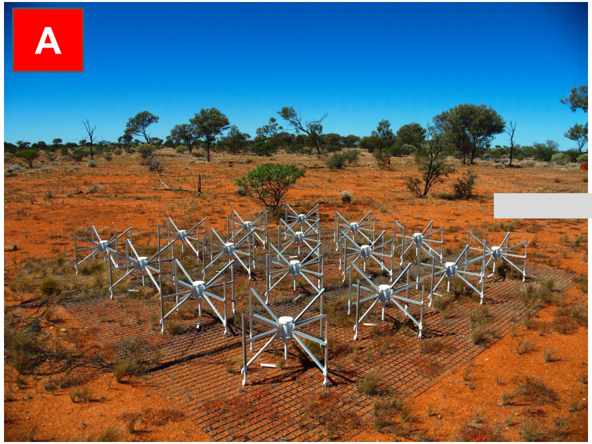

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Previous searches of FRBs using MWA:
(blind & targeted)
- Tingay et al., 2015
- Rowlinson et al., 2016
- Sokołowski et al., 2018
- Tian et al., 2023

Searches led to successful upper-limits on:
- FRB rates
- FRB flux densities

No FRB has been discovered with the MWA (or EDA2)

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In Summary: Background + Motivation

To summarise the motivations:

Motivation 1

For these specifications of:
- number of antennas
- image-size

Image-based methods of preparing data for FRB searches seem to be faster than beamforming based methods

Telescope	N_a	N_{px} X N_{px}	Beamforming cost	Imaging cost
MWA	128	1000 x 1000	~ 1.28×10^8	~ 1.993×10^7
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Motivation 2

Since existing imagers involve an additional cost of converting data into specific input formats, we want to implement a new imager
- Operating on GPUs
- To speed up the imaging process
- Minimise the operations of converting input data to a specific format
- Keep data in the GPU memory (as much as possible) from the beginning

Motivation 3

Initial target instruments of this GPU imager:
- EDA2
- MWA

Part 2: Principles of Radio Astronomy Imaging

Principles of Radio Astronomy Imaging (Correlation)

Imaging of radio data is the process of creating an image of the sky at radio frequencies, starting from voltages recorded by multiple antennas in a radio telescope

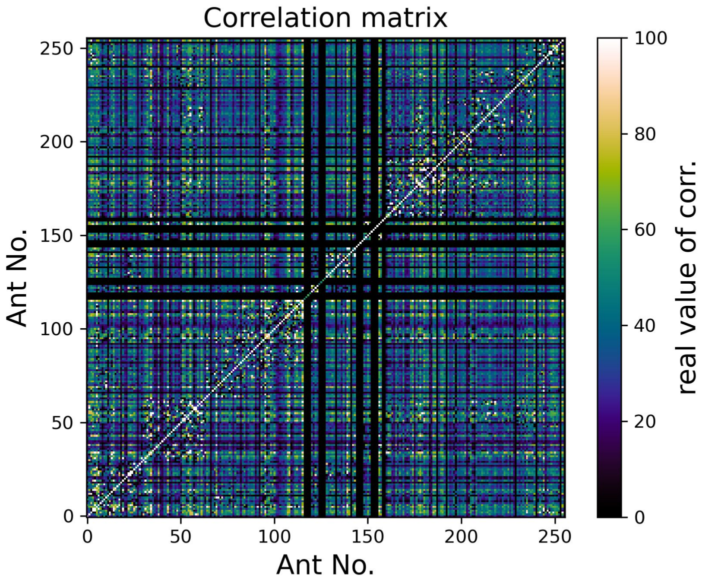
Signals from all the antenna-pair combinations are correlated and integrated over a certain time interval, to generate correlation products, or 'visibilities'

Auto-correlation products:
The products obtained by the correlation of a signal with itself (visible along the diagonal)

Cross-correlation products:
The products obtained by the correlation of different signals

For a telescope with N_a antennas:

- Number of auto-correlation products: N_a
- Number of cross-correlation products: $N_a(N_a - 1)$



Correlation matrix (format: .fits files)
Generated from visibilities obtained from EDA2, at 166 MHz

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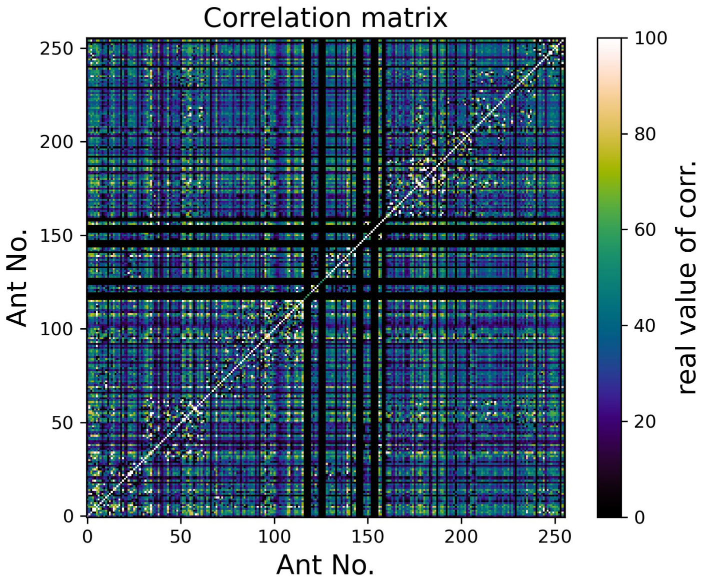

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Correlation products/visibilities: Input for Imaging

Principles of Radio Astronomy Imaging (Imaging)

- An image is created for a given frequency and a given point in time, from the visibilities obtained from all the baselines

- Visibility is related to the the image of the sky through van Cittert-Zernike theorem, simplified to the following equation:

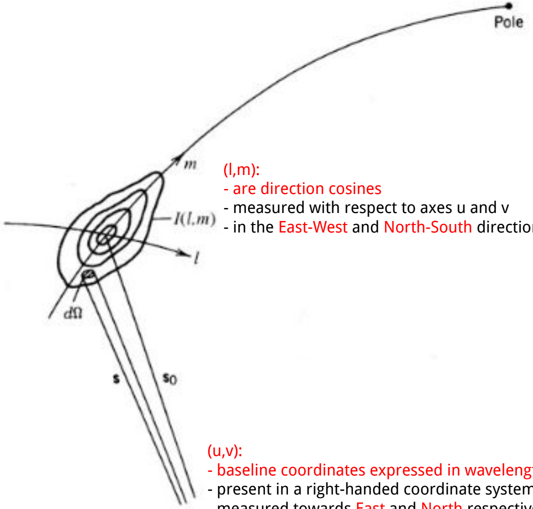
Complex Visibility function **Sky brightness distribution - Sky Image**

$$\boxed{V(u,v)} = \iint \boxed{I(l,m)}\, e^{-i2\pi(ul+vm)}\, dl\, dm$$

For derivation: See Ch.14 TMS
Thompson, A., Moran, J., & Swenson, Jr, G. 1991, Interferometry and Synthesis in Radio Astronomy

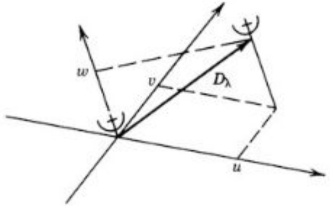
- Fourier transform relation between Visibility & Sky Brightness
- Visibility and Sky Brightness form a Fourier pair

- To get, what is called a 'dirty image' of the sky, a 2D inverse Fourier transform is applied on the visibilities to calculate I(l,m) from V(u,v)



(l,m):
- are direction cosines
- measured with respect to axes u and v
- in the East-West and North-South directions

(u,v):
- baseline coordinates expressed in wavelengths
- present in a right-handed coordinate system
- measured towards East and North respectively
- in a plane parallel to the plane of the source



Principles of Radio Astronomy Imaging (Imaging, Gridding)

- In practice, a 2D discrete Fourier transform (DFT) is performed by the computer, represented by the below equation:

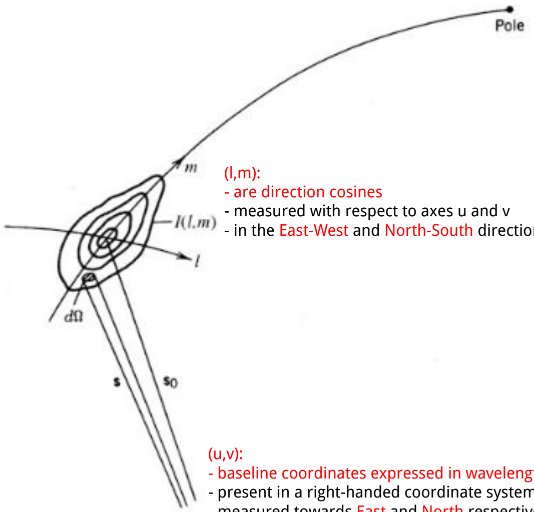
$$I(l, m) = \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} V(u_i, v_j) e^{-i2\pi\left(\frac{ul}{N} + \frac{vm}{M}\right)}$$

- 2D DFT has a high computational complexity: O(N^2M^2)

- Implemented through 2D "Fast fourier transform (FFT)" algorithm

- 2D FFT has a reduced computational complexity: O(NM log(NM))

- 2D FFT requires data to be placed on a regularly spaced grid in the UV-plane



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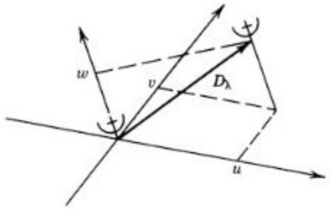

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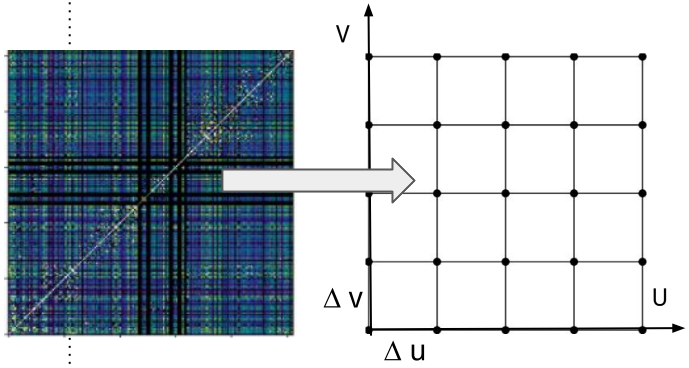

Gridding is the process of re-sampling the visibilities on a grid of regularly spaced cells

One visibility corresponding to a cell	Cell will have that value
No visibility corresponding to a cell	Cell will have a zero value
Many visibilities corresponding to a cell	Visibilities are summed with some weighting and assigned to the cell

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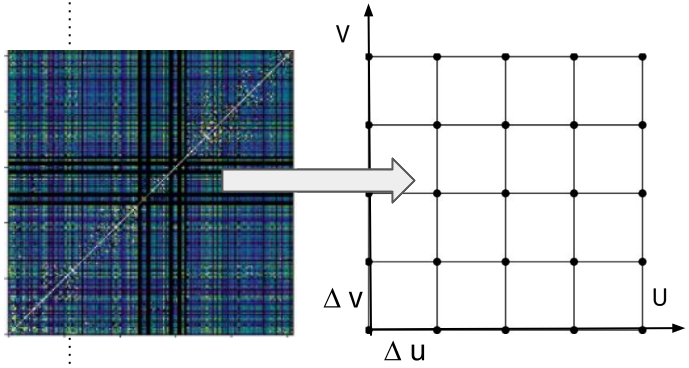

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One visibility corresponding to a cell	Cell will have that value
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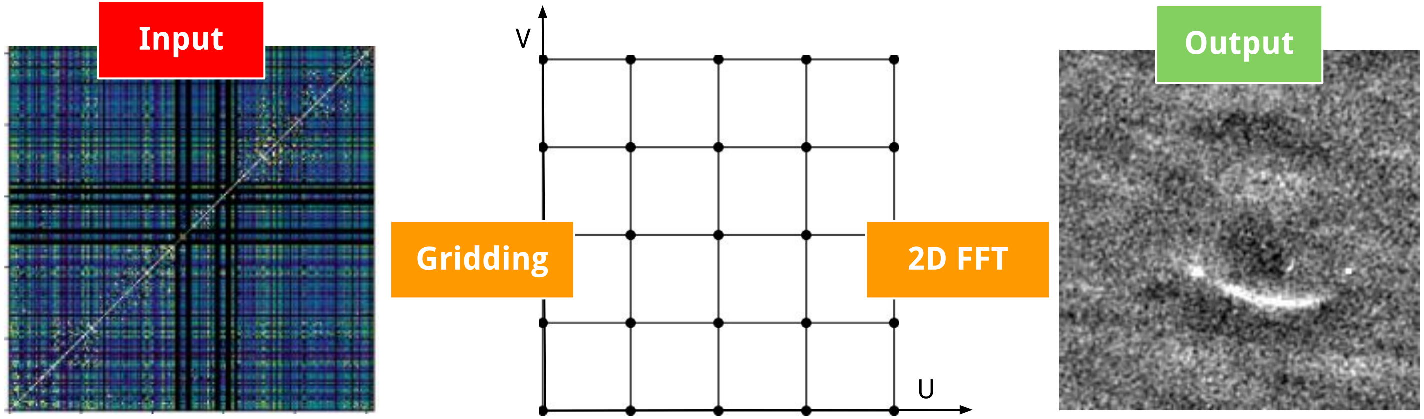
Natural weighting:
- All data receive the same weight
- Number of visibilities in each cell decide the weighting

Uniform weighting:
- All cells receive the same weight
- If there are multiple values per cell, they are averaged to make the weights of the cell same

Principles of Radio Astronomy Imaging (Summary)



$$V(u,v) = \iint I(l,m)e^{-i2\pi(ul+vm)}\, dl\, dm$$

$$I(l,m) = \sum_{i=0}^{N-1}\sum_{j=0}^{M-1} V(u_i,v_j)e^{-i2\pi\left(\frac{ul}{N}+\frac{vm}{M}\right)}$$

1) Signals from all the baselines are correlated and integrated over a certain time interval to generate visibilities

2) Visibilities are re-sampled/gridded on a regularly spaced grid

3) 2D FFT is performed on the gridded visibilities to give the output sky image

Part 3: Work done so far

Work done so far

Project 1

Task 1

Developed two standalone test versions of the GPU imager, generating all-sky images from EDA2 data (from Marcin's CPU imager as a starting point)

- Test GPU imager for a single time-step having a single-channel
- Test GPU imager for a single time-step having multiple-channels

Task 2

Testing and Verification:

Tested and verified the GPU imager by comparing the resulting images with the reference CPU images

Task 3

Benchmarking:

- Compared performance of the GPU and the CPU versions of the imager on Topaz and Setonix
- Compared the performance of different versions of parallel gridding implementations done on Topaz and Setonix

Project 2

Processing & Analysis:

- Analysed a few hours of EDA2 data, and searched for potential FRB candidates

Project 1

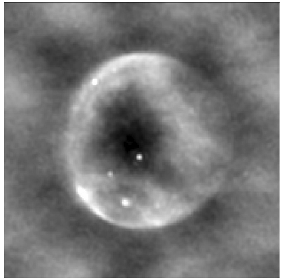
Started with: Marcin's CPU Imager (BLINK)

CPU imager generated images of the entire visible hemisphere (all-sky images)
- using visibilities from SKA-Low stations (mostly EDA2)
- for a single time stamp and a single frequency channel
- CPU for both gridding and imaging
- Fourier transform was performed using the fftw library

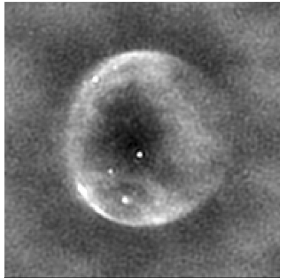
Tested on real data:
Resulting CPU image was compared to images produced by the well established imagers using options corresponding to the CPU imager (Natural weighting, no cleaning etc, frequency = 160 MHz)

Tested on simulated data:
Visibilities were simulated using CASA, from MWA antenna positions
- using Hydra A radio galaxy as model source, frequency = 154 MHz
- generated images using both WSCLEAN and BLINK imager

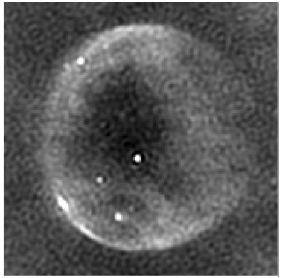
BLINK Image



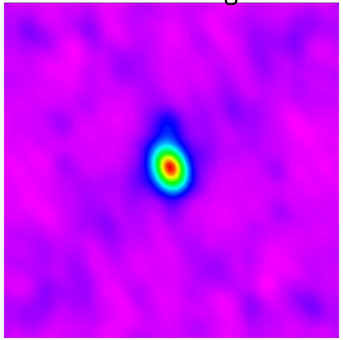
CASA Image



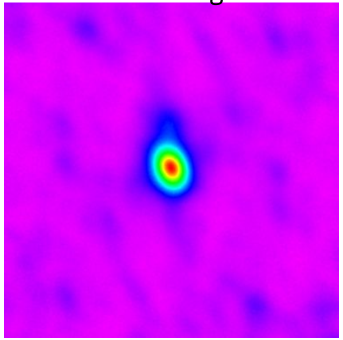
MIRIAD Image



WSClean Image



BLINK Image



Started with: Marcin's CPU Imager (BLINK)

CPU imager generated images of the entire visible hemisphere (all-sky images)
- using visibilities from SKA-Low stations (mostly EDA2)
- for a single time stamp and a single frequency channel
- CPU for both gridding and imaging
- Fourier transform was performed using the fftw library

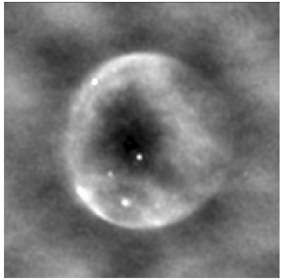
These comparisons verified that the test CPU imager generated correct images

These CPU images were my reference images for future comparisons

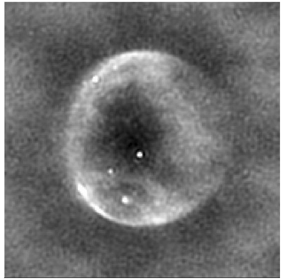
Tested on real data:
Resulting CPU image was compared to images produced by the well established imagers using options corresponding to the CPU imager (Natural weighting, no cleaning etc, frequency = 160 MHz)

Tested on simulated data:
Visibilities were simulated using CASA, from MWA antenna positions
- using Hydra A radio galaxy as model source, frequency = 154 MHz
- generated images using both WSCLEAN and BLINK imager

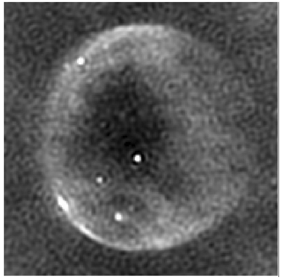
BLINK Image



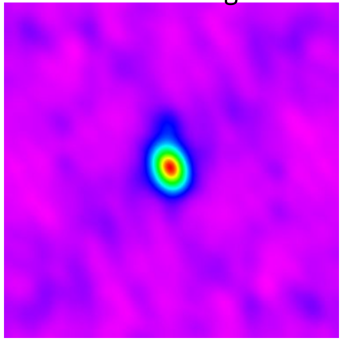
CASA Image



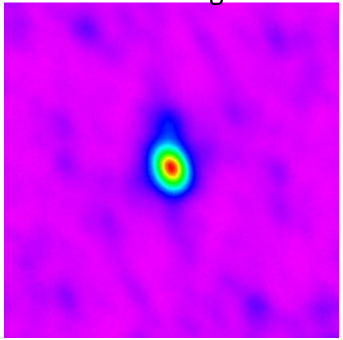
MIRIAD Image



WSClean Image



BLINK Image



GPU Imager: Single time-step, single channel

Project 1

Task 1

Implemented based on:
single time-step, single channel CPU imager

Code was written in CUDA:
- CUDA stands for “Compute Unified Device Architecture”
- Parallel programming framework developed by NVIDIA
- CUDA code is written in C/C++
- It has similar tools and libraries
(to simplify the process of writing GPU code)

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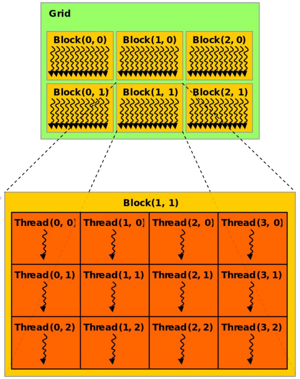
What happens on the GPU?
- Kernels/GPU functions are executed on the GPU
- By multiple "GPU threads" in parallel

- CUDA kernel is launched with a **GRID of BLOCKS of THREADS**
- Maximum threads in a block: 1024
- Maximum blocks: 2.2 Billion
- Grid: 1D, 2D or 3D



Source: Wikipedia

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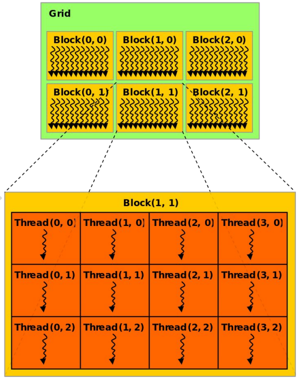

Source: Wikipedia

Gridding: CUDA kernel

For each visibility, calculate the (x, y) index in the UV grid

Assigning and adding (if required) the visibility at this index in the UV-grid

Parallelise this process over all the visibilities

Addition of visibilities was done using atomicAdd operations, to ensure that two threads don’t write to the same UV cell at the same time

Project 1

Task 1

GPU Imager: Single time-step, single channel

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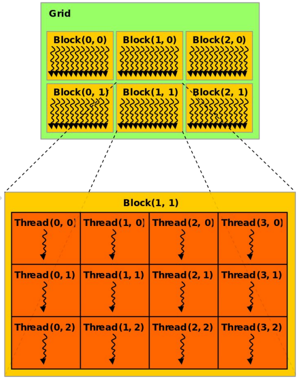
- Grid: 1D, 2D or 3D

CPU: fftw library

Imaging:
Fourier transform

GPUs: cuFFT library



Source: Wikipedia

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Assigning and adding (if required) the visibility at this index in the UV-grid

Parallelise this process over all the visibilities

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GPU Imager: Single time-step, multi-channel

Project 1

Task 1

GPU imager was implemented for multiple frequency channels (f), within a given time-step

Project 1
Task 1

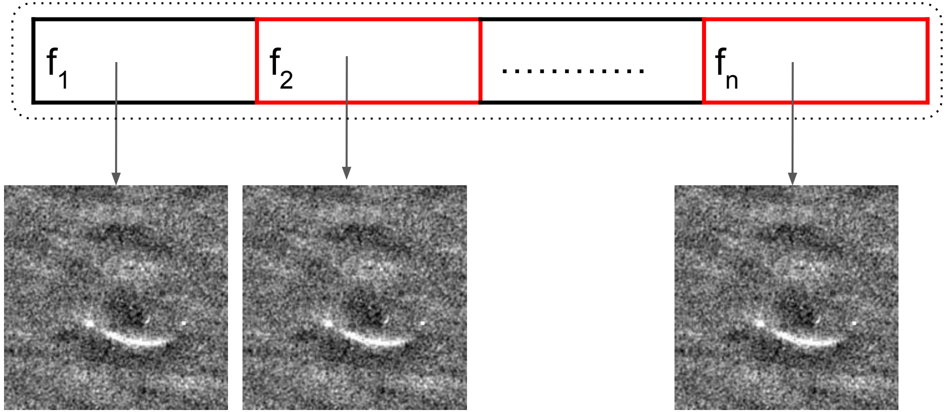
GPU Imager: Single time-step, multi-channel

GPU imager was implemented for multiple frequency channels (f), within a given time-step

For FFT: cuFFTPlanMany() was used:
- batched FFTs on multiple gridded visibilities in a single step

cuFFTPlanMany() + cuFFTExecC2C: creation + execution

Gridded visibilities for 1 time-step have f frequency channels, stored as a 1D array



GPU Imager: Single time-step, multi-channel

Project 1
Task 1

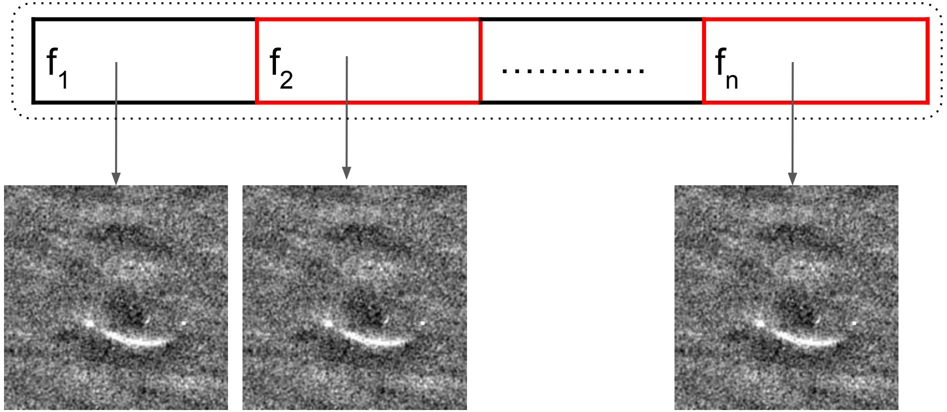
GPU imager was implemented for multiple frequency channels (f), within a given time-step

For FFT: cuFFTPlanMany() was used:
- batched FFTs on multiple gridded visibilities in a single step

Gridding: parallel manner over the frequency channels

cuFFTPlanMany() + cuFFTExecC2C: creation + execution

Gridded visibilities for 1 time-step have f frequency channels, stored as a 1D array



Using CUDA streams

Different kernels executed independently on different streams

With NTHREADS = 1024
nBLOCKS = 64
Array of 15 streams

Kernel is launched for every frequency channel of a given time-step

Total number of kernel launches
$= f_{channels} \times T_{time\text{-}steps}$

Using 2D-grid of CUDA Blocks

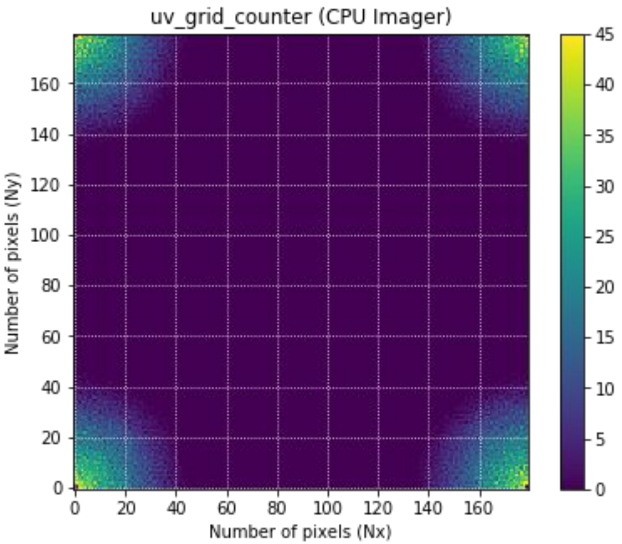
CUDA stream creation has some over-heads + more kernel launches

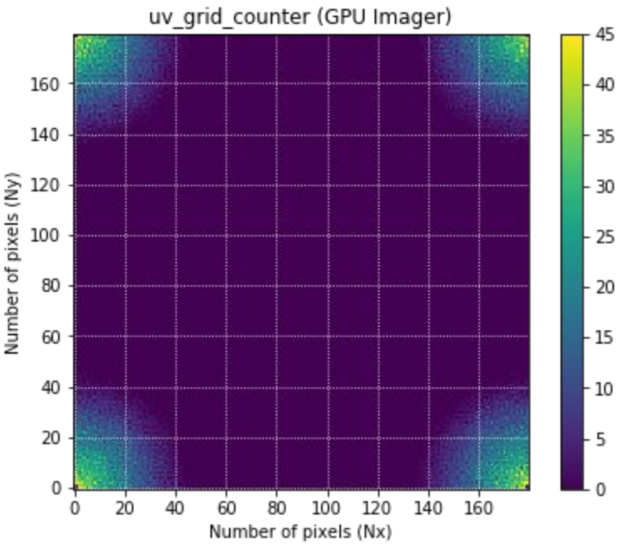
With NTHREADS = 1024
2D grid of CUDA Blocks
2D grid : ($64 \times nT_{time\text{-}steps}$)

Kernel is launched ONLY ONCE for a given time-step

Total number of kernel launches
$= T_{time\text{-}steps}$

Validation of GPU images: UV grid counter





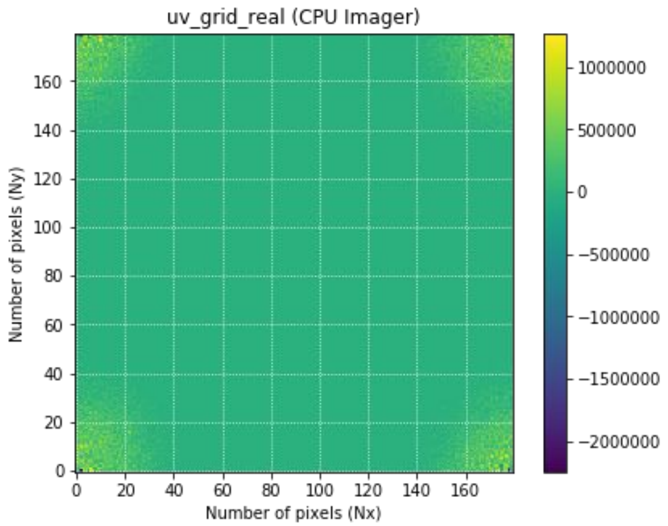
- **UV-grid counter:** gives a ‘count’ for how many visibilities have been added to a specific cell

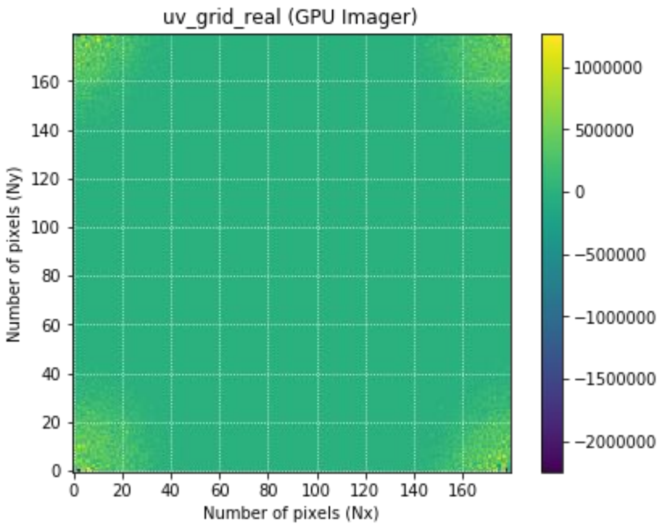
- UV-grid counter of the GPU imager perfectly matched with the UV-grid counter of the CPU imager

- Equal number of visibilities have been placed into each corresponding cell within the UV grid

- This alignment confirmed the proper functionality of the GPU gridding kernel

Validation of GPU images: UV grid (real)





CPU and GPU UV-grids were also similar

Small fractional differences of the order of 0.25

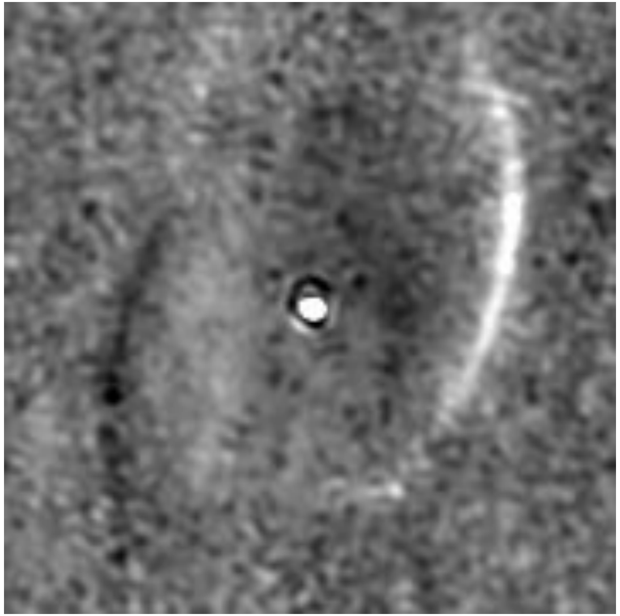
CPU: Sequential gridding

GPU:
- Parallel gridding using atomicAdd operations
- Random order of additions in every execution
- Rounding errors, caused by using float

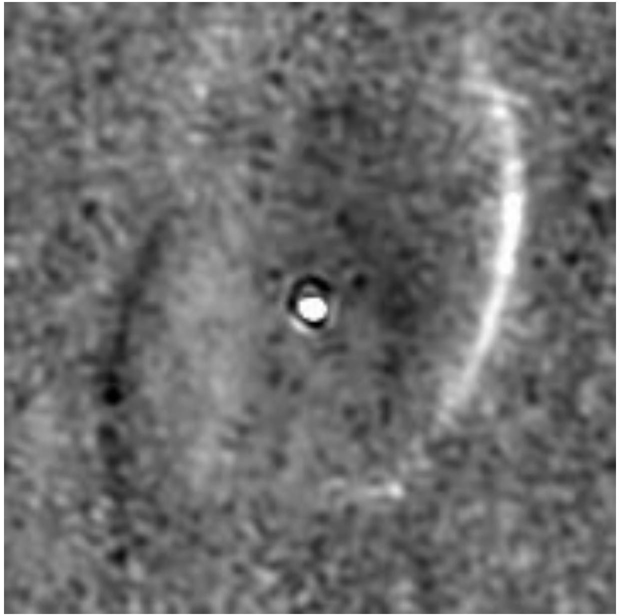
Validation of GPU images: dirty image (real)

Project 1

Task 2



CPU



GPU

GPU images matched with that the reference CPU images

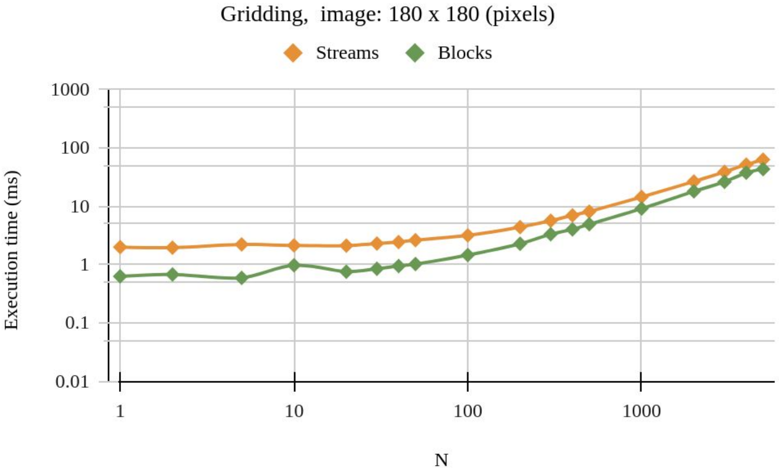
Though there were small differences of the order of 0.0001 Jy in the final real and imaginary dirty image
(due to small fractional differences in gridded visibilities)

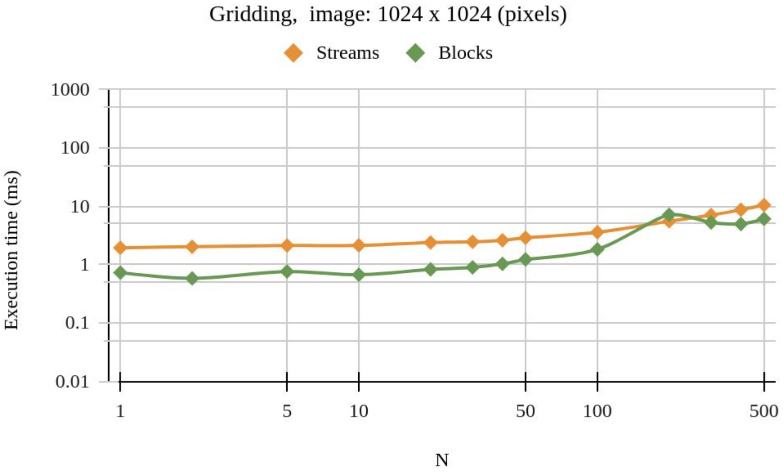
These differences can be safely discarded!

Project 1

Task 3

Benchmarks: Streams vs Blocks (Setonix)





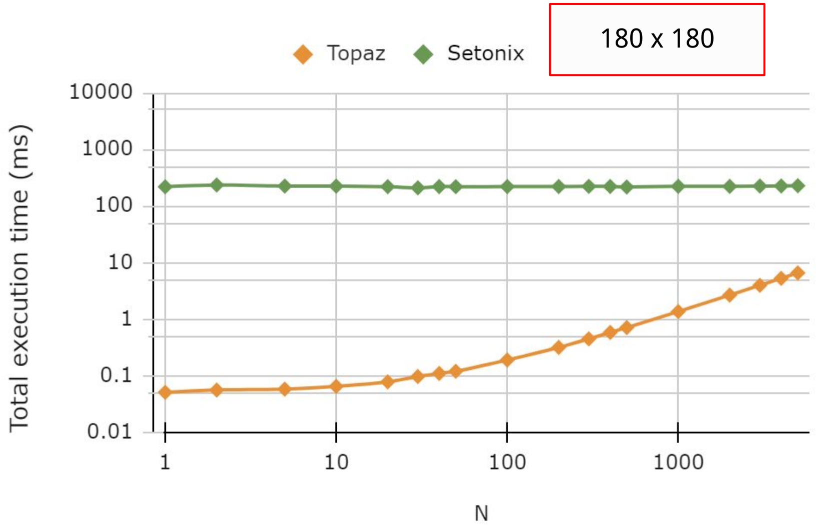
For smaller & higher image sizes:
- CUDA blocks are around slightly faster (1.5 to 2 times) than CUDA streams (on average)

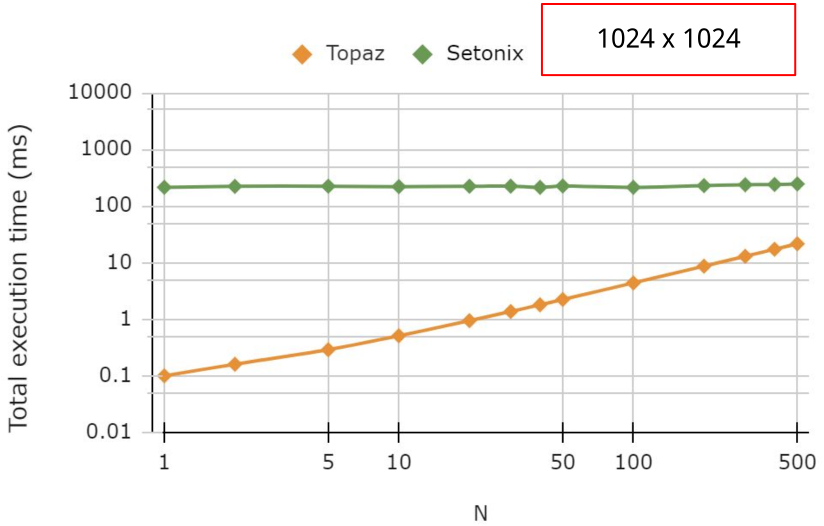
- Similar performance was observed on Topaz!

Topaz vs Setonix: cuFFT PlanMany

Project 1

Task 3





PlanMany creation:
~ 360 ms (Topaz)
~ 9 ms (Setonix)

PlanMany creation run-times times are constant irrespective of number of images (N) generated simultaneously

Happens only once before the entire execution

PlanMany execution:
For both image sizes,
Regardless of the image size and the number of images generated per execution,
On Topaz:
- The run-time of PlanMany executions increases with the increasing number of images generated per execution

On Setonix:
- The total run-time for PlanMany execution remains nearly constant
- Around 220 ms

Why?
- HIP framework handles FFT PlanMany operations differently than CUDA

- Some calculations are probably moved from PlanMany creation to PlanMany execution in the HIP?

Benchmarks: Gridding (summary)

The most important thing to note here is that the GPU gridding performs extremely fast on both Topaz and Setonix!

Topaz

NVIDIA V100 GPUs

180 x 180

Number of images	Execution time
5000	6.06 ms
1	1.2 μs

1024 x 1024

Number of images	Execution time
500	7.61 ms
1	15.2 μs

Setonix

AMD MI250X GPUs

180 x 180

Number of images	Execution time
5000	43.61 ms
1	8.7 μs

1024 x 1024

Number of images	Execution time
500	6.11 ms
1	12.2 μs

From these values, it's clear that it takes only a few microseconds to perform gridding for a single image!

Benchmarks: FFTs (summary)

Project 1

Task 3

The most important thing to note here is that the FFT performs extremely fast on both Topaz and Setonix!

Topaz — NVIDIA V100 GPUs

180 x 180

Number of images	Execution time
500	0.71 ms
1	1.42 µs

1024 x 1024

Number of images	Execution time
500	21.46 ms
1	42.92 µs

Setonix — AMD MI250X GPUs

180 x 180

Number of images	Execution time
500	216.30 ms
1	432.61 µs

1024 x 1024

Number of images	Execution time
500	244.89 ms
1	489.68 µs

- It can be seen that performing the operation of FFT using GPUs is remarkably fast

- From these values, it's clear that it takes only a few (µs to ms) to perform FFT to generate a single image!

Project 1

Task 3

Benchmarks: FFTs (summary)

The most important thing to note here is that the FFT performs extremely fast on both Topaz and Setonix!

Topaz

Decommissioned!

180 x[redacted]

Number of images	Executi[redacted]
500	[redacted]
1	[redacted]

[redacted]24 x 1024

[redacted]	Execution time
[redacted]	[redacted]ms
1[redacted]	[redacted]s

Setonix

All future processing on Setonix

180 x 180

Number of images	
500	21
1	432.61

1024 x 1024

ber images	Execution time
500	244.89 ms
1	489.68 μs

- It can be seen that performing the operation of FFT using GPUs is remarkably fast

- From these values, it's clear that it takes only a few (μs to ms) to perform FFT to generate a single image!

Can we do close to real time imaging?

Time taken to image (considering only gridding + FFT)
- 1 minute of data
- if we want to image 32 channels in 100 ms time resolution
- for image sizes (180 x 180, 1024 x 1024)

Number of images in 1 minute of data, 100 ms imaging:
60s/100ms = 600 images
Time taken to generate 30 images → 0.28 ms
Time taken to generate 32 x 600 images → ??

Question:
Can we process a large amount of data, offline in a reasonable amount of time?

Setonix performs fast enough for us to further process a larger amount of data!

Image Size	System	Execution time for 30 images (ms)	Estimated execution time for 32 x 600 images (minutes)
180 x 180	Topaz	0.28	0.003
	Setonix	211.79	$\boxed{2.26}$
1024 x 1024	Topaz	1.37	0.01
	Setonix	223.63	$\boxed{2.39}$

Topaz, CUDA : 1 minute of data ~ <<< 1 min to process

Setonix: 1 minute of data ~ 2.3 minutes to process

Project 2

Project 2: Pilot FRB searches using EDA2 data

Next step?

Test this BLINK imager on a larger EDA2 data, and perform pilot FRB searches to see what we can see in these images?

Data used:

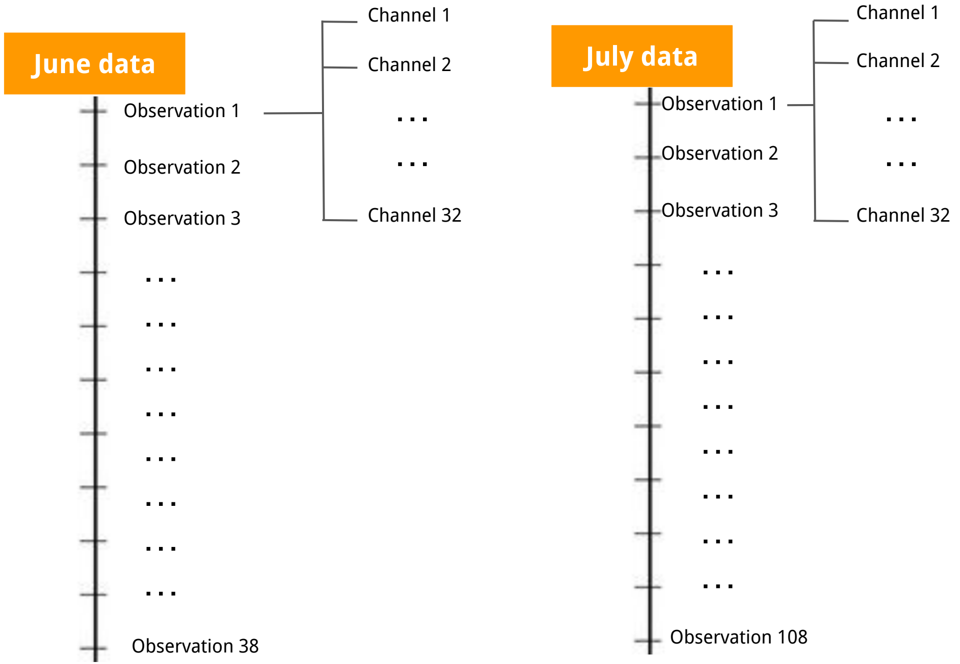
- Marcin recorded EDA2 visibilities in 100ms time resolution and bandwidth of about 0.94 MHz fine channelised into 32 fine channels (centre frequency of 230 MHz)
- These visibilities were imaged into 180 x 180 all-sky images on Setonix

- The observations were recorded on:
- **6th June 2023:**
    - 38 observations (~ 38 minutes duration)
- **9th July 2023:**
    - 108 observations (~ 108 minutes duration)

- Each observation was 1 minute long

- Thus, the total number of images produced,
  1 observation: 32 x 600 = 19200

- June data: 38 x 32 x 600 = 729,600
- July data: 108 x 32 x 600 = 2,073,600



Data Preparation

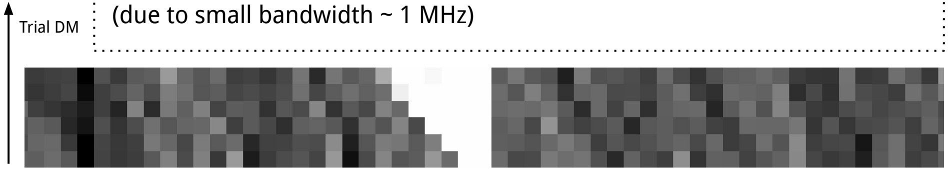
Using existing software mentioned in Anderson et al., 2021,
for each pixel (i.e. for every direction in the sky):

Latest EDA2 all-sky image, 32 channels, centre frequency = 230 MHz, UTC: 10:37:08 (1st June 2023)

Dynamic spectra was generated using all the images obtained across all the time steps and frequency channels

Dynamic spectrum at pixel (144, 69)

De-dispersed time series was generated for different DM trials, ranging from 0 to 1000 pc cm^{-3}, in DM steps of 150 pc cm^{-3}
(due to small bandwidth ~ 1 MHz)



De-dispersed time series

Data Preparation

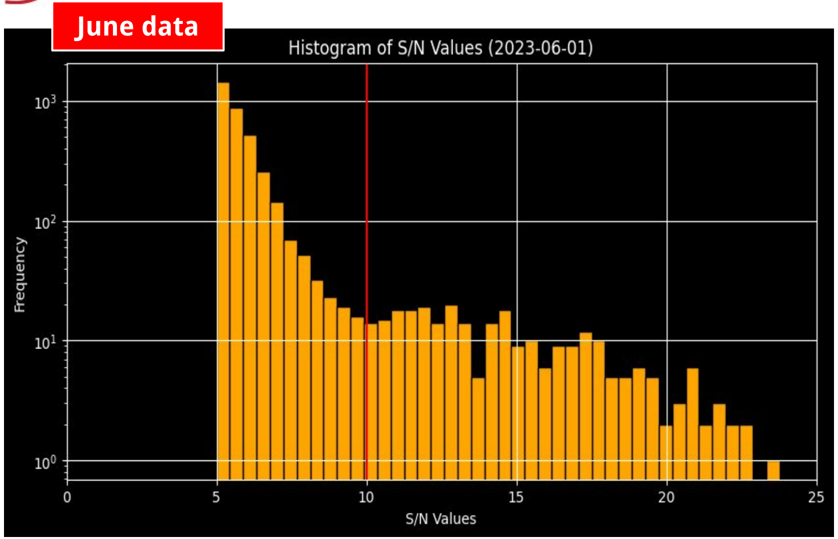
The last step was to iterate through all values of these time-series FITS files to look for values that had S/N > 5 and store the results in .txt files, one for each June and July data.

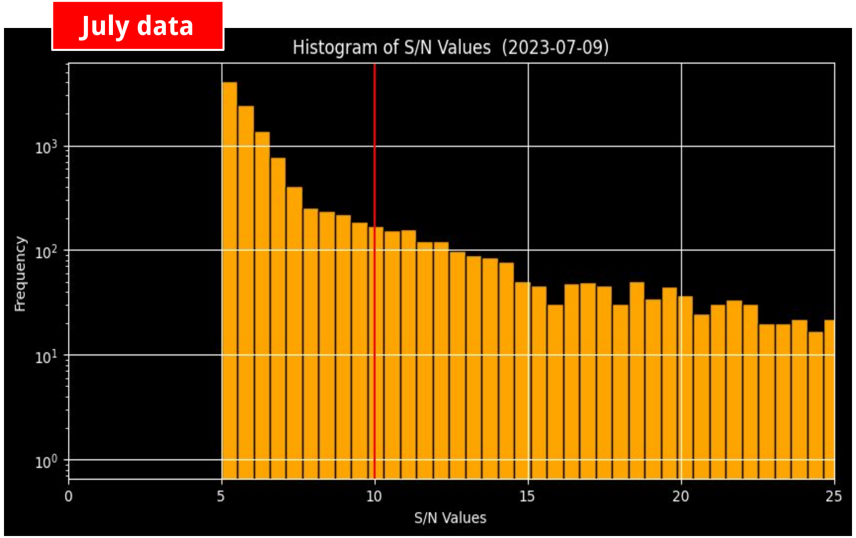
The resulting .txt files had the following format:

Candidate INDEX	Observing time step	Pixel X	Pixel Y	DM Index	sampno	S/N
0	103049	50	84	4	597	5.52
1	103049	56	81	4	598	5.59
2	103049	59	120	5	597	6.32
3	103049	61	110	5	597	5.24
…	…	…	…	…	…	…

This data was given to me for further analysis and test FRB search:
1. Images from all the 38 (June) and 108 (July) observations
2. Dynamic spectra plots for each pixel
3. De-dispersed time-series plots for each pixel
4. The resulting .txt files which had all candidates, from all obs with S/N > 5

Distribution of S/N





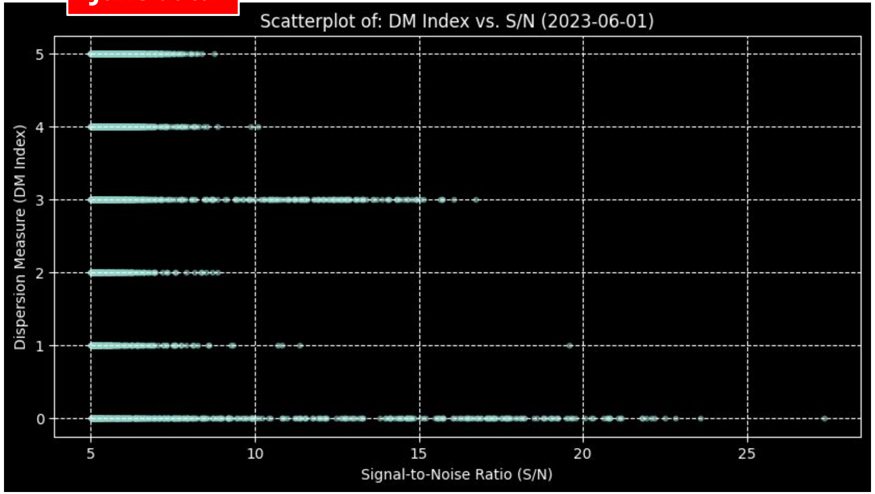
Vertical red line is at: S/N = 10 on the x-axis

Number of candidates kept dropping until S/N = 10

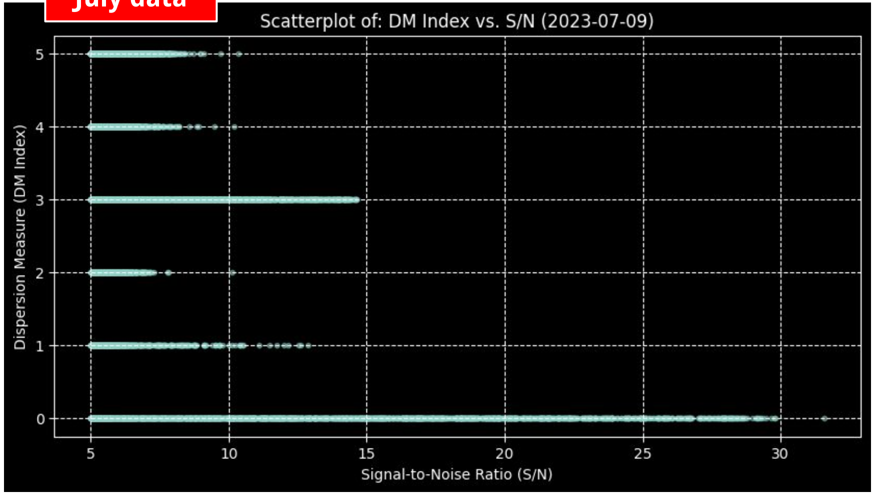
From S/N = 10 onwards, the number of candidates stayed more or less constant

Distribution of DM vs S/N

June data



July data



Most of the high S/N candidates (with S/N > 10), had a DM-index of 0
(DM_{max} = 150 pc cm^{-3})

Very few candidates had S/N > 10 and DM-index 4, 5
(DM_{max} = 750, 900 pc cm^{-3})

Data Analysis

The next step was to inspect these candidates

June data

S/N > 5

- Candidates: 3726
- Time-steps: 30

July data

S/N > 5

- Candidates: 11920
- Time-steps: 70

Data Analysis

The next step was to inspect these candidates

June data

S/N > 5

- Candidates: 3726
- Time-steps: 30

- Impossible to inspect 3000+ candidates
- Hence, decided to have a higher threshold of S/N > 10
- To reduce these candidates for inspection

July data

S/N > 5

- Candidates: 11920
- Time-steps: 70

Data Analysis

The next step was to inspect these candidates

June data

S/N > 5

- Candidates: 3726
- Time-steps: 30

S/N > 10 →

- Candidates: 272
- Time-steps: 30

July data

S/N > 5

- Candidates: 11920
- Time-steps: 70

S/N > 10 →

- Candidates: 1829
- Time-steps: 70

Data Analysis

The next step was to inspect these candidates

June data

S/N > 5

- Candidates: 3726
- Time-steps: 30

S/N > 10

- Candidates: 272
- Time-steps: 30

Excluded:
- Time-steps which had a lot of candidates
- In some cases even up to 300 candidates from a single time-step
- Possibly because these time-steps could have been affected by RFI
- So, all these candidates would be rubbish, false positive candidates

July data

S/N > 5

- Candidates: 11920
- Time-steps: 70

S/N > 10

- Candidates: 1829
- Time-steps: 70

Data Analysis

The next step was to inspect these candidates

June data

S/N > 5

- Candidates: 3726
- Time-steps: 30

$\xrightarrow{\text{S/N > 10}}$

- Candidates: 272
- Time-steps: 30

$\xrightarrow{\text{Remove RFI}}$

- Candidates: 13
- Time-steps: 5

July data

S/N > 5

- Candidates: 11920
- Time-steps: 70

$\xrightarrow{\text{S/N > 10}}$

- Candidates: 1829
- Time-steps: 70

$\xrightarrow{\text{Remove RFI}}$

- Candidates: 8
- Time-steps: 6

Data Analysis

The next step was to inspect these candidates

June data

S/N > 5

- Candidates: 3726
- Time-steps: 30

S/N > 10

- Candidates: 272
- Time-steps: 30

Remove RFI

- Candidates: 13
- Time-steps: 5

On Horizon (5)

Remaining Candidates: 8

July data

S/N > 5

- Candidates: 11920
- Time-steps: 70

S/N > 10

- Candidates: 1829
- Time-steps: 70

Remove RFI

- Candidates: 8
- Time-steps: 6

On Horizon (3)

Remaining Candidates: 5

Data Analysis

The next step was to inspect these candidates

June data

S/N > 5

- Candidates: 3726
- Time-steps: 30

S/N > 10

- Candidates: 272
- Time-steps: 30

Remove RFI

- Candidates: 13
- Time-steps: 5

On Horizon (5)

Remaining Candidates: 8

All these candidates had their DM values within 150 pc cm^{-3}
Flux density ~ mJy

FRBs?

July data

S/N > 5

- Candidates: 11920
- Time-steps: 70

S/N > 10

- Candidates: 1829
- Time-steps: 70

Remove RFI

- Candidates: 8
- Time-steps: 6

On Horizon (3)

Remaining Candidates: 5

Data Analysis

The next step was to inspect these candidates

June data

S/N > 5

- Candidates: 3726
- Time-steps: 30

S/N > 10 →

- Candidates: 272
- Time-steps: 30

Remove RFI →

- Candidates: 13
- Time-steps: 5

On Horizon (5) →

Remaining Candidates: 8

Check if any of these candidates could be due to pulsars or nearby satellites?

FRBs? ✗

Pulsars ?

Satellites ?

July data

S/N > 5

- Candidates: 11920
- Time-steps: 70

S/N > 10 →

- Candidates: 1829
- Time-steps: 70

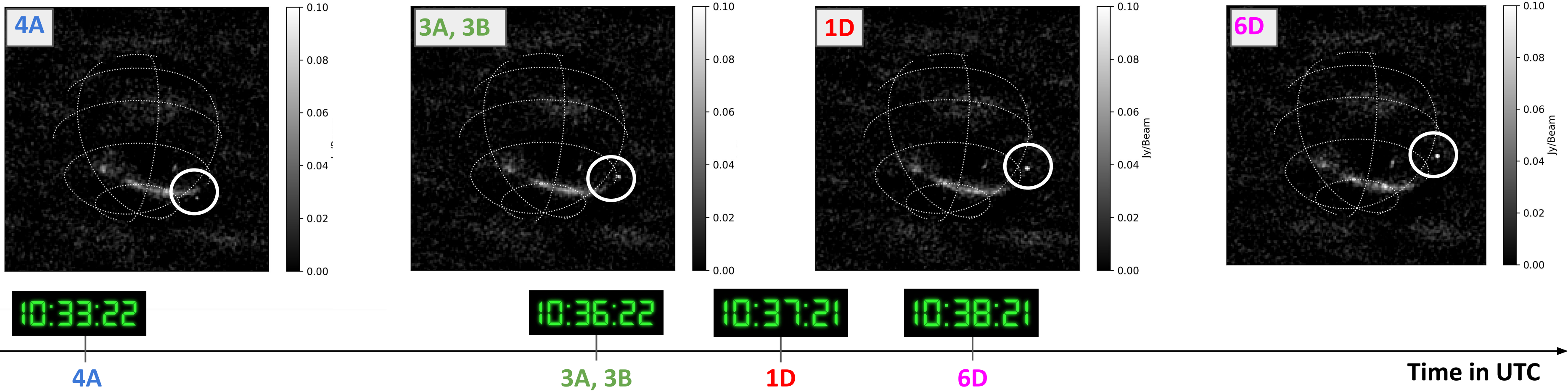
Remove RFI →

- Candidates: 8
- Time-steps: 6

On Horizon (3) →

Remaining Candidates: 5

Results: (June data) Almost on-horizon: 5 candidates

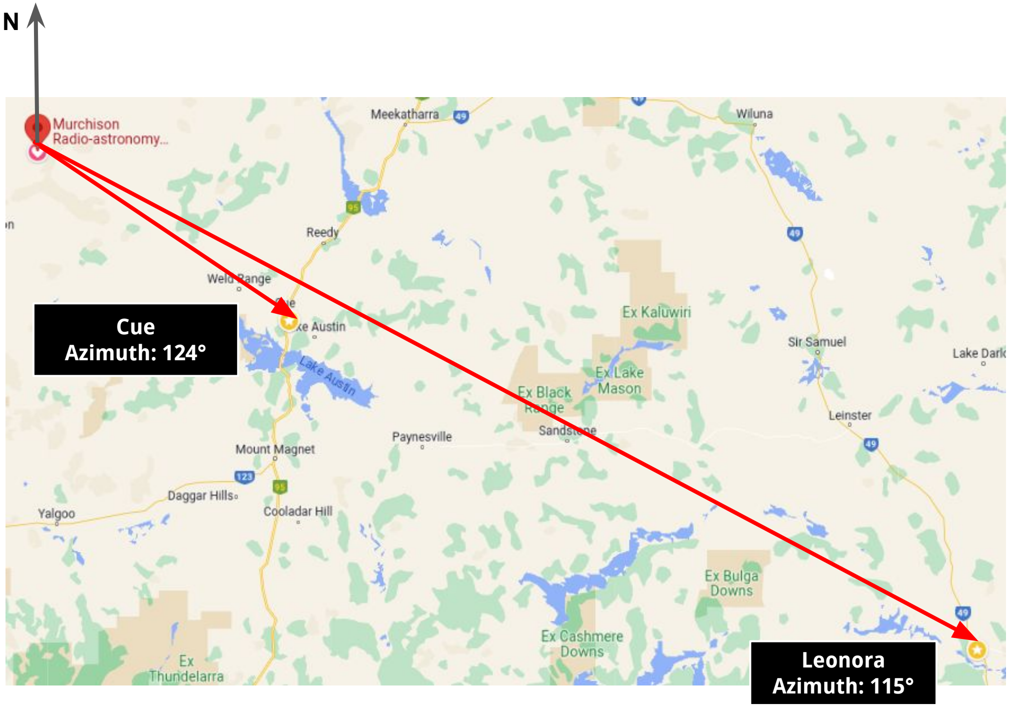


- These candidates were observed within a few minutes of each other

- All 5 candidates were clearly visible in the images

- The location of the candidates in the images is marked with white circles

Results: (June data) Almost on-horizon: 5 candidates



Radio signals could be coming from towns near MRO, in the direction of
- Cue Airport
- Leonora Airport

- Other RFI from towns near MRO?

Candidate Number	S/N	DM Index	Azimuth (Degrees)	Elevation (Degrees)
4A	**23.58**	**0**	124.01	29.46
3A	**19.58**	**1**	118.02	26.1
3B	**18.49**	**0**	118.26	25.64
1D	**27.35**	**0**	115.97	24.96
6D	**17.69**	**0**	113.57	24.24

Results: Not on-horizon candidates, pulsar check?

- I looked for pulsars that could present in a 5-degree and 3-degree radius from the ATNF pulsar catalogue

- For the pulsar candidates, I performed the following two checks:

DM limit check?

Flux density check?

Results: Not on-horizon candidates, pulsar check?

- I looked for pulsars that could present in a 5-degree and 3-degree radius from the ATNF pulsar catalogue

- For the pulsar candidates, I performed the following two checks:

DM limit check?

- We know the bandwidth we used to record this data (i.e. 1 MHz)
- Based on the dynamic spectrum, we could see that the maximum dispersive delay observed was less than 100 ms

- So, the maximum DM any of these candidates could have should not exceed 150 pc cm^{-3}

This check eliminated pulsars above this DM limit

Flux density check?

Results: Not on-horizon candidates, pulsar check?

- I looked for pulsars that could present in a 5-degree and 3-degree radius from the ATNF pulsar catalogue

- For the pulsar candidates, I performed the following two checks:

DM limit check?

- We know the bandwidth we used to record this data (i.e. 1 MHz)
- Based on the dynamic spectrum, we could see that the maximum dispersive delay observed was less than 100 ms

- So, the maximum DM any of these candidates could have should not exceed 150 pc cm^{-3}

This check eliminated pulsars above this DM limit

Flux density check?

- In these images (not flux-calibrated), the estimated sensitivity (σ) was ~ around 75 Jy

- So, to get detected in a 10σ detection, a pulsar should have a flux density of at least 750 Jy

Results: Not on-horizon candidates, pulsar check?

- I looked for pulsars that could present in a 5-degree and 3-degree radius from the ATNF pulsar catalogue

- For the pulsar candidates, I performed the following two checks:

DM limit check?

- We know the bandwidth we used to record this data (i.e. 1 MHz)
- Based on the dynamic spectrum, we could see that the maximum dispersive delay observed was less than 100 ms

- So, the maximum DM any of these candidates could have should not exceed 150 pc cm^{-3}

This check eliminated pulsars above this DM limit

Flux density check?

- In these images (not flux-calibrated), the estimated sensitivity (σ) was ~ around 75 Jy

- So, to get detected in a 10σ detection, a pulsar should have a flux density of at least 750 Jy

- All the pulsar candidates we got had their flux densities of the order of a few mJy at GHz frequencies

- After extrapolating these values to get their flux densities at 230 MHz (using the mean spectral index value of -1.6 (Jankowski et. al., 2018)), they were of the order of mJy

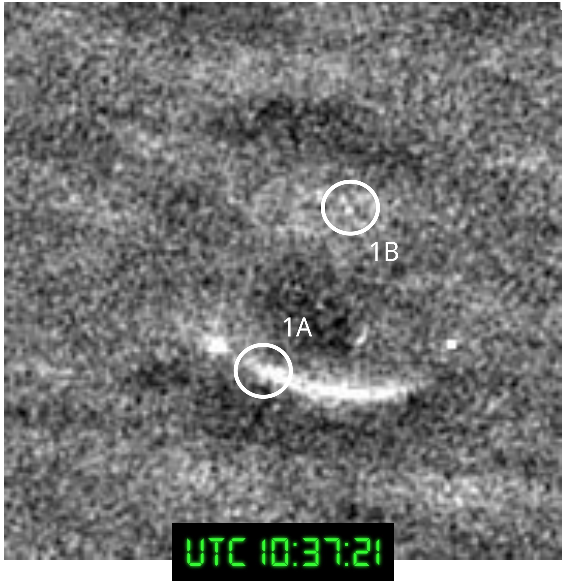
This essentially eliminated the possibility of any of these candidates being pulsars

Results: (June data) Candidate 1A and 1B

Candidates were observed at the same time

Dynamic spectrum of 1A

Dynamic spectrum of 1B



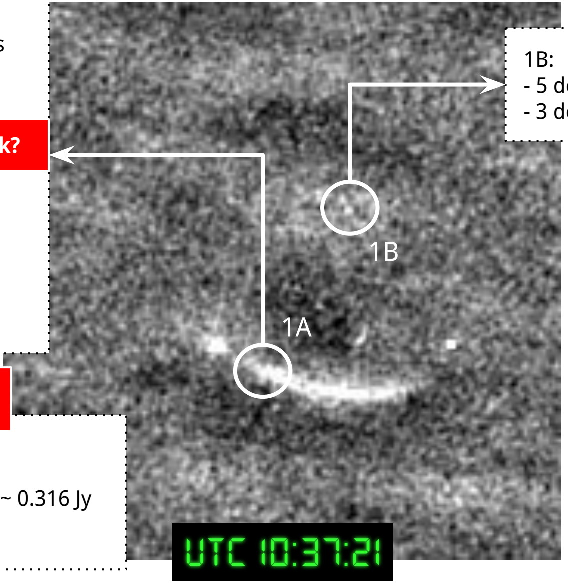
Results: (June data) Candidate 1A and 1B

Candidates were observed at the same time

Pulsar check?

Dynamic spectrum of 1A

Dynamic spectrum of 1B



1A:
- 5 degree radius : 2 pulsars
- 3 degree radius: 1 pulsar

Closest pulsar:
- J1418-3921
- DM = 60.49 pc cm^{-3}
- Min-Freq Flux density: 24 mJy at 400 MHz
- Angular distance: 1.7

DM check?

1B:
- 5 degree radius : 0 pulsars
- 3 degree radius: 0 pulsar

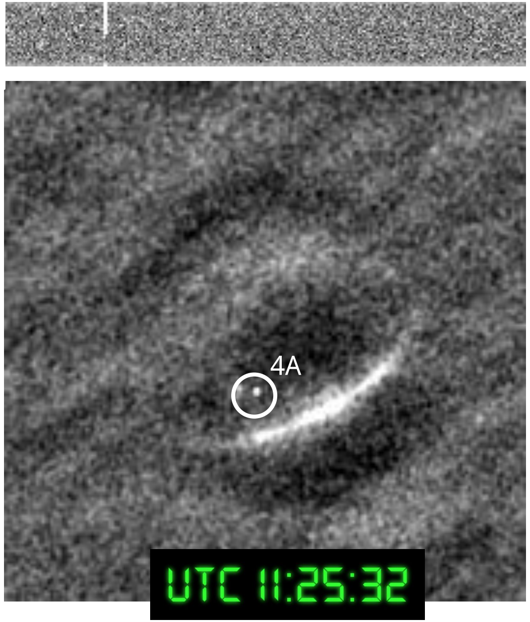
Flux density check?

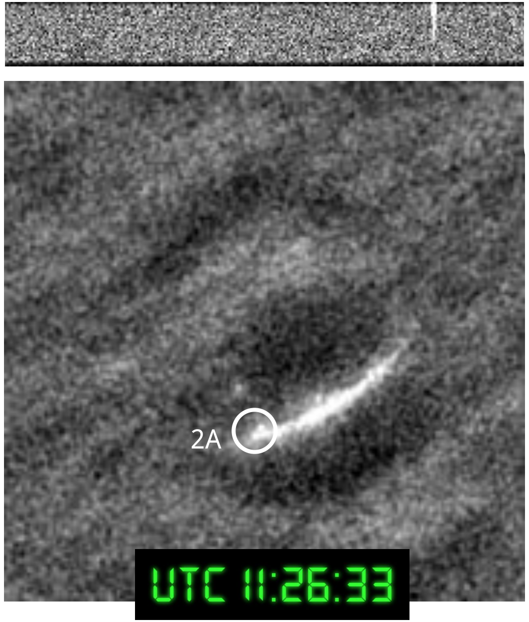
1A:
- Spectral Index: -4.66
- Flux Density at 230 MHz ~ 0.316 Jy
- Below 10σ threshold
- Not a pulsar

Results: (July data) Candidate 2A and 4A

Candidates were observed within a minute of each other

Dynamic spectrum of 4A





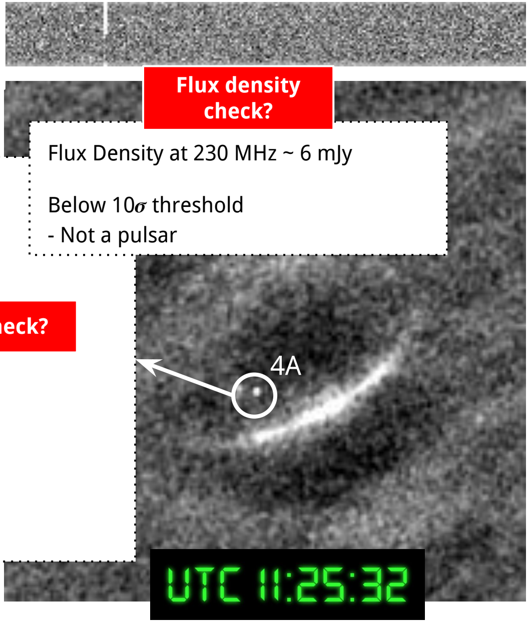
Dynamic spectrum of 2A

Results: (July data) Candidate 2A and 4A

Candidates were observed within a minute of each other

Pulsar check?

Dynamic spectrum of 4A



Flux density check?

Flux Density at 230 MHz ~ 6 mJy

Below 10σ threshold
- Not a pulsar

4A:
- 5 degree radius : 6 pulsars
- 3 degree radius: 3 pulsar

Closest pulsar:
- J1405-4656

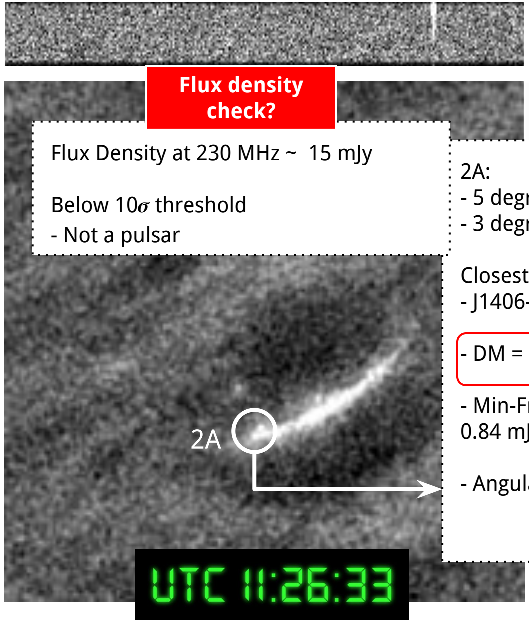
DM check?

- DM = 79.7 pc cm^{-3}

- Min-Freq Flux density:
0.31 mJy at 1400 MHz

- Angular distance: 1.89

Dynamic spectrum of 2A



Flux density check?

Flux Density at 230 MHz ~ 15 mJy

Below 10σ threshold
- Not a pulsar

2A:
- 5 degree radius : 61 pulsars
- 3 degree radius: 20 pulsar

Closest pulsar:
- J1406-5808

DM check?

- DM = 229 pc cm^{-3}

- Min-Freq Flux density:
0.84 mJy at 1400 MHz

- Angular distance: 0.981

Results: Not on-horizon candidates, satellite check?

- I also looked for satellites that could present in a 5-degree and 3-degree radius

- For the satellite candidates, I performed the following three checks:

Check 1

I eliminated all candidates that were either debris or rocket-bodies

Check 2

I eliminated all the the suspected satellite candidates that were not active

Check 3

I checked if the down-link frequencies of any of these satellites were around 230 MHz

Results: Not on-horizon candidates, satellite check?

- I also looked for satellites that could present in a 5-degree and 3-degree radius

- For the satellite candidates, I performed the following three checks:

Check 1

I eliminated all candidates that were either debris or rocket-bodies

Check 2

I eliminated all the the suspected satellite candidates that were not active

Check 3

I checked if the down-link frequencies of any of these satellites were around 230 MHz

There were no satellites that generally transmitted signals in this downlink frequency range

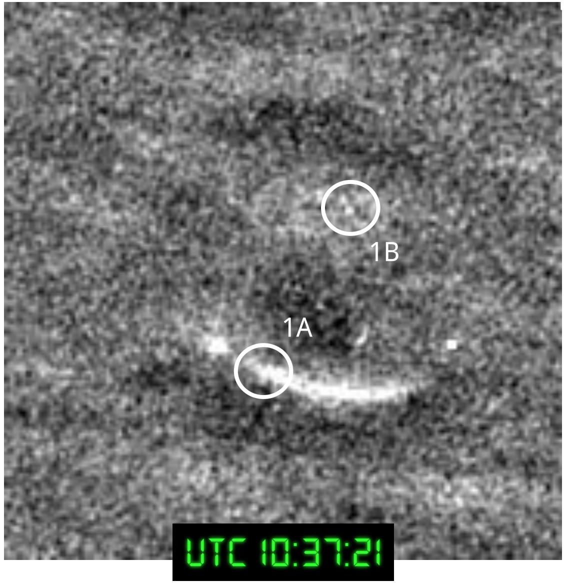
I am currently working with a PhD student from the Space Surveillance group (Dylan)
- to further see if any of these signals were possibly from satellites?
- as these could be unintended transmissions from these satellites?

Results: (June data) Candidate 1A and 1B

Candidates were observed at the same time

Dynamic spectrum of 1A

Dynamic spectrum of 1B



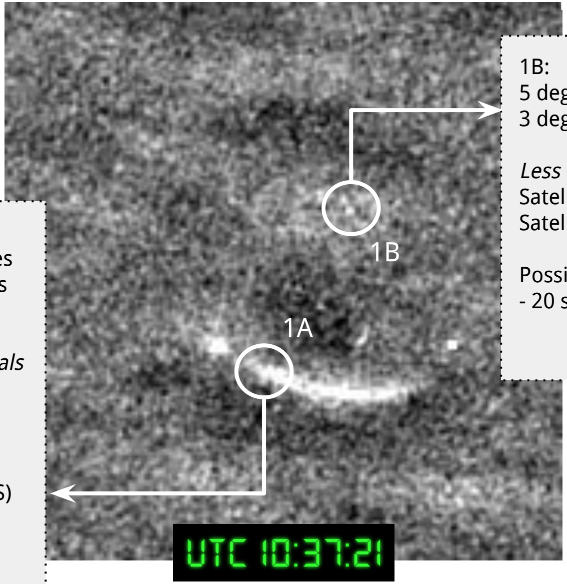
Results: (June data) Candidate 1A and 1B

Candidates were observed at the same time

Satellite check?

Dynamic spectrum of 1A

Dynamic spectrum of 1B



1B:
5 degree radius : 60
3 degree radius: 28

Less likely to transmit signals
Satellite debris: 7
Satellite rocket bodies: 1

Possible satellite?
- 20 satellites?

1A:
5 degree radius : 7 satellites
3 degree radius: 3 satellites
(2 DEB, 1 R/B)

Less likely to transmit signals
Satellite debris: 4
Satellite rocket bodies: 2

Possible satellite?
- COSMOS_2465_(GLONASS)
- Russian military satellite
- 19036.887 km (altitude)

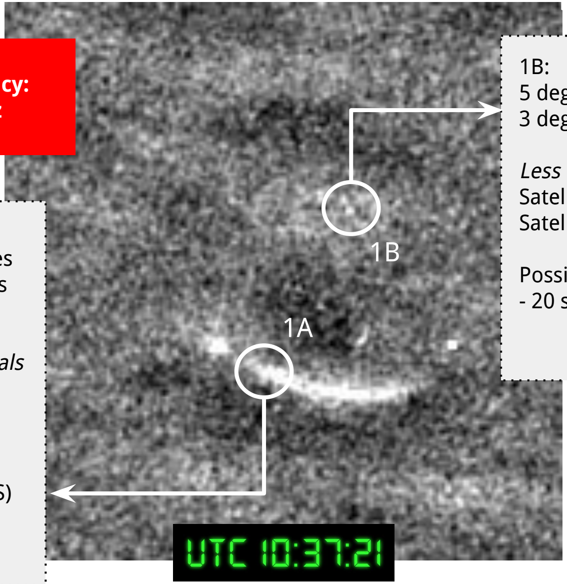
Results: (June data) Candidate 1A and 1B

Candidates were observed at the same time

Satellite check?

Dynamic spectrum of 1A

Dynamic spectrum of 1B



Downlink Frequency:
- 1200 to 1600 MHz

Active

1A:
5 degree radius : 7 satellites
3 degree radius: 3 satellites
(2 DEB, 1 R/B)

Less likely to transmit signals
Satellite debris: 4
Satellite rocket bodies: 2

Possible satellite?
- COSMOS_2465_(GLONASS)
- Russian military satellite
- 19036.887 km (altitude)

Active

1B:
5 degree radius : 60
3 degree radius: 28

Less likely to transmit signals
Satellite debris: 7
Satellite rocket bodies: 1

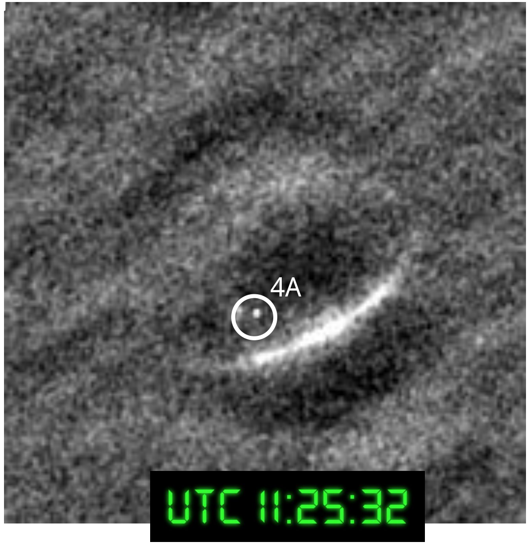
Possible satellite?
- 20 satellites?

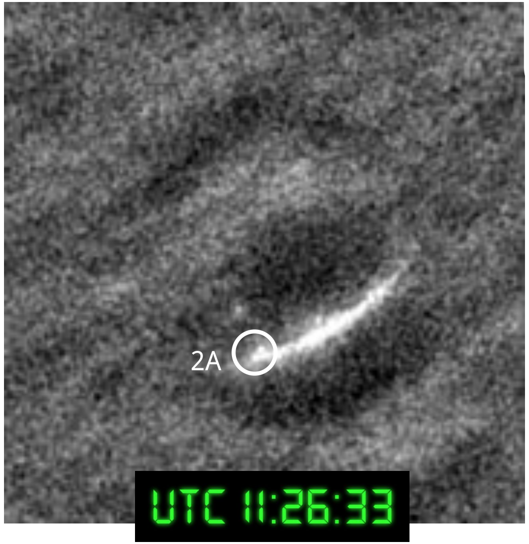
Downlink Frequencies:
- 400 MHz (4)
- 1200 to 1600 MHz (2)
- 8025 to 8400 MHz (3)
- 10.7 to 12.7 GHz (10)

Results: (July data) Candidate 2A and 4A

Candidates were observed within a minute of each other

Dynamic spectrum of 4A





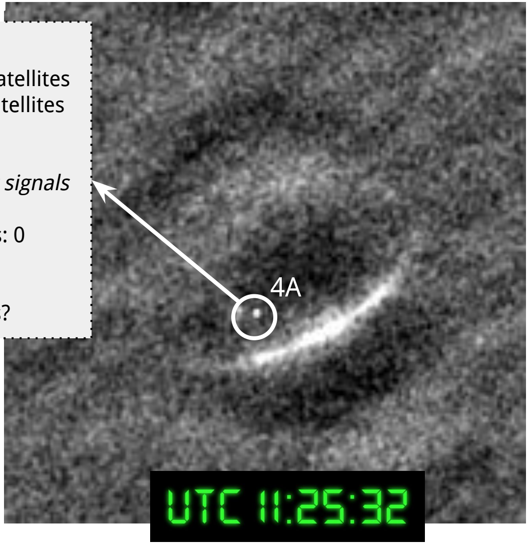
Dynamic spectrum of 2A

Results: (July data) Candidate 2A and 4A

Candidates were observed within a minute of each other

Satellite check?

Dynamic spectrum of 4A

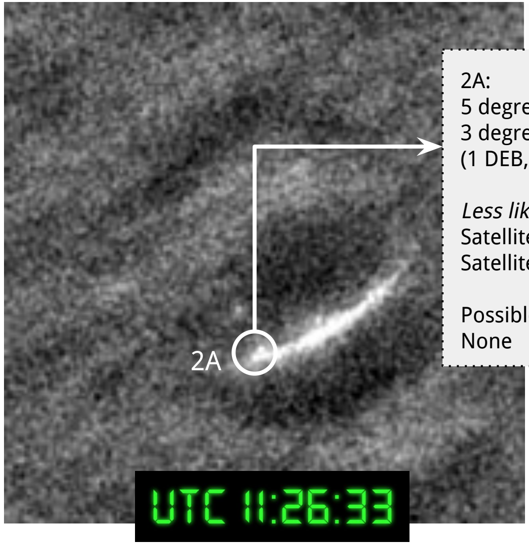


4A:
5 degree radius : 68 satellites
3 degree radius: 22 satellites
(1 DEB, 1R/B)

Less likely to transmit signals
Satellite debris: 10
Satellite rocket bodies: 0

Possible satellite?
- 12 possible satellites?

Dynamic spectrum of 2A



2A:
5 degree radius : 4 satellites
3 degree radius: 2 satellites
(1 DEB, 1R/B)

Less likely to transmit signals
Satellite debris: 2
Satellite rocket bodies: 2

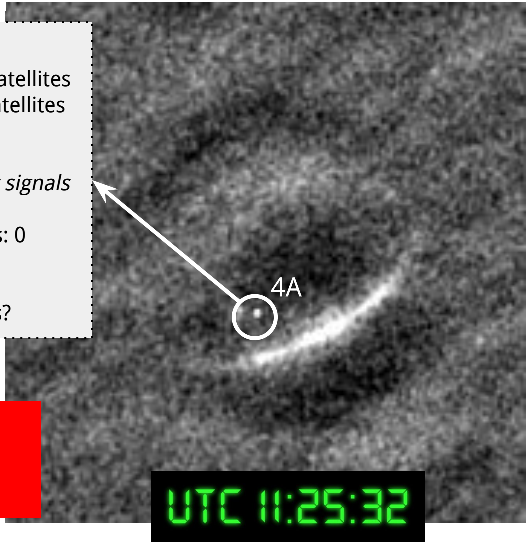
Possible satellite?
None

Results: (July data) Candidate 2A and 4A

Candidates were observed within a minute of each other

Satellite check?

Dynamic spectrum of 4A



4A:
5 degree radius : 68 satellites
3 degree radius: 22 satellites
(1 DEB, 1R/B)

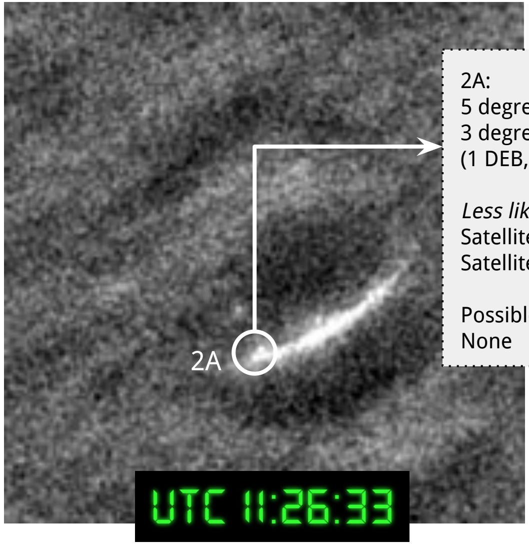
Less likely to transmit signals
Satellite debris: 10
Satellite rocket bodies: 0

Possible satellite?
- 12 possible satellites?

Active (11)

Downlink Frequency:
- 10.7 to 12.7 GHz
- 2235.4 MHz

Dynamic spectrum of 2A



2A:
5 degree radius : 4 satellites
3 degree radius: 2 satellites
(1 DEB, 1R/B)

Less likely to transmit signals
Satellite debris: 2
Satellite rocket bodies: 2

Possible satellite?
None

Summary & future work?

Developed two standalone test versions of the GPU imager, generating all-sky images from EDA2 data
(from Marcin's CPU imager as a starting point)

Tested and verified that the GPU imager produced correct mages
- By comparing it to reference CPU images

Benchmarked its performance on Topaz & Setonix:
- Gridding & imaging was extremely fast
- A few microseconds to grid/FFT a single image

Processed a few hours of EDA2 data to search for FRBs
(~around 2 hours)

FRBs?

Pulsars

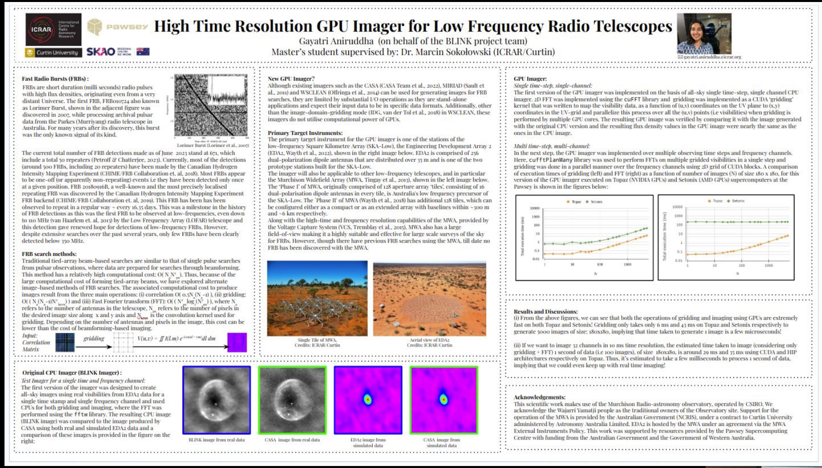
Satellites

Future:

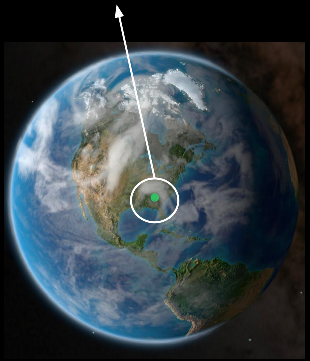
Perform a search with:
- More observing BW?
- More observing time?

INTERNATIONAL HPC SUMMER SCHOOL 2023

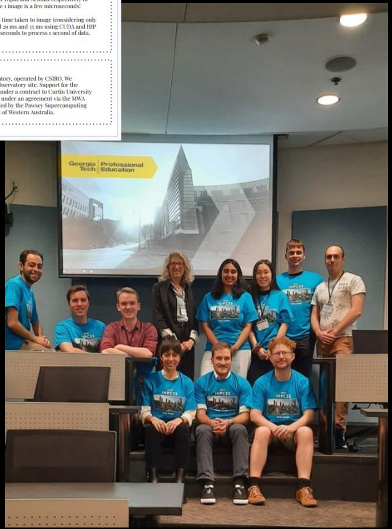
9 - 14 July 2023



Atlanta, USA



Poster presentation

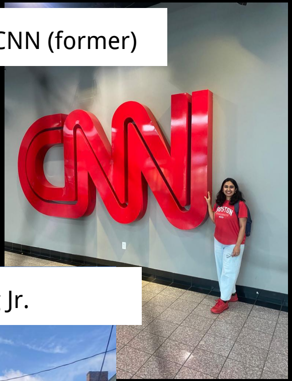


The group from Australia

The entire group of staff & students

Fun stuff!

College Football



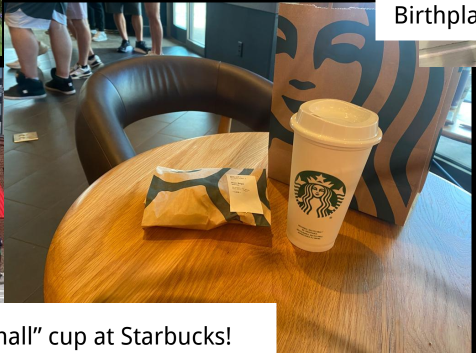
Headquarters of CNN (former)

Botanical Gardens

Birth house of Martin Luther King Jr.

Centennial Olympic Park ('96)

Waffle House



"Small" cup at Starbucks!

Birthplace of Coca Cola

Timeline

Plan from December 2021	PhD start in: December 2021, PhD to Masters conversion: March 2023							
Months since 10 Dec, 2021	3	6	9	12	15	18	21	24
Literature Review								
Familiarisation with Computing & Imaging Tools								
GPU Coding								
Thesis Chapters								
✔ Chapter I: Introduction and Background								
✔ Chapter II: Methodology								
✔ Chapter III: High time-resolution GPU Imager								
Chapter IV: Pilot FRB searches using EDA2 data								
Chapter V: Summary								

Thesis Progress

Submit: 8 Dec 2023

Chapter 1: Introduction & Background **(Completed)**
Chapter 2: Methodology **(Completed)**
Chapter 3: GPU Imager **(Completed)**
Chapter 4: Pilot FRB searches on EDA2 data **(On-going)**
Chapter 5: Summary **(On-going)**

Thank you!

Extra-slides

Dynamic Spectra plots of the on-horizon candidates

4A

3A, 3B

1D

Candidate Number	Time -Step	UTC	Pixel X	Pixel Y	S/N	sampno	DM Index
4A	**20230601_103241_100ms_ch294**	10:33:22	**130**	**50**	**23.58**	**413**	**0**
3A	**20230601_103608_100ms_ch294**	10:36:22	**141**	**64**	**19.58**	**139**	**1**
3B	**20230601_103608_100ms_ch294**	10:36:22	**142**	**63**	**18.49**	**140**	**0**
1D	**20230601_103708_100ms_ch294**	10:37:21	**144**	**69**	**27.35**	**126**	**0**
6D	**20230601_103808_100ms_ch294**	10:38:21	**146**	**75**	**17.69**	**131**	**0**

Project 2: Pilot FRB searches using EDA2 data

Results: (June data)
Remaining not on-horizon:
8 candidates

Clearly visible (3)

1A:
- 5 degree radius : 2 pulsars
- 3 degree radius: 1 pulsar

Closest pulsar:
J1418-3921
DM = 60.49 pc cm^{-3}

1A:
5 degree radius : 7
3 degree radius: 3

Less likely to transmit signals
Satellite debris: 4
Satellite rocket bodies: 2

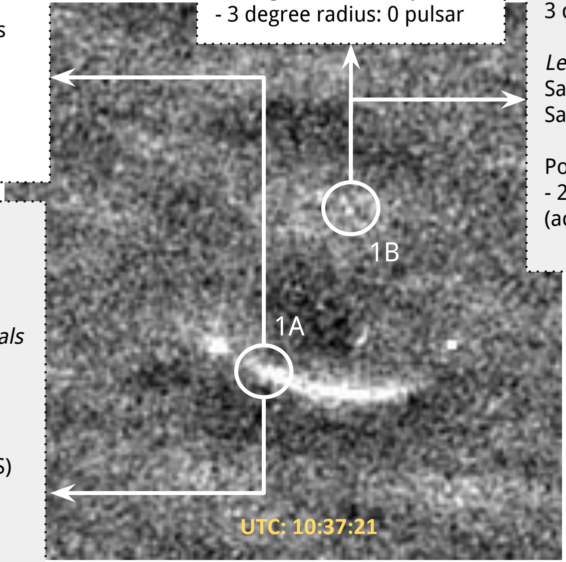
Possible satellite?
- COSMOS_2465_(GLONASS)
- Russian military satellite
- 19036.887 km (altitude)
(active)

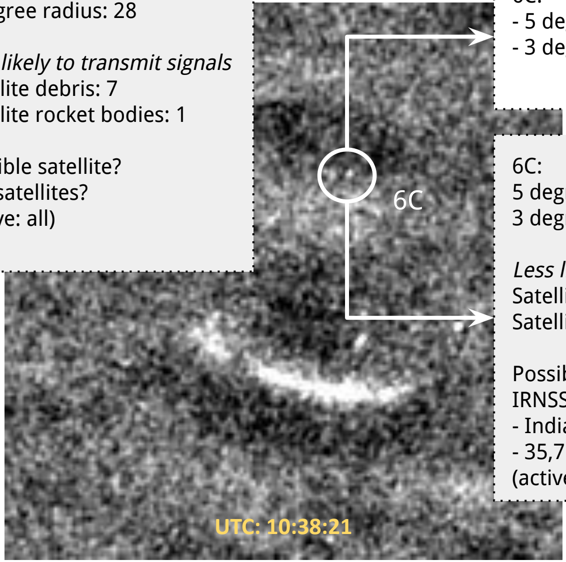
1B:
- 5 degree radius : 0 pulsars
- 3 degree radius: 0 pulsar

1B:
5 degree radius : 60
3 degree radius: 28

Less likely to transmit signals
Satellite debris: 7
Satellite rocket bodies: 1

Possible satellite?
- 20 satellites?
(active: all)





6C:
- 5 degree radius : 0 pulsars
- 3 degree radius: 0 pulsar

6C:
5 degree radius : 4
3 degree radius: 0

Less likely to transmit signals
Satellite debris: 1
Satellite rocket bodies: 2

Possible satellite?
IRNSS-1D
- Indian navigation satellite
- 35,715.383 km
(active)

Project 2: Pilot FRB searches using EDA2 data

Results: (June data)
Remaining not on-horizon:
8 candidates

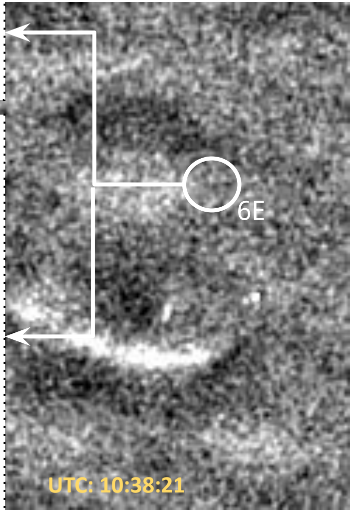
Faintly visible (2)

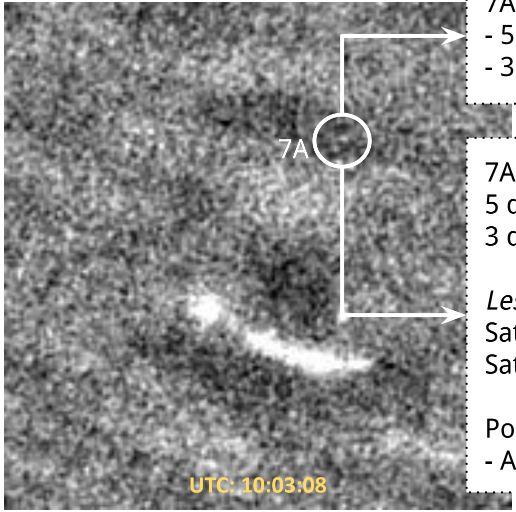
6E:
- 5 degree radius : 4 pulsars
- 3 degree radius: 1 pulsar

6E:
5 degree radius : 3
3 degree radius: 2

Less likely to transmit signals
Satellite debris: 0
Satellite rocket bodies: 2

Possible satellite?
- BEIDOU_3M24
- Chinese Navigation satellite
- 21538.932 km (alt)
(active)





7A:
- 5 degree radius : 1 pulsars
- 3 degree radius: 0 pulsar

7A:
5 degree radius : 34
3 degree radius: 11

Less likely to transmit signals
Satellite debris: 3
Satellite rocket bodies: 1

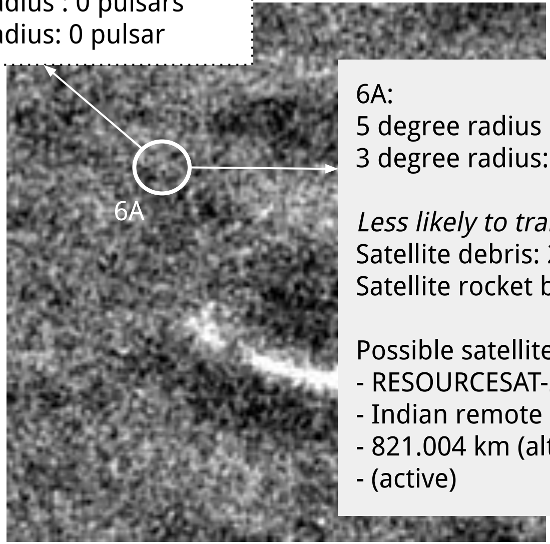
Possible satellite?
- All remaining 7 were active

Project 2: Pilot FRB searches using EDA2 data

Results: (June data)
Remaining not on-horizon:
8 candidates

Not visible (3)

6A:
- 5 degree radius : 0 pulsars
- 3 degree radius: 0 pulsar

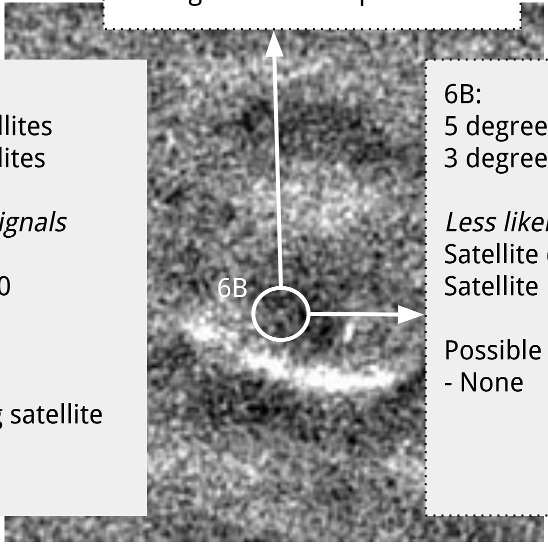


6A:
5 degree radius : 5 satellites
3 degree radius: 3 satellites

Less likely to transmit signals
Satellite debris: 2
Satellite rocket bodies: 0

Possible satellite?
- RESOURCESAT-2
- Indian remote sensing satellite
- 821.004 km (altitude)
- (active)

6B:
- 5 degree radius : 0 pulsars
- 3 degree radius: 0 pulsar



6B:
5 degree radius : 2
3 degree radius: 0

Less likely to transmit signals
Satellite debris: 2
Satellite rocket bodies: 0

Possible satellite?
- None

Project 2: Pilot FRB searches using EDA2 data

Clearly visible (2)

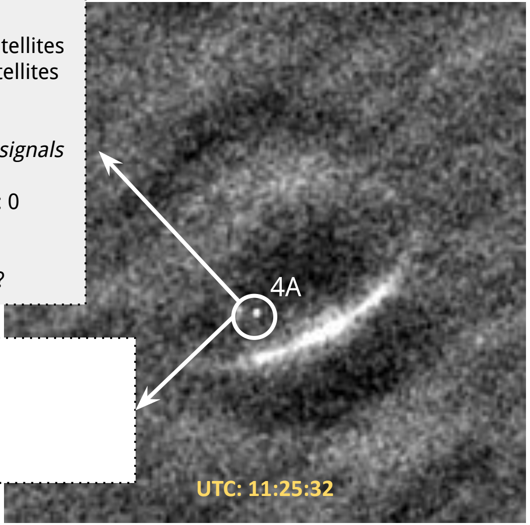
Results: (July data)
On-horizon candidates: 3 (almost)
Remaining not on-horizon: 5 candidates

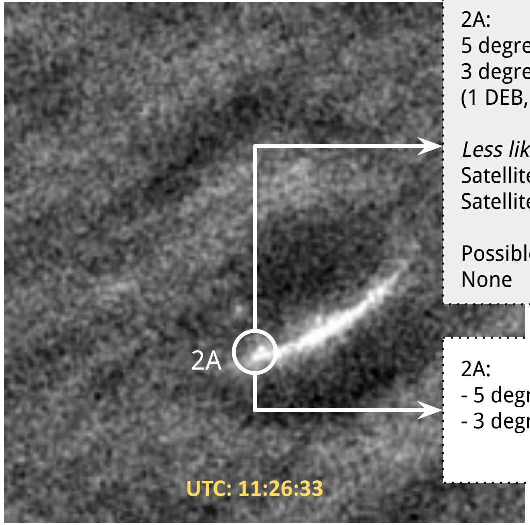
4A:
5 degree radius : 68 satellites
3 degree radius: 22 satellites
(1 DEB, 1R/B)

Less likely to transmit signals
Satellite debris: 10
Satellite rocket bodies: 0

Possible satellite?
- 12 possible satellites?

4A:
- 5 degree radius : 3 pulsars
- 3 degree radius: 2 pulsar





2A:
5 degree radius : 4 satellites
3 degree radius: 2 satellites
(1 DEB, 1R/B)

Less likely to transmit signals
Satellite debris: 2
Satellite rocket bodies: 2

Possible satellite?
None

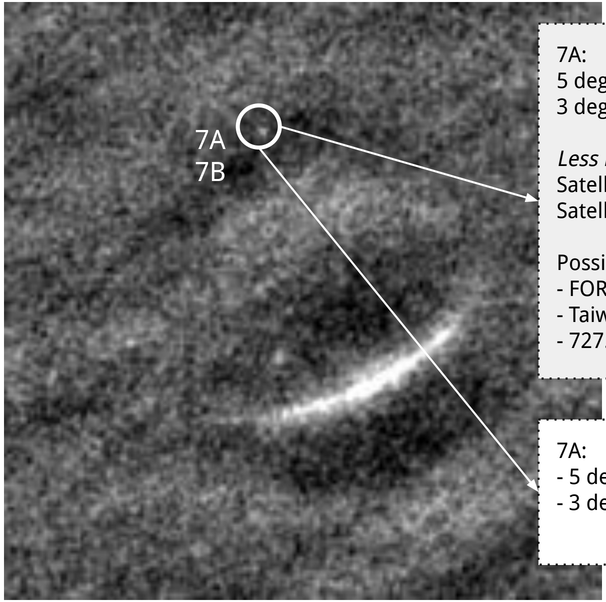
2A:
- 5 degree radius : 61 pulsars
- 3 degree radius: 20 pulsar

Project 2: Pilot FRB searches using EDA2 data

Results: (July data)
On-horizon candidates: 3 (almost)
Remaining not on-horizon: 5 candidates

Faintly visible (2)

Candidate No:	Time_Step	Pixel_X	Pixel_Y	S/N	sampno	DM Index
7A	20230709_111534_100ms_ch294	78	140	21.82	205	0
7B	20230709_111534_100ms_ch294	78	140	10.8	204	3



7A:
5 degree radius : 5 satellites
3 degree radius: 4 satellites

Less likely to transmit signals
Satellite debris: 3
Satellite rocket bodies: 0

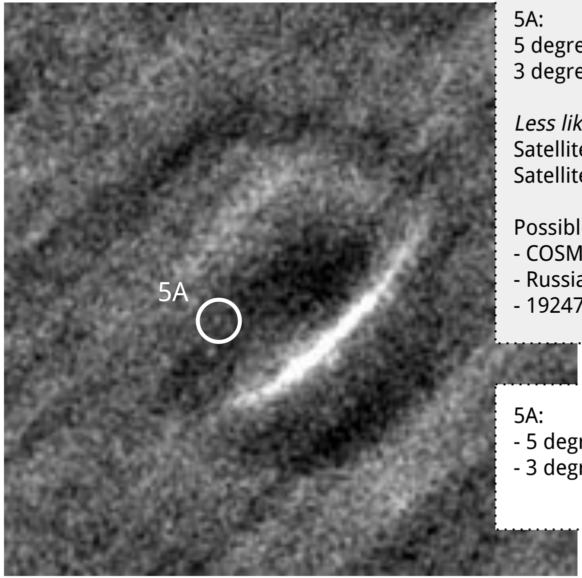
Possible satellite?
- FORMOSAT_3D
- Taiwanese American Satellite
- 727.328 km (altitude)

7A:
- 5 degree radius : 2 pulsars
- 3 degree radius: 1 pulsar

Project 2: Pilot FRB searches using EDA2 data

Results: (July data)
On-horizon candidates: 3 (almost)
Remaining not on-horizon: 5 candidates

Not visible (1)



5A:
5 degree radius : 5 satellites
3 degree radius: 3 satellites

Less likely to transmit signals
Satellite debris: 2
Satellite rocket bodies: 0

Possible satellite?
- COSMOS_2404_(GLONASS)
- Russian military satellite
- 19247.456 km (altitude)

5A:
- 5 degree radius : 3 pulsars
- 3 degree radius: 2 pulsar