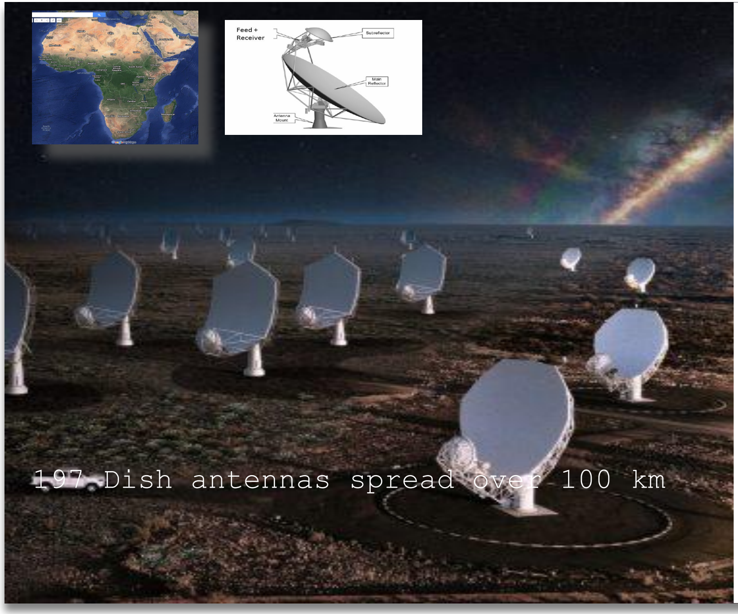
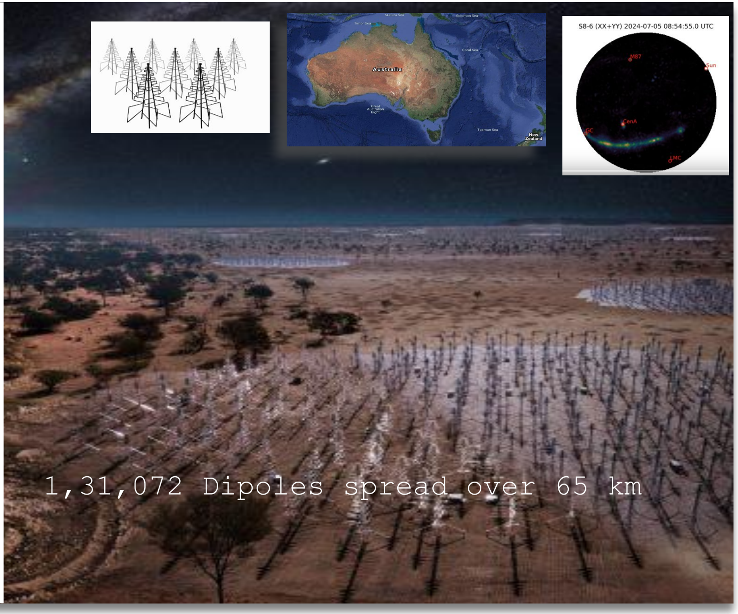
Indian signal processing contributions to development related to SKA

1. South Africa



2. Western Australia



Sahana &
Kamini, Madhavi, Abhishek, Arul, Prabu
Raman Research Institute, Bangalore

I acknowledge the valuable technical interactions with **SKA colleagues- Gianni, Riccardo, MCCS team, GMRT team** and **RRI colleagues** during the course of this work

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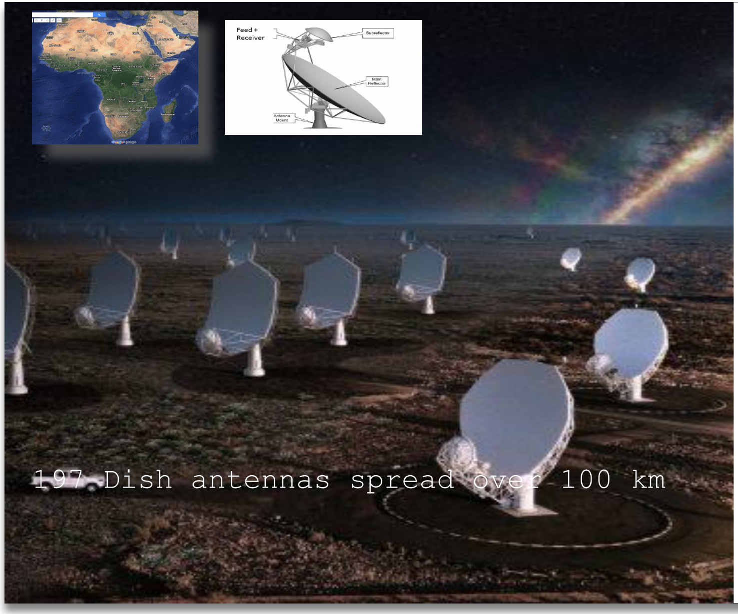

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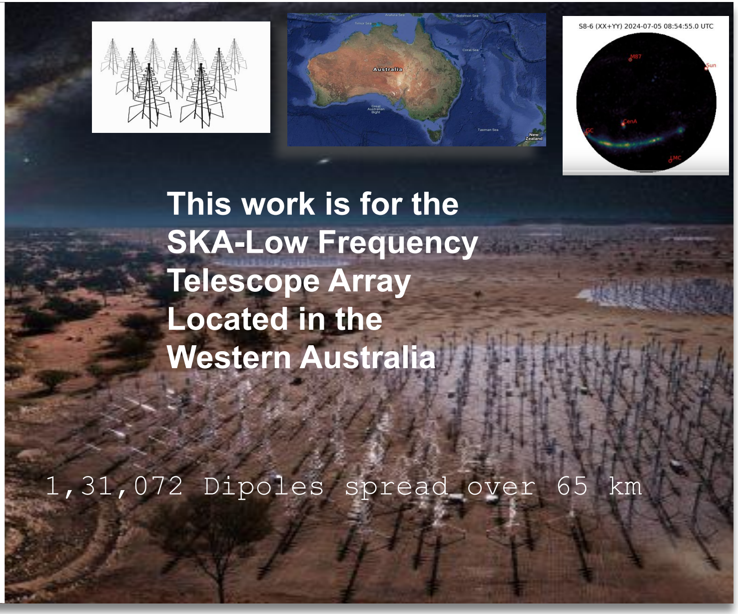

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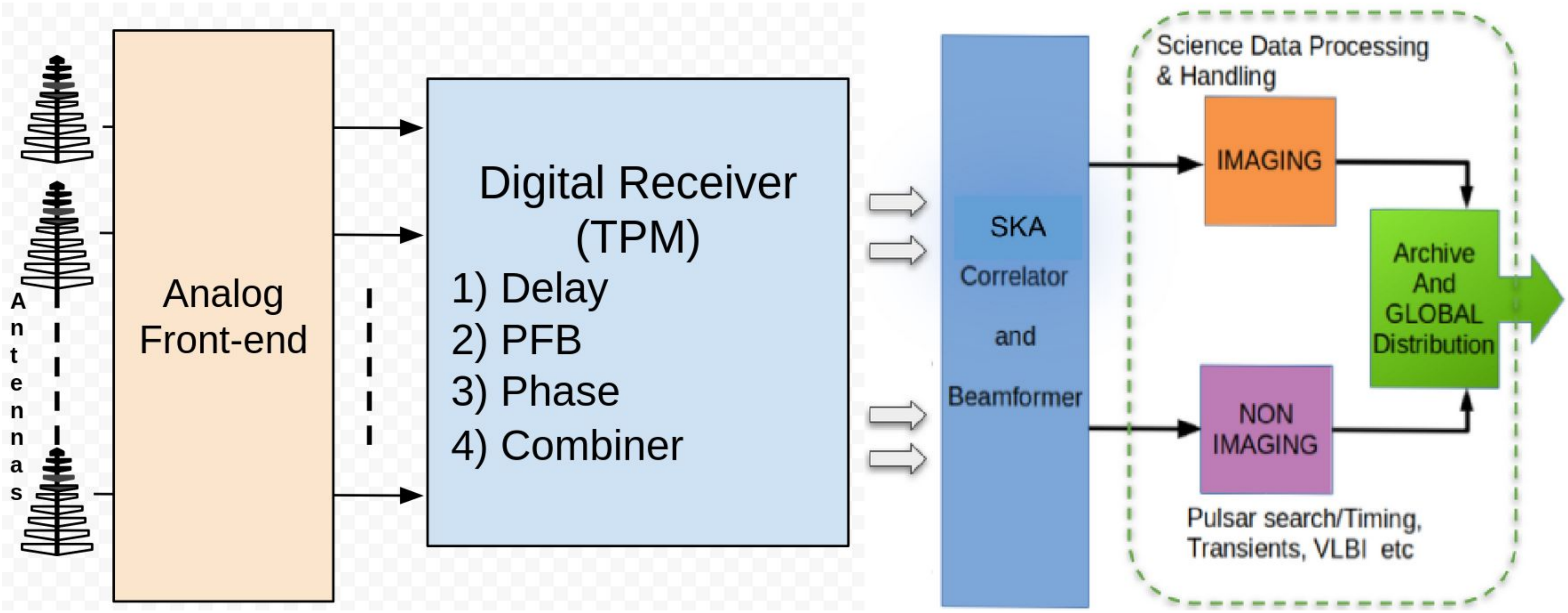
Content

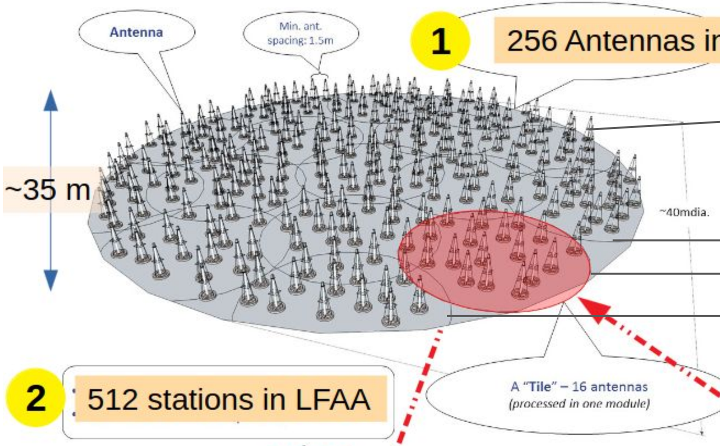
1. Motivation
2. Design
3. Validation and Results
4. Ongoing Efforts
5. Going beyond

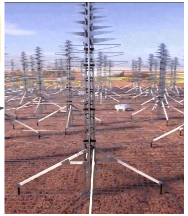
SKA Signal flow overview - Imaging and Non-imaging applications



SKA- Low Frequency Array antenna arrangements

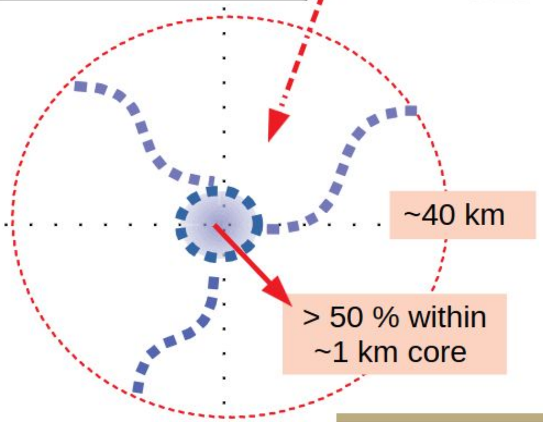
1 256 Antennas in one station



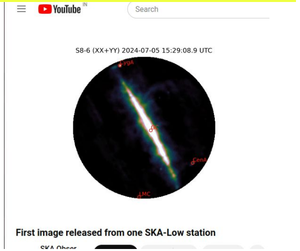


2 512 stations in LFAA

3



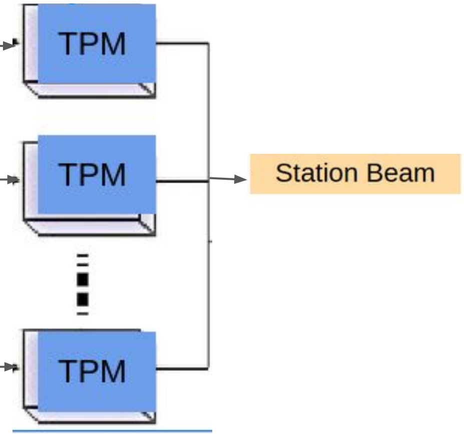
Recent Result



Small antennas
Large in number
No moving parts

1,31,072

500 directions – survey
Enormous Signal Processing



www.skatelescope.org https://population.com.au/lga/56160 https://en.wikipedia.org/wiki/Bangalore_Urban_district

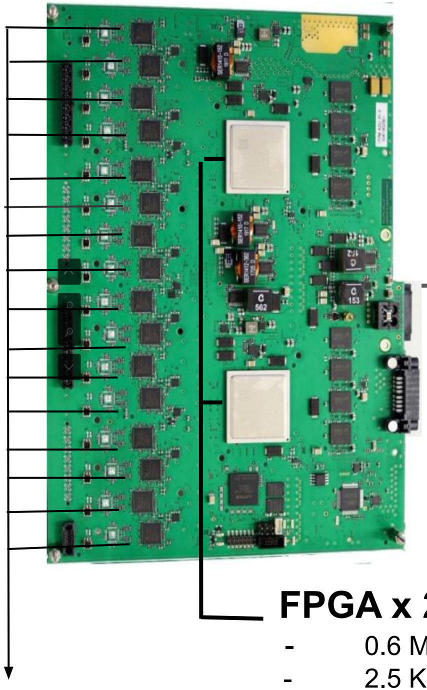
1. Motivation

- 2017 SKAIC interest in SKA-Low participation
- Beamforming identified as one of the areas
- As of Critical Design Review: TPM produced Single PA beam
- It was desired to have 48 station beams (for survey etc)
- ==> Feature enhancement / new-VHDL-designs for existing TPM F/W
    - Hence this work has been carried out by our team at RRI

2. Design

Outline of this work

TPM : Tile Processing module



FPGA x 2

- 0.6 MLCells
- 2.5 K DSP

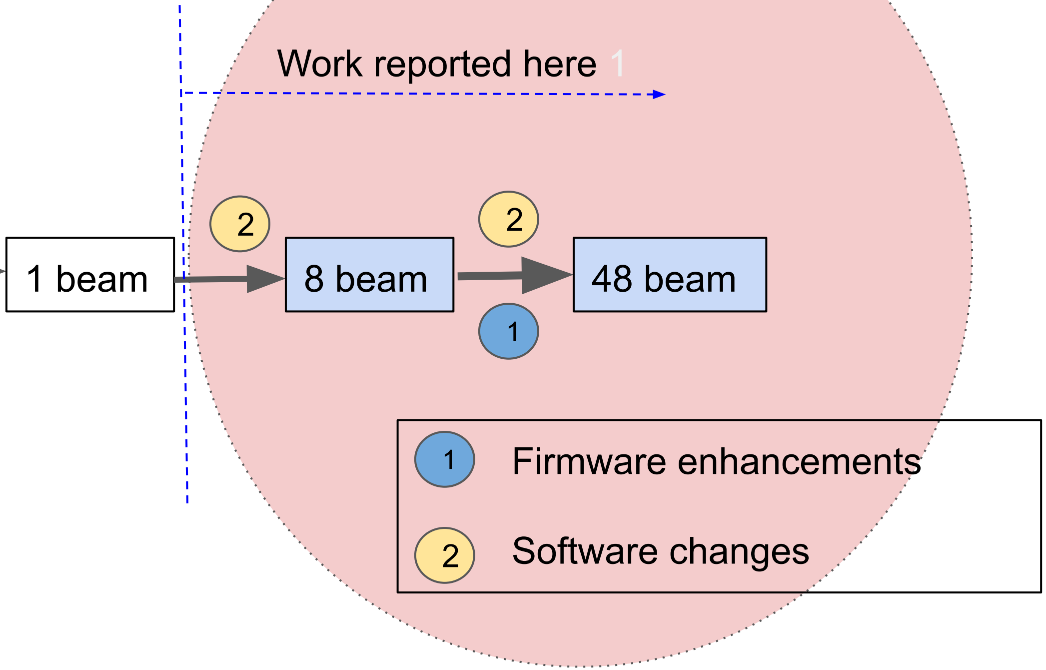
Firmware

- Delay
- PFB
- Phase

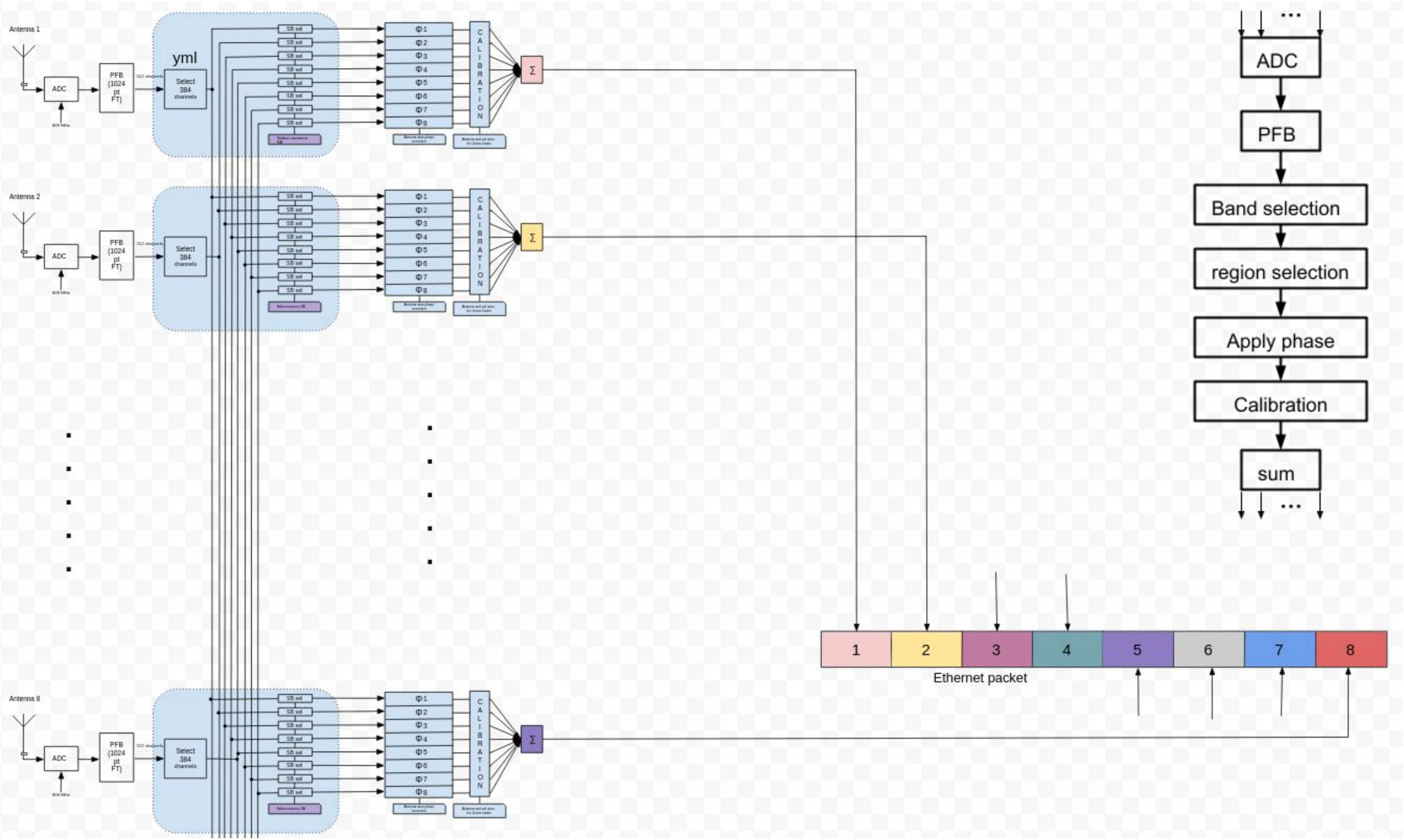
ADC x 16 dual

- 14 bit
- 800 MSps

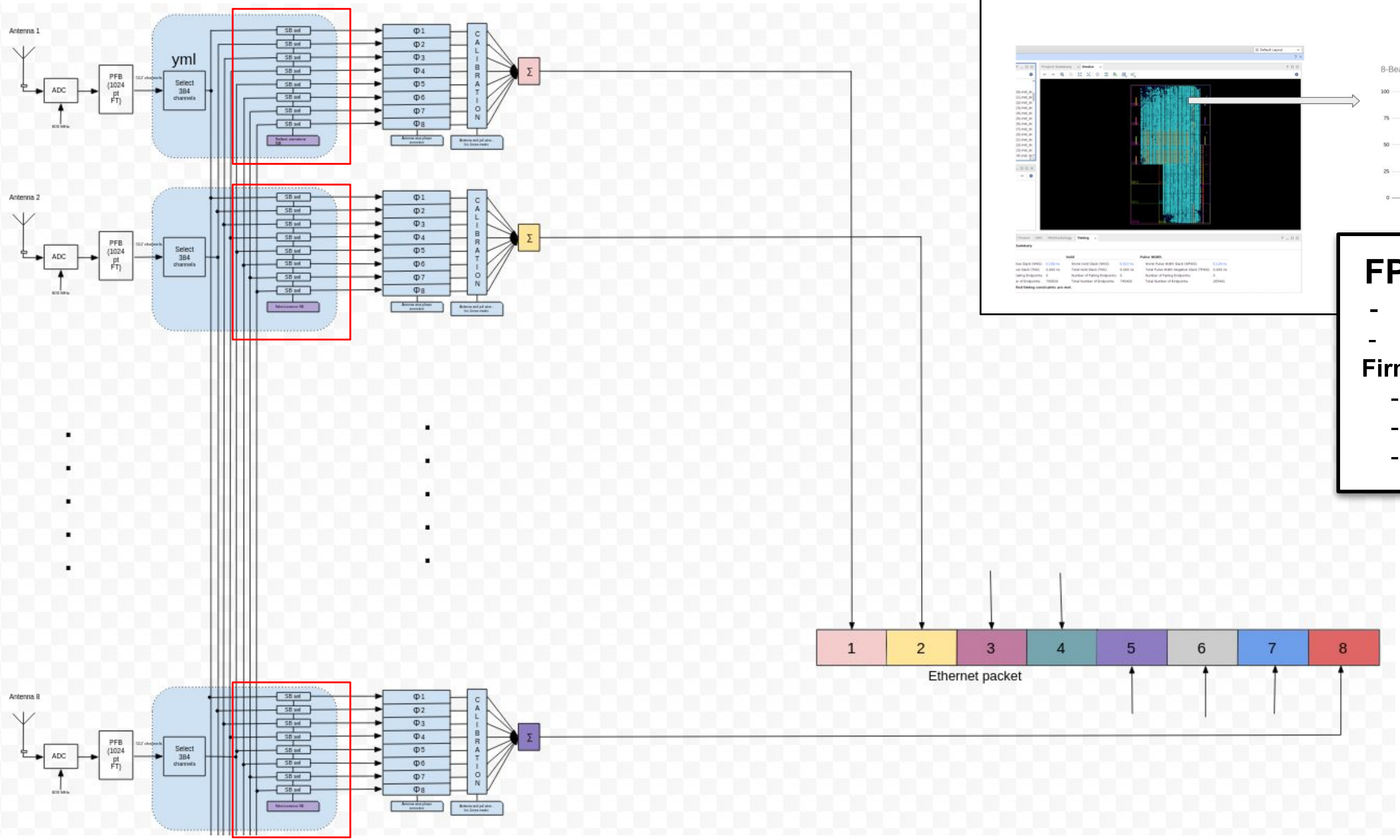
Feature enhancement
new-VHDL-designs for 48 Beams

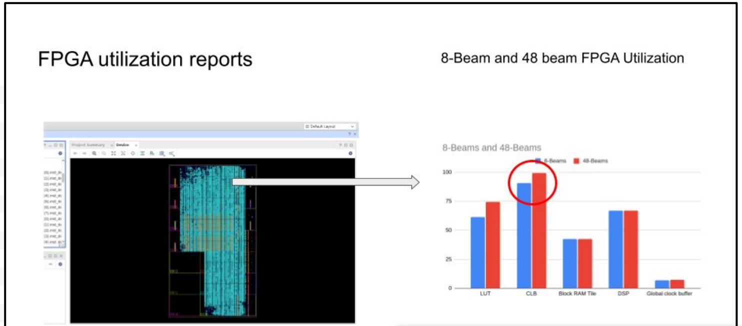


Firmware Internal functionality for Beamforming



Firmware enhanced to provide 48 beams





FPGA x 2

- 0.6 MLCells
- 2.5 K DSP

Firmware

- Delay
- PFB
- Phase

3. Validation and Results

Brief overview of TPM Beams

- Minimum bandwidth for each beam : 6.25 MHz
- Upto 48 such beams from each station
- Beams can point same or different directions
- Beams can have same band / sky-frequency
- Instantaneous channels limit to 384 (300 MHz)

Simulation: Expected beamforming

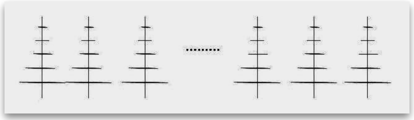
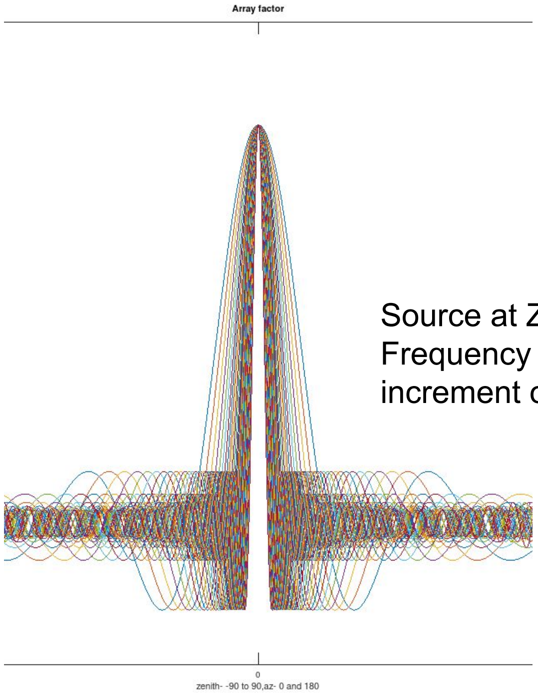


Illustration:
Config for 16 Antennas
E-W linear array 1 meter apart



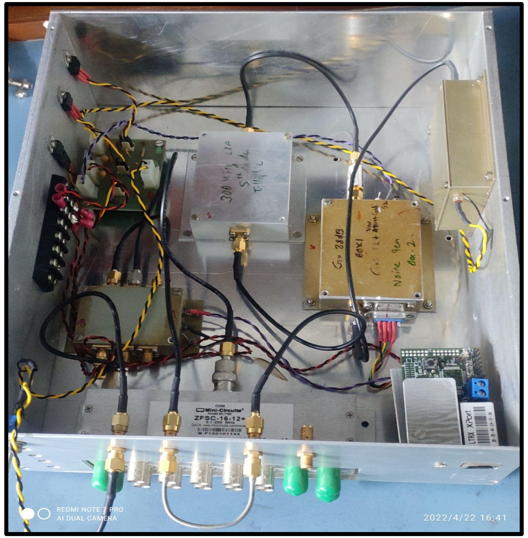
Source at Zenith
Frequency : 50 MHz to 350 MHz
increment of 6.25 MHz

Matlab simulation

Upcoming pulsar array at GBD covers SKA range of frequencies. Hence can be used for **Field Verification**

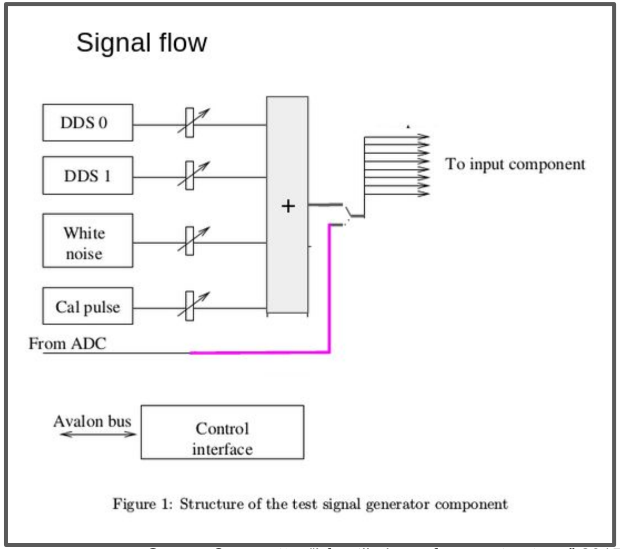
LAB based Validation: Testing the TPMs in a Lab Environment

1. Externally fed white noise
2. Externally fed tones



Kasthuri et al, RRI

1. Internally generated white noise
2. Internal tones



G. e. a. Comoretto, "Lfaa tile beamformer structure," 2015.

Mock Observation

Mock observation carried out in 3 steps

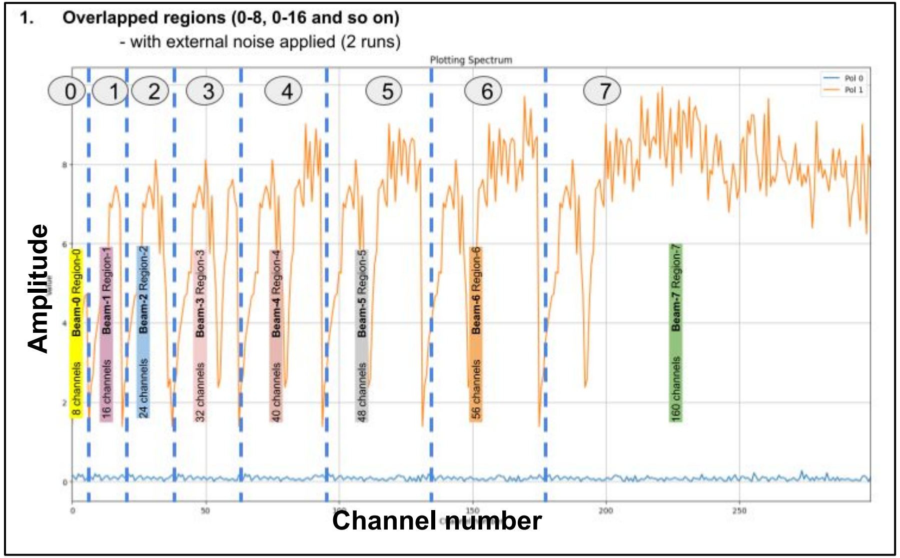
1. Beam association with the band
2. Validation of 8 beam formation
3. Validation of 48 beams (after enhancing VHDL design)

Testing multiple options of beamforming
- 1. Beam association with the band

Software changes / enhancements to achieve 8 beams

a) Associating regions to beam
b) Associating delays to beam

- Eight regions formed
- Each region had different length of channels
- Regions associated with beams
- TPM noise band captured & plotted
- Single ADC input used for this test



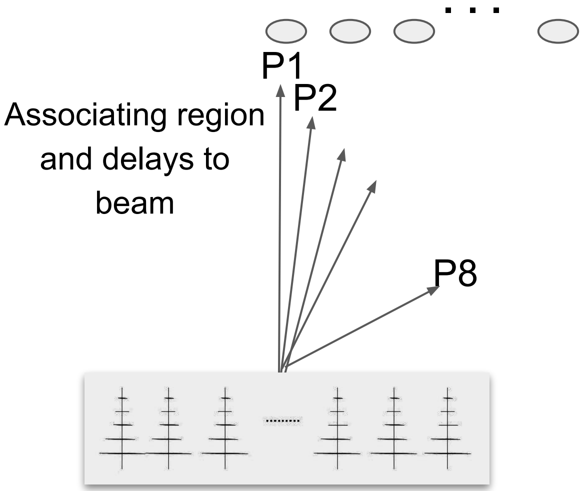
Simple test based on external noise in lab. Successive channels bunched and plotted

1. Region association
2. Overlapped region (variable length of channels)

2. Validation of 8 beam formation

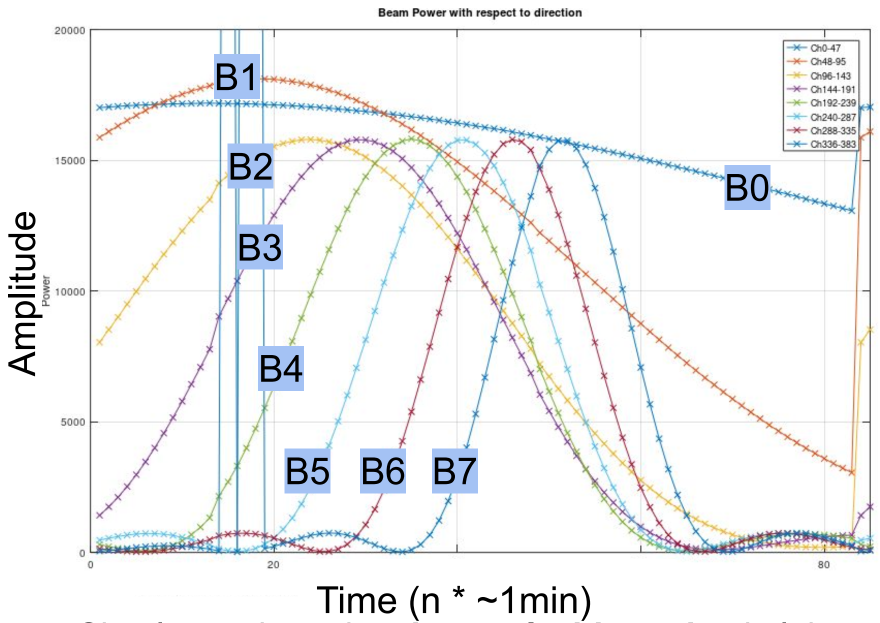
After Software Enhancements

- Beams point 5 min in RA ahead of each other from zenith eastward
- TPM Beams track source coordinates
- **Mock observation** beam sees maximum when source passes zenith



Config for 16 Antennas
E-W linear array 1 meter apart

Mock observation with 8 beams



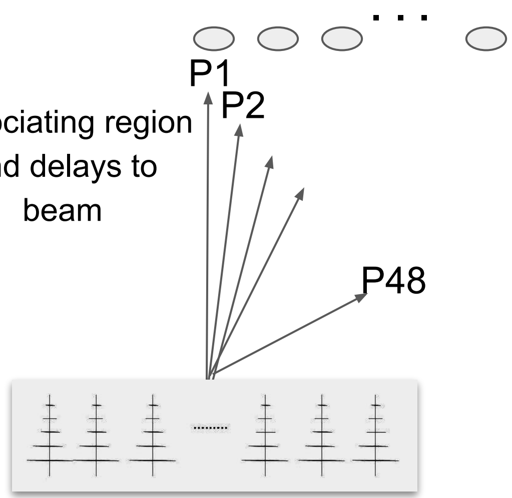
Simple test based on **internal white noise** in lab.
Successive 48-channels bunched and plotted

3. Validation of 48 beams (after enhancing VHDL design)

After Firmware & Software Enhancements

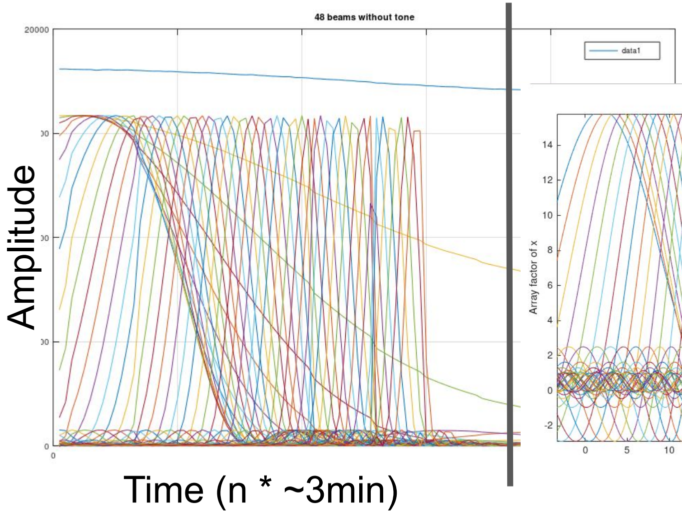
- Beams point 5 min in RA ahead of each other from zenith eastward
- TPM Beams track source coordinates
- **Mock observation** beam sees maximum when source passes zenith

Associating region and delays to beam

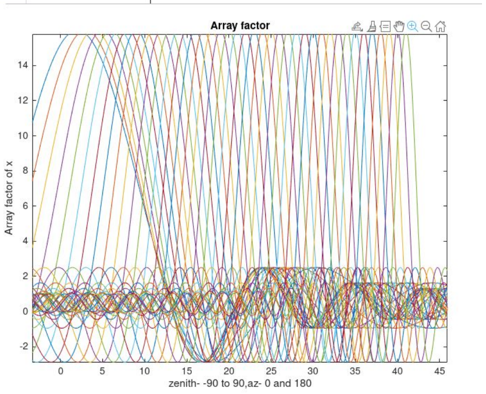


Config for 16 Antennas
E-W linear array 1 meter apart

Mock observation with 48 beams



TPM output with Simple test based on internal white noise in lab.



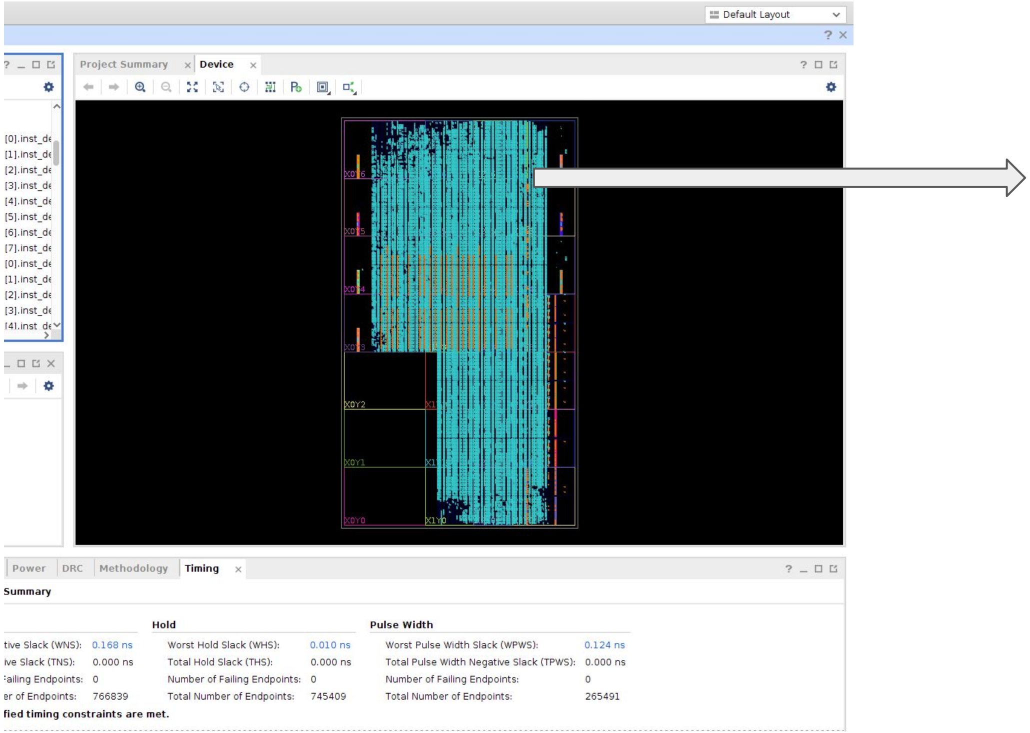
Matlab code output, written to verify the expected beamforming.

Successive 8-channels bunched and plotted

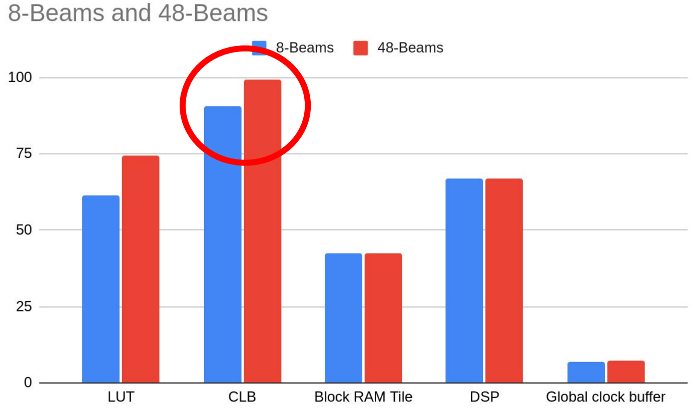
4. Ongoing efforts

FPGA utilization reports

FPGA resources are near fully utilized !

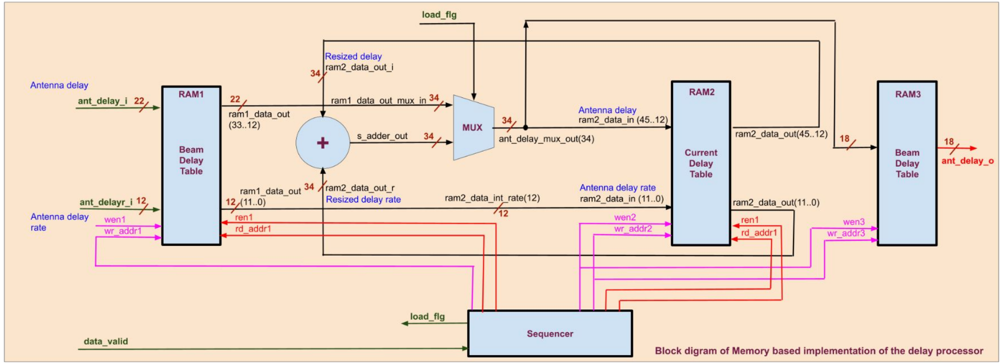


8-Beam and 48 beam FPGA Utilization



We are looking at an efficient implementation

1. **Efficient implementation** of delay processor

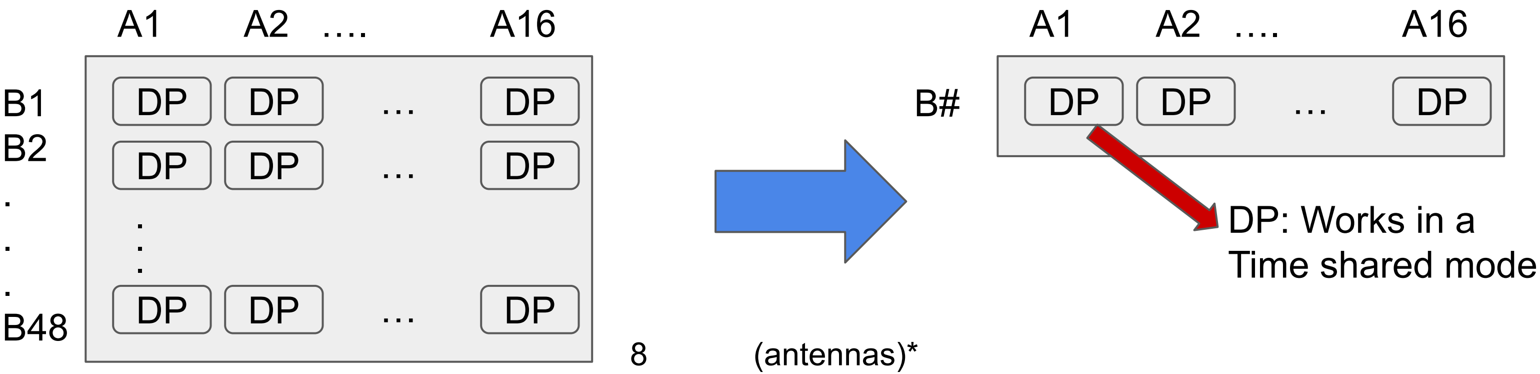


Kamini PA, Madhavi, RRI

1. Module design ✅
2. Integration ✅
3. Simulations 🏃
4. Validation

LFAA Tile Beamformer structure
G. Comoretto
March 17, 2021

What this means?

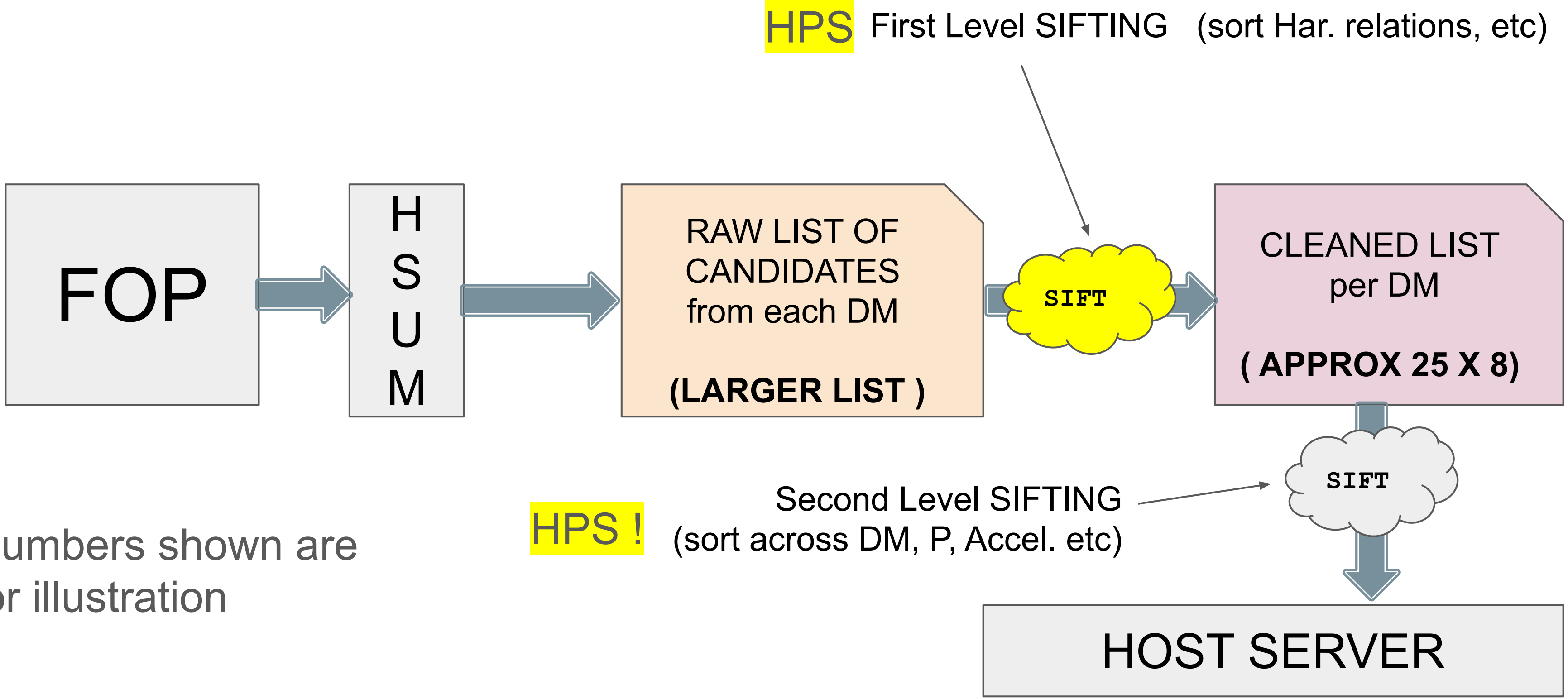


8 (antennas)*

5. Pulsar Search

BACKGROUND: Two layers of sifting (a slide from 2020)

SIFTING TASK slides from 2020: SIFTING_Discussion_22May2020



Numbers shown are for illustration

References

1. P. J. . S. R. T. . L. T. J. L. W. Dewdney, P. E Hall, “The Square Kilometre Array,” IEEE, vol. 97, pp. 1482–1496, Aug 2009.
2. “SKA Phase-1 Executive Summary 2020, SKA Organisation; available online at https://skao.canto.global/pdfviewer/viewer/viewer.html?share=share
3. B. S. G. et. al, “Progression of digital-receiver architecture: From mwa to ska1-low, and beyond,” The Journal of Astrophysics and Astronomy, 2023.
4. T. P. et. al, “A full-band voltage beam forming mode for the Murchison Widefield Array digital receiver,” ASI Conference Series, vol. 13, p. 369– 373, 2014.
5. T. P. et. al, “A Digital-Receiver for the Murchison Widefield Array,” Experimental Astronomy, 2015.
6. S. M. O. et. al, “Mwa tied-array processing I: Calibration and beamformation,” Astronomical society of Australia, 2019.
7. G. Comoretto and R. C. et. al, “The signal processing firmware for the low frequency aperture array,” vol. 6, p. 17, Aug. 2017.
8. G. e. a. Comoretto, “Lfaa tile beamformer structure,” 2015.
9. Thompson, A. Richard, James M. Moran, and George W. Swenson. Interferometry and synthesis in radio astronomy. Springer Nature, 2017.
10. Aafreen, R., et al. "High-Performance Computing for SKA Transient Search: Use of FPGA based Accelerators--a brief review." arXiv preprint arXiv:2207.07054 (2022).

Thank you …

Antenna arrangements and phase calculation

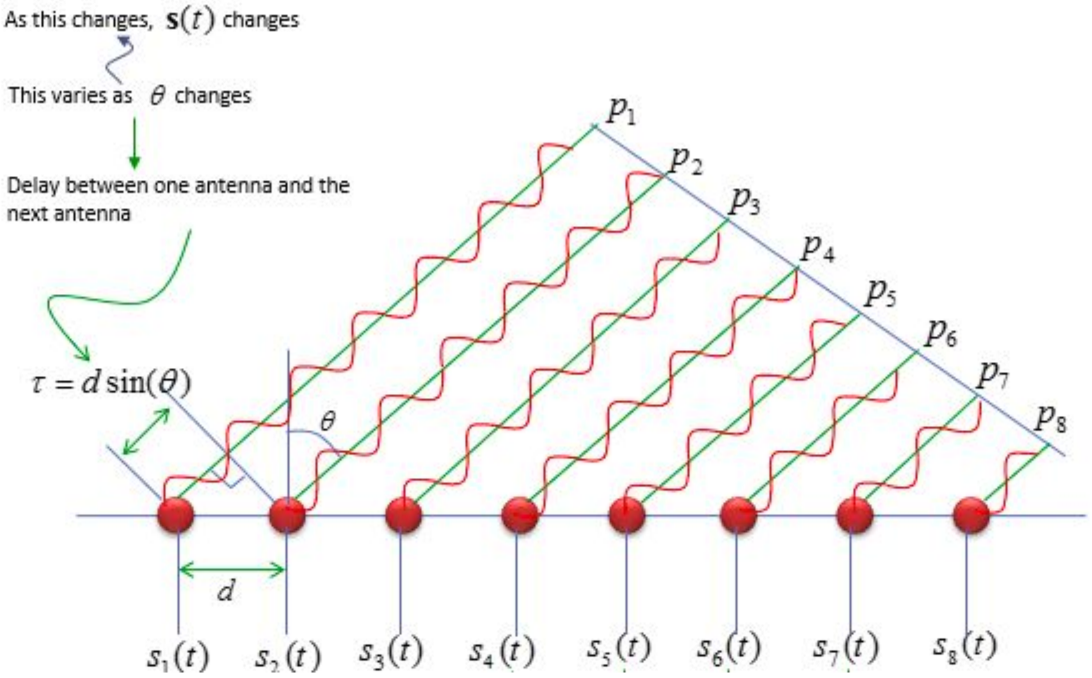
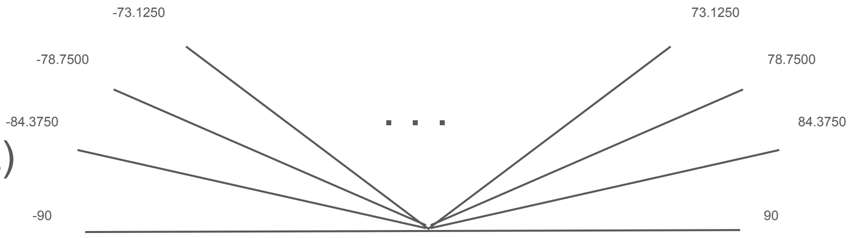


Illustration of FFT Beamforming

Assumptions :

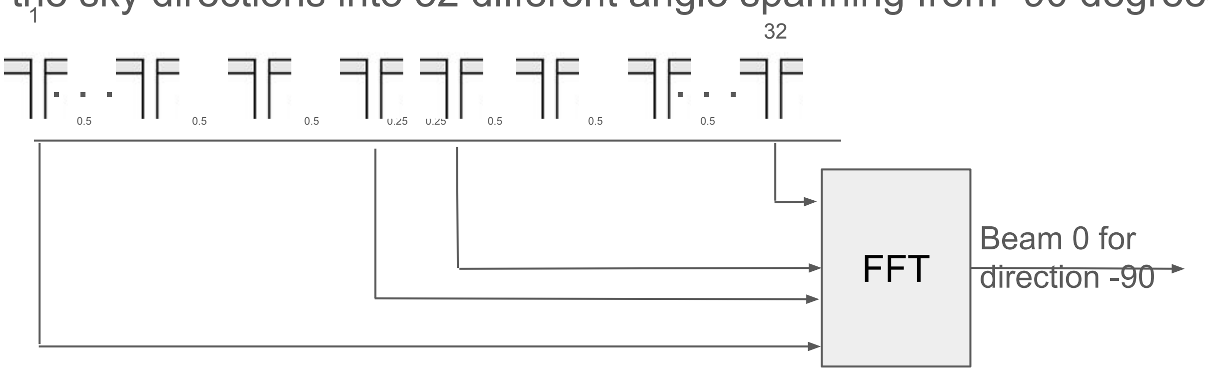
Antenna spacing is 0.5 λ (where λ is wavelength)

λ = 1 unit (for example : 1 m for frequency 299 MHz)



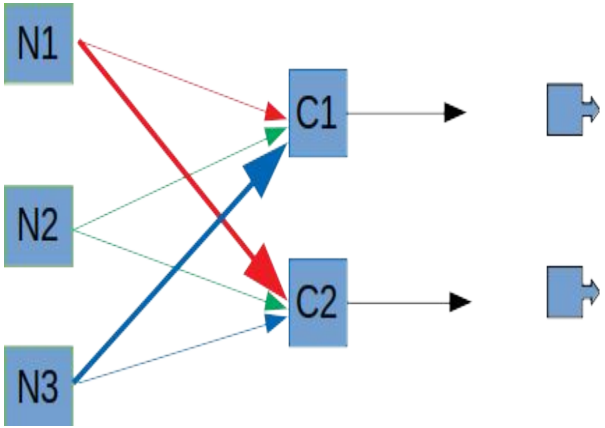
32 antennas in total

Divide the sky directions into 32 different angle spanning from -90 degrees to +90 degrees



How do we do FFT beamforming?

Noise
Source



Input
1

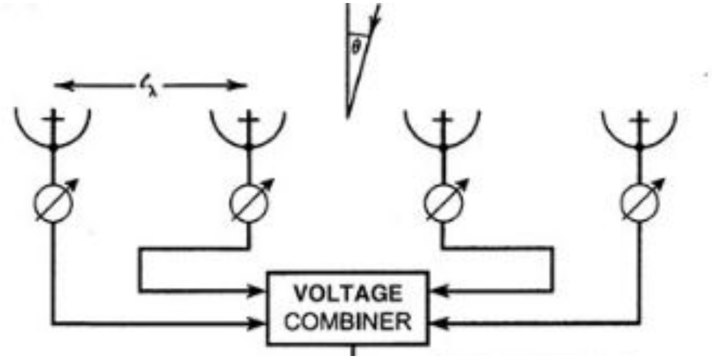
Inpu
t 2

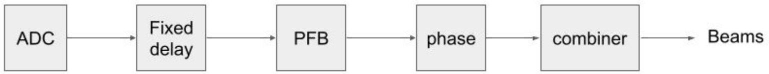
$$X[k] = \sum_{n=0}^{N-1} x[n] e^{-j\frac{2\pi}{N}nk} \quad k = 0, \dots, N-1$$

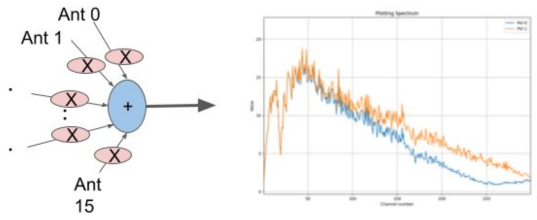
Content

1. What is Beamforming ?
2. Why FFT beamforming ?
3. Types of beamforming
4. Antenna arrangements and phase calculation
5. How do we form beam using FFT ?
6. Illustration of FFT beamforming
7. Results
8. Future work

What is Beamforming and Digital Beamforming?





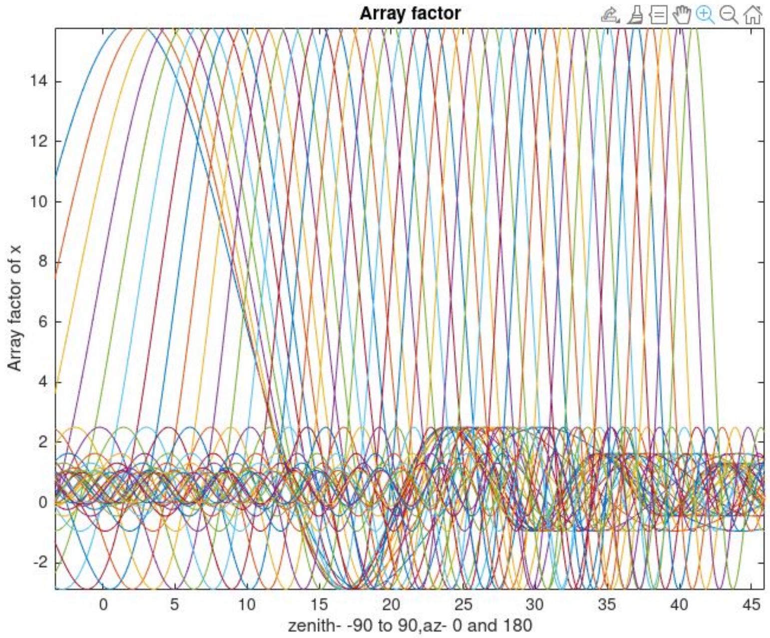


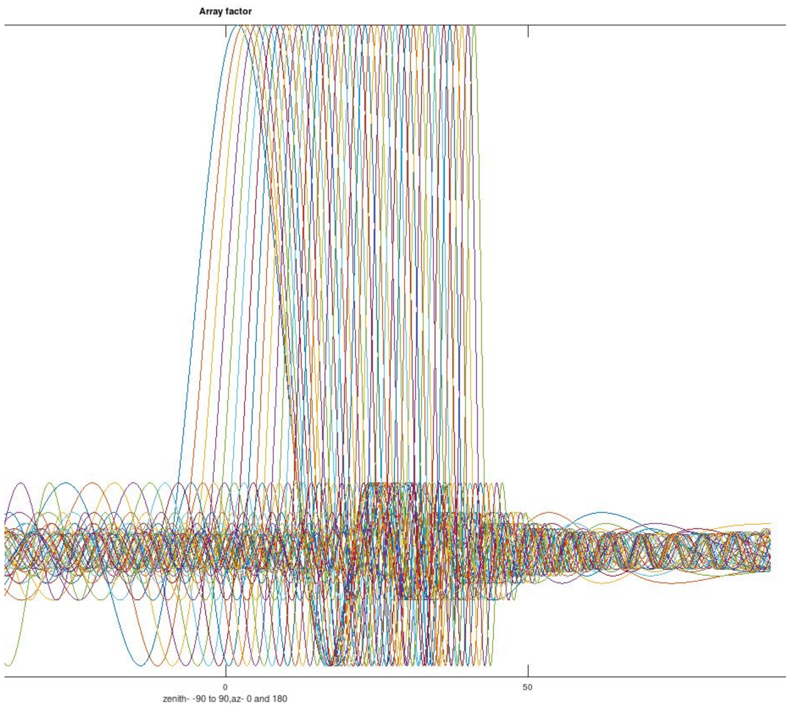
Digital beamforming is a technique to steer the antenna beam electronically. The required phase adjustments to point the beam at a particular direction can be done digitally. This enables the faster control of the adjustments than compared to mechanically steering antenna or using the phase shifters as in case with the analog beamforming. Digital beamforming even allows formation of more number of beams practically limited only by the resource utilization of the hardware

Expected beam

/MATLAB Drive/kraus_v4_shiftedoutput.m

```
zenithangler = deg2rad(zenithangle);
A = ones(1,M);

y = 1;


%Source direction
sourcedirdze = 0;
nofelem = 1:1:M;
sourcedirzer = deg2rad(sourcedirdze);
delta = -k.*dx.*sin(sourcedirzer);
for   m = 1:1:length(delta)
        %w2 = zeros(181,17);
        for p =  1:length(zenithangler)
            w2(p,1:M) = A(nofelem).*exp(1i.*(nofelem-1).*(k(m).*dx.*sin(zenithangler(p))+de
            AF(m,p) = sum(w2(p,1:M));
        end
        %[maxP,maxIdx]=max(AF2);

end

for beam = 1:1:40
    set(beam,:) = circshift(AF(beam,:),10+10*beam);
    plot(zenithangle,set(beam,:));
    hold on;
end


ylabel('Array factor of x');
xlabel('zenith- -90 to 90,az- 0 and 180');
title('Array factor')
```

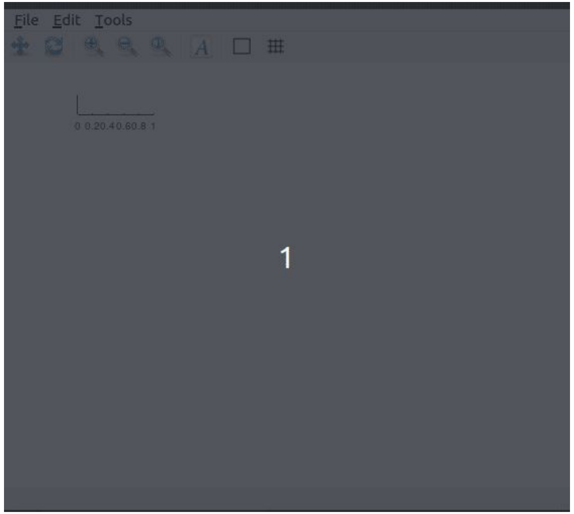



Array factor
0
50
zenith- -90 to 90,az- 0 and 180

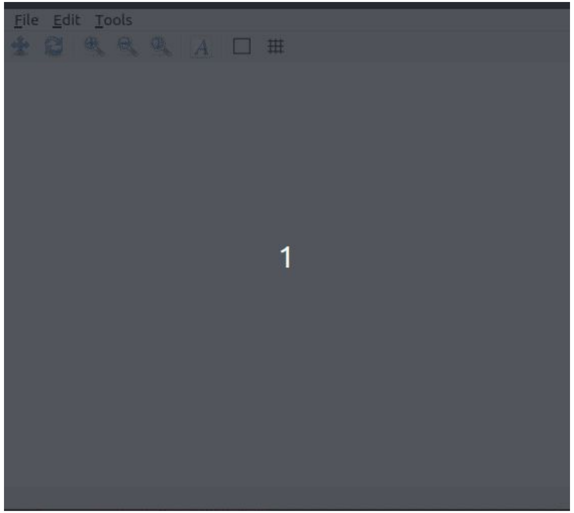
Results

Results have been obtained for below two methods

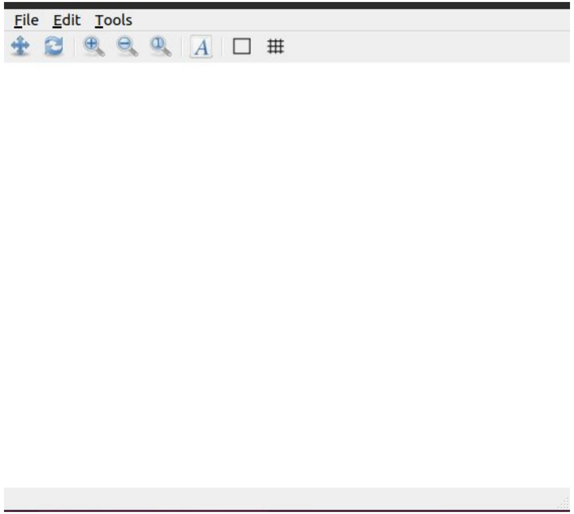
1) Without zero padding with complex noise : Beam power has a sudden transition (32 point FFT)
2) With zero padding (1024 point FFT) : Beam power has a smooth transition
3) Without complex noise(1024 point FFT) : Beam power is same in all directions.



Without zero padding with complex noise



With zero padding



Without adding complex noise