

A real-time post-correlation beamformer and correlator for the SPOTLIGHT

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FTSKy - A program in the field of Fast Radio Transients
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The upgraded GMRT

- GMRT = **G**iant **M**etrowave **R**adio **T**elescope.
- **30 antennas** arranged in a Y-shaped configuration.
- Parabolic dishes, each dish is **45 metres** wide.
- Operating over **120 to 1460 MHz**.
- Instantaneous bandwidth of **200/400 MHz**.
- Shortest baseline = **~100 m**, longest baseline = **~25 km**.
- One of the *most sensitive* radio telescopes in the world.
- Supports two modes of operation
 - Interferometry
 - Array mode
- Excellent instrument for time-domain studies!



GMRT Wideband Backend (GWB)

- Digital Backend for the upgraded GMRT
- Implemented using FPGAs and GPUs - a hybrid backend
- Instantaneous bandwidth = 400 MHz (max)
Supports 200 MHz, 100 MHz and narrowband modes
Spectral channels - 16384 (max)
- Maximum 4 beams - IA/PA/PC at 20 microseconds resolution
Coherent De-dispersion pipeline attached to spectral voltage beam

Observing transients with the GMRT

- High sensitivity and wide-band coverage (**300 - 1460 MHz**) at lower frequencies.
- An interferometer with arc-second imaging localisation capability
- Lack of field-of-view : SPOTLIGHT converts GMRT from a sensitive follow-up telescope into a survey telescope

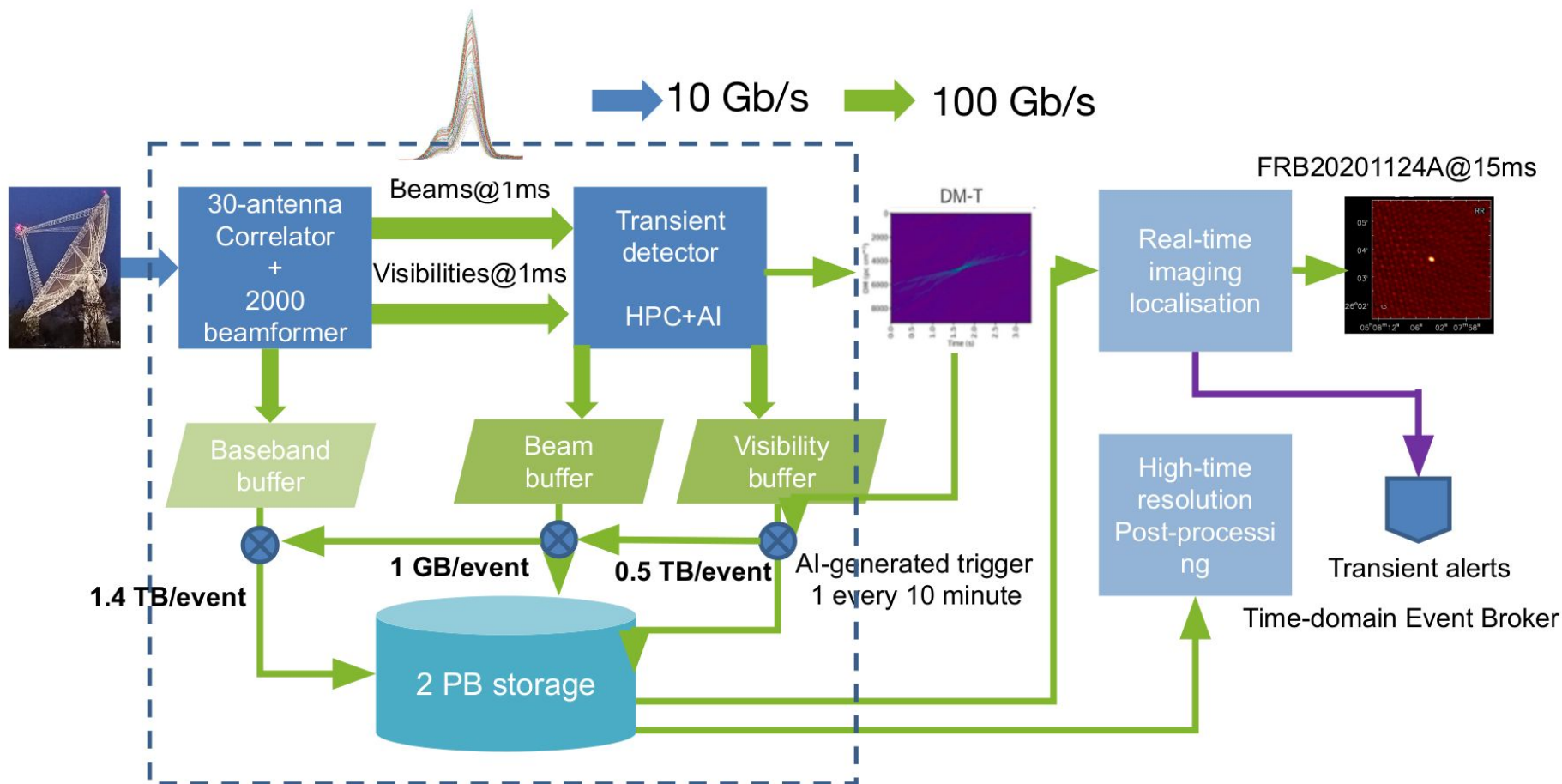
SPOTLIGHT enables commensal 24/7 fast transient surveys with the GMRT

SPOTLIGHT - Survey for sPoradic radiO bursts via a commensaL multi-beam Gpu-powered Hpc at the gmrT

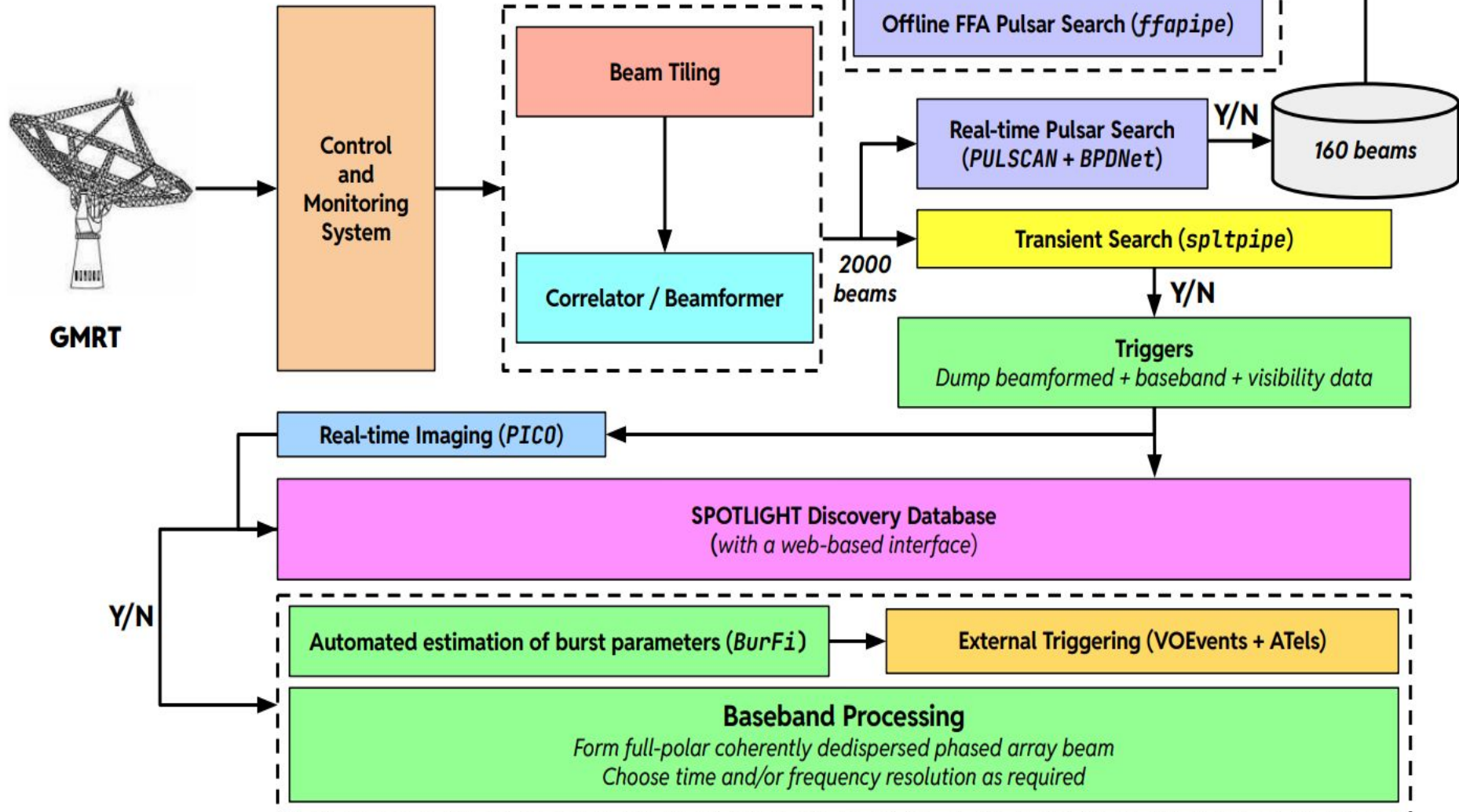
The SPOTLIGHT project

- A petaflop Real-time commensal system for pulsar and FRB search at the GMRT
- Funded by the National Supercomputing Mission (NSM)

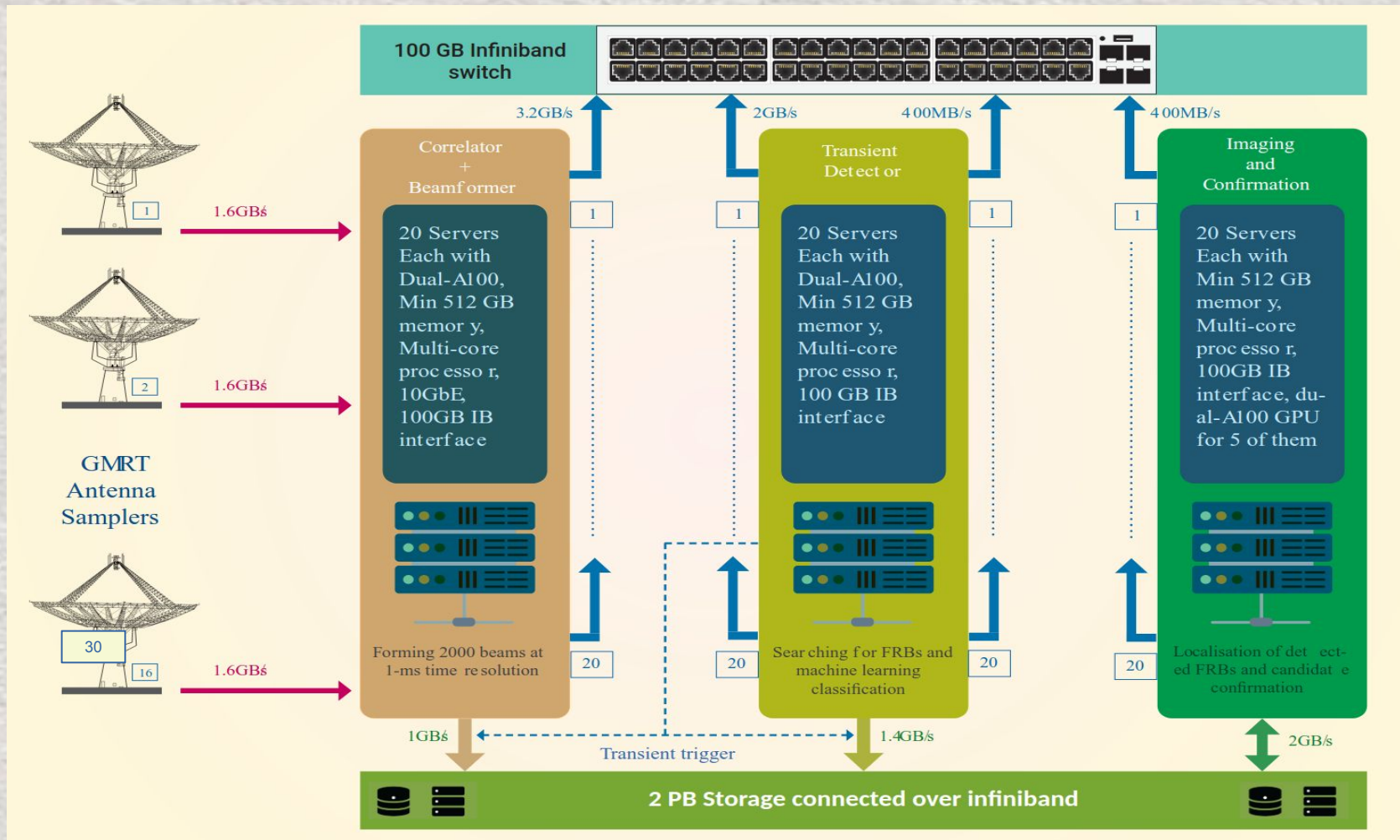
SPOTLIGHT processing flow



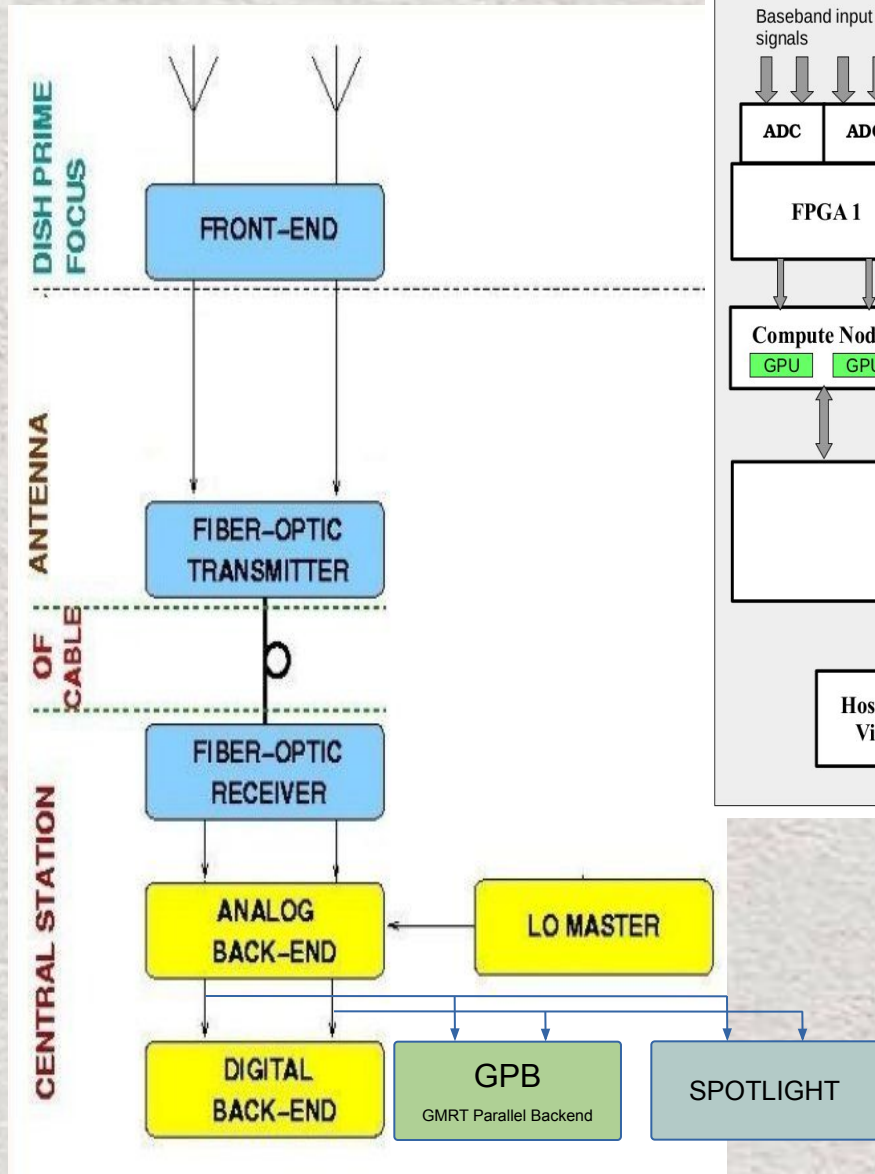
The SPOTLIGHT system



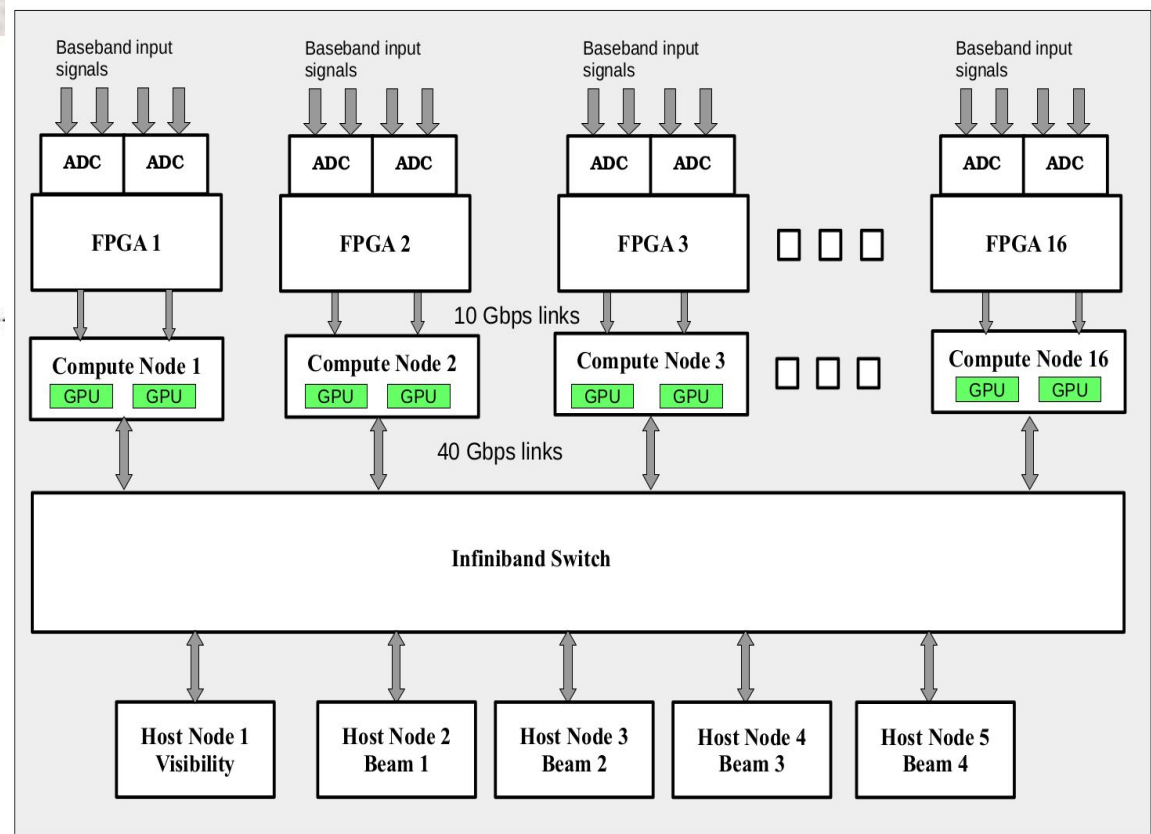
- Consists of **60** Rudra servers and **90** NVIDIA A100 GPUs, capable of **~ 1 PetaFLOPs**.
- Data rate = **~24 GB/s** for voltages, **~6 GB/s** for beamformed data.
- Forms **2000** *post-correlation* phased array beams on the sky.



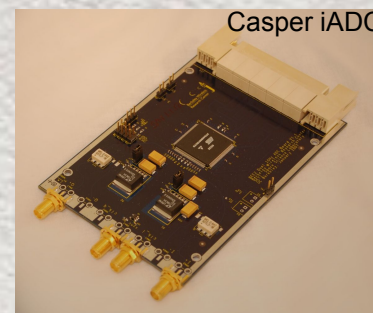
Signal flow from GMRT antennas to the SPOTLIGHT



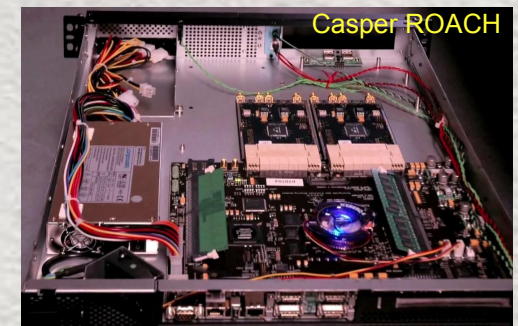
GMRT signal flow



GWB top-level design

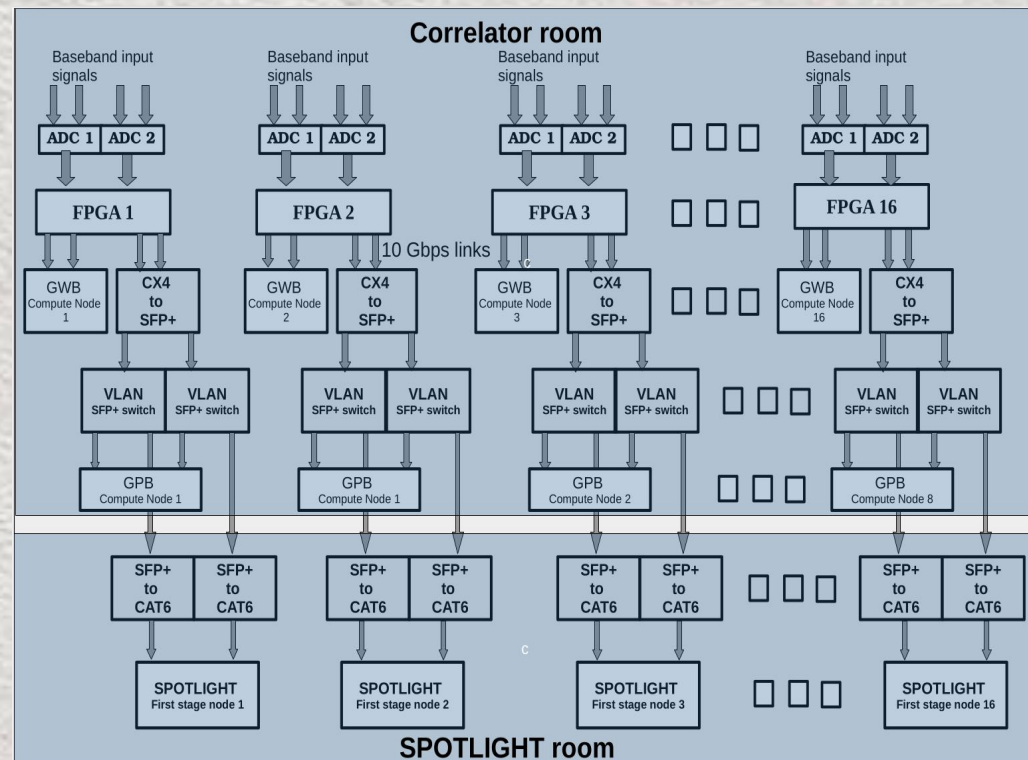
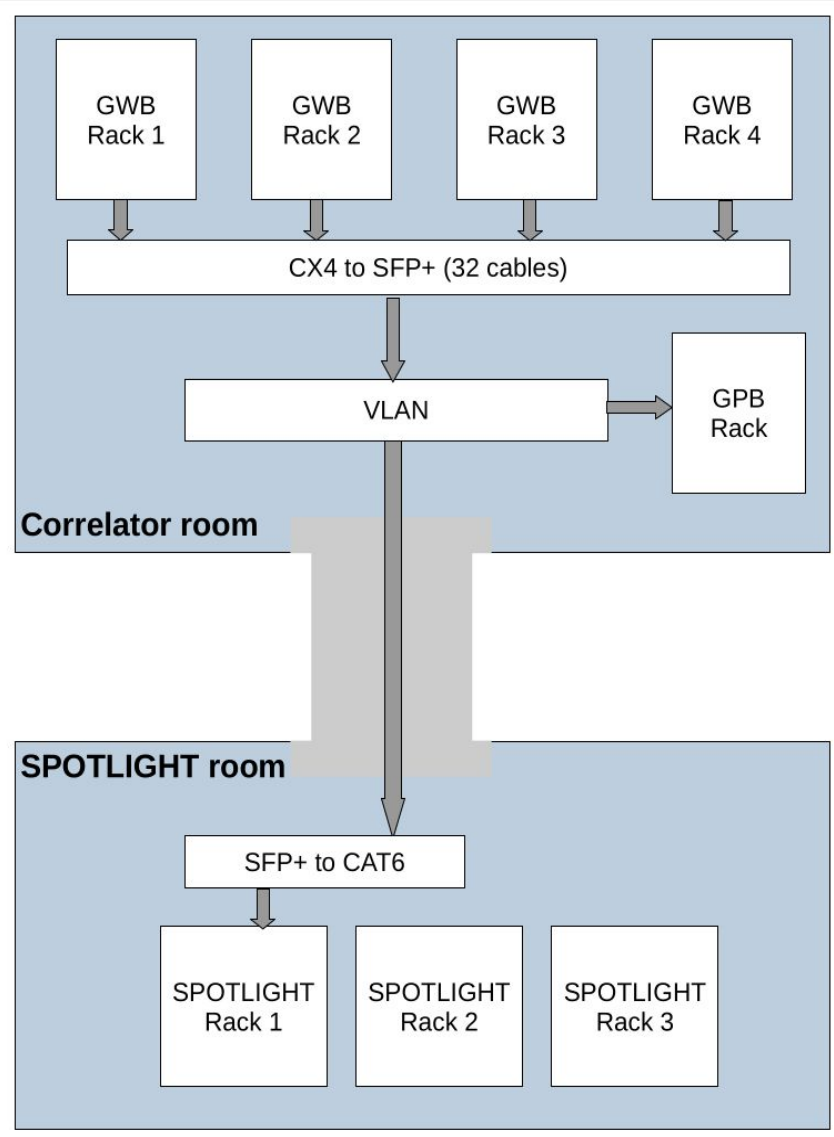


ADC



FPGA board

Signal flow from GMRT antennas to the SPOTLIGHT



SPOTLIGHT Correlator and Beamformer : Specifications

- Features – Post correlation beamformer

Baseline based steering of beams, Flagging of shorter baselines

Recording of **raw voltages** of all antennas and **visibility data** (half float) at 1.3 ms resolution upon **detection**

- Instantaneous bandwidth = 400 MHz (max)

Supports 200 MHz and 100 MHz

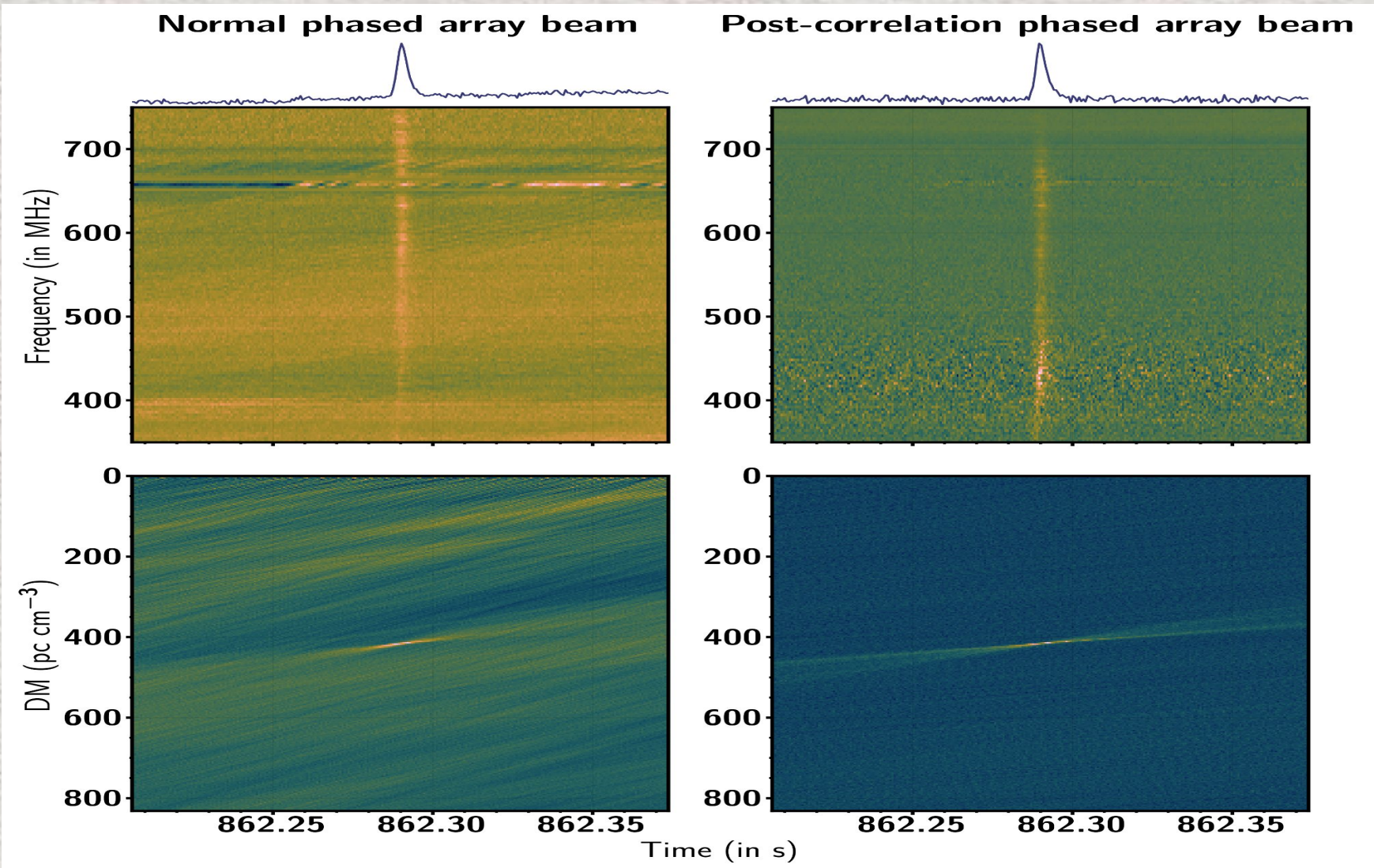
Spectral channels – 4096

No. of beams ~ 2000 @ 1.3 ms resolution (current release supports 800 beams)

- **Time-slicing** model
- Real-time processing : Total computation load ~ **85 Tflops**

Process	Computation load
Correlator	10 Tflops
Beamformer	25 Tflops
Beam Steering	50 Tflops

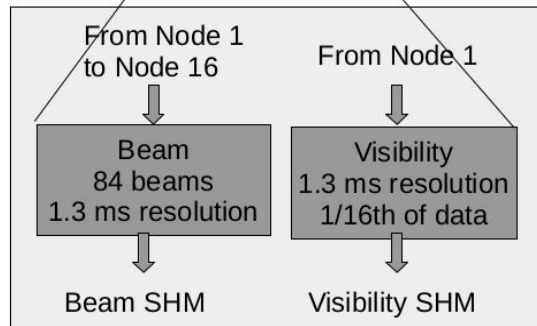
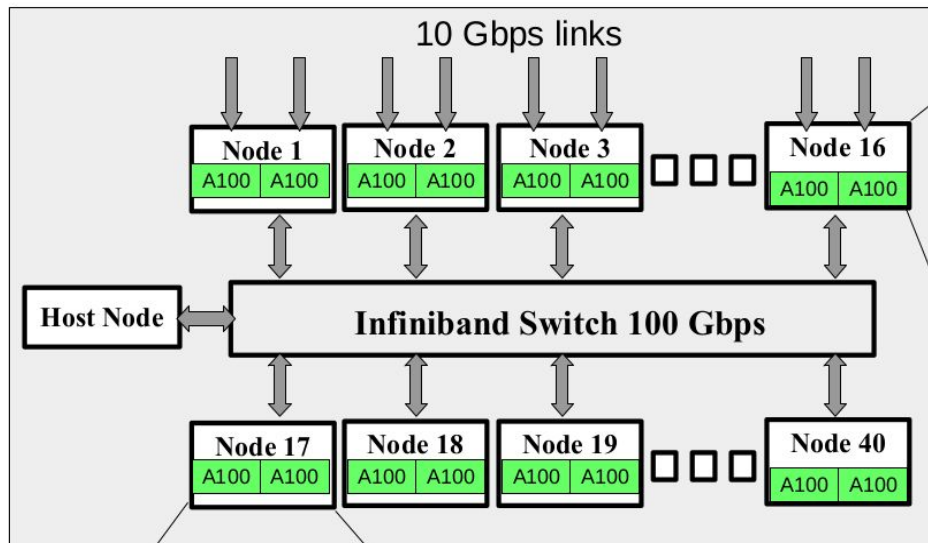
Post-correlation beam : less susceptible to RFI and systematics



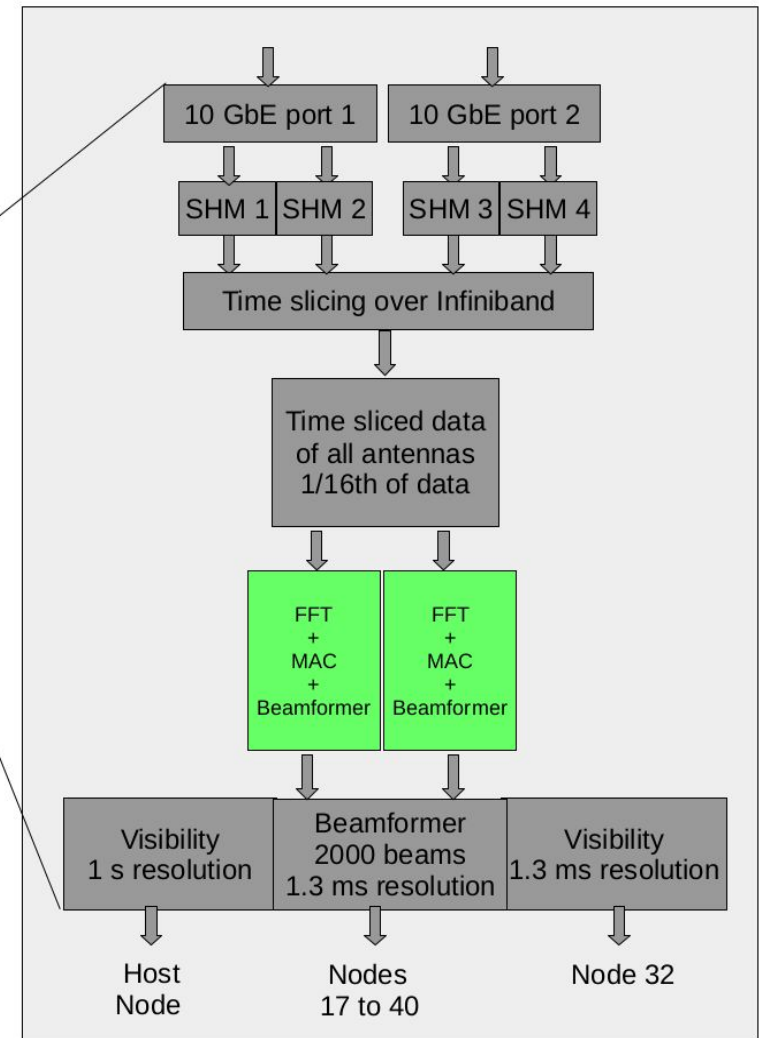
Comparison of phased array (PA) beam (left panel) and post-correlation (PC) beam (right panel) data from FRB 201124A in GMRT's Band 4 (550 to 950 MHz).

Design and data flow

Spotlight correlator and beamformer – Top level design



Data flow in a single second stage node – Node 17 here



Data flow in a single first stage node – Node 16 here

Computation and IO requirements

GPU IO requirement

IO	Per node (MB/s)	Per GPU (MB/s)
Input	1600	800
Beam data	787.5	393.75
Visibility at 1.3 ms	726.5	363
Total	1557	
	10% of peak bandwidth over PCIe x16 Gen4	

Computation requirement

Per node	5.3 Tflops
Per GPU	2.65 Tflops
27% of peak double precision performance of A100 GPU	

MPI transfer IO requirement (First stage nodes)

Time slicing	1500 (bi-directional)
Beam data	787.5
Visibility at 1.3 ms	726.5
Total	3014
	24% of peak bandwidth of 100 Gbps

MPI transfer IO requirement (Second stage nodes)

Beam data	787.5
Visibility at 1.3 ms	726.5 *Nodes 16-32
Total *Nodes 16-32	1514.5 12% of peak bandwidth of 100 Gbps

Memory requirements

First stage nodes	
Data from 10 GbE to SHM	25.6 GB
Raw voltages SHM	300 GB *4-bits per sample
Total	325.6 GB 42% of available 768 GB RAM

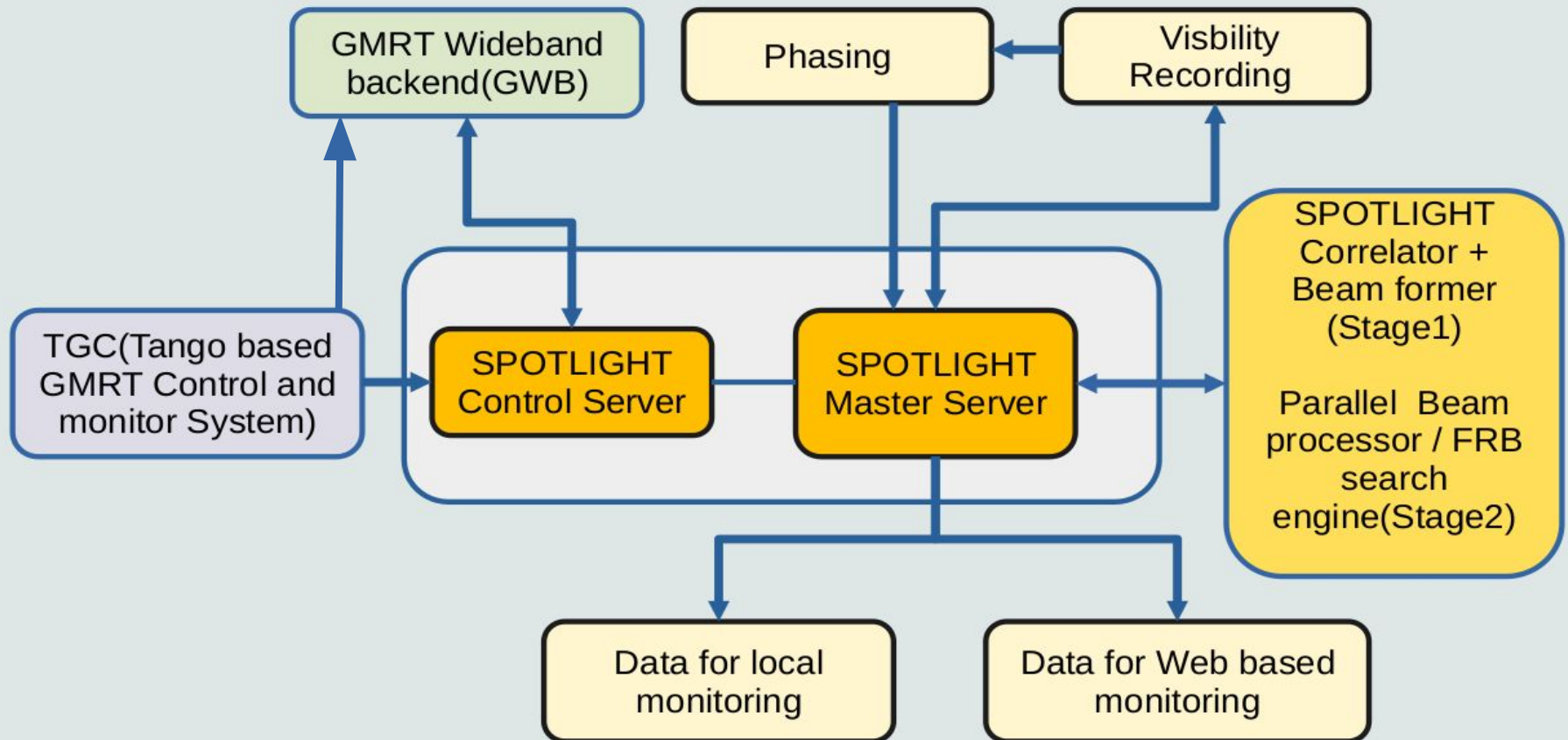
Second stage nodes	
Beam data SHM	99.61 GB *8-bit data
Visibility at 1.3 ms SHM	309.4 GB *half float data
Total	409 GB 53% of available 768 GB RAM

Raw voltages SHM, Beam data SHM and Visibility at 1.3 ms SHM requires buffering of ~ 400 seconds
Dispersive delay for an FRB with $DM = 1000 \text{ pc cm}^{-3}$ at Band 3 (300 to 500 MHz) is 29.5 s (Ujjwal's talk)

Total memory requirement over two stages	
Data from 10 GbE to SHM	0.4 TB
Raw voltages SHM	4.8 TB
Beam data SHM	2.4 TB
Visibility at 1.3 ms SHM	5 TB
Total	12.6 TB 42% of available 30 TB RAM

Control and Monitoring

- **TGC** - The primary control and monitoring system central to all GMRT operations
- TGC -> supplies and updates **metadata** information -> real-time processing of astronomical signals in the **GWB** - > copy available in **shared memory** of **GWB**.



Block diagram of online control for the SPOTLIGHT

Modes of operation

Commensal Backend

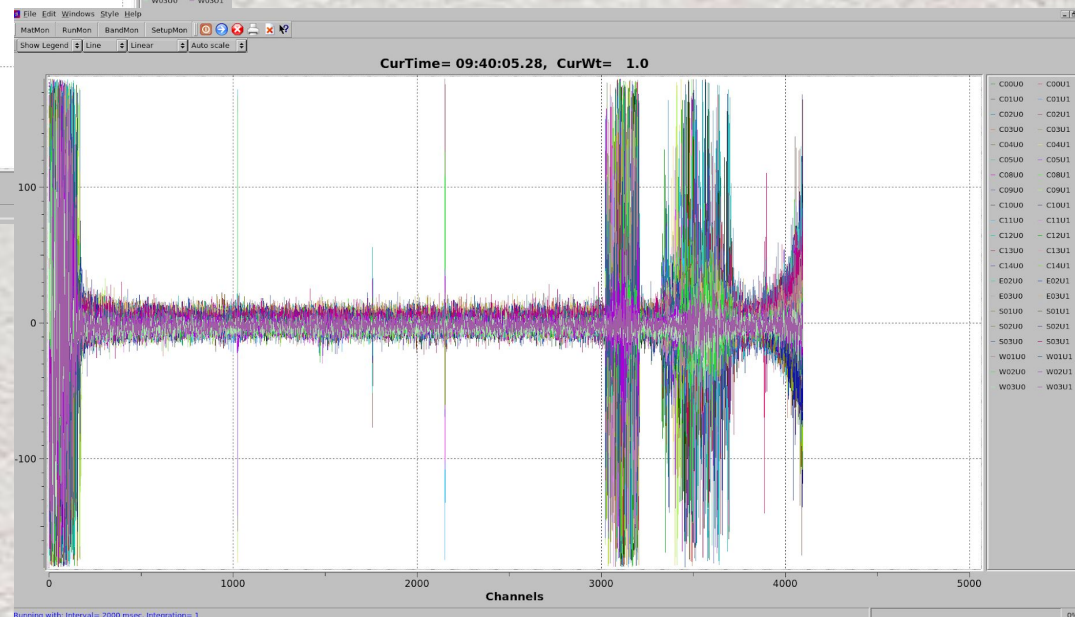
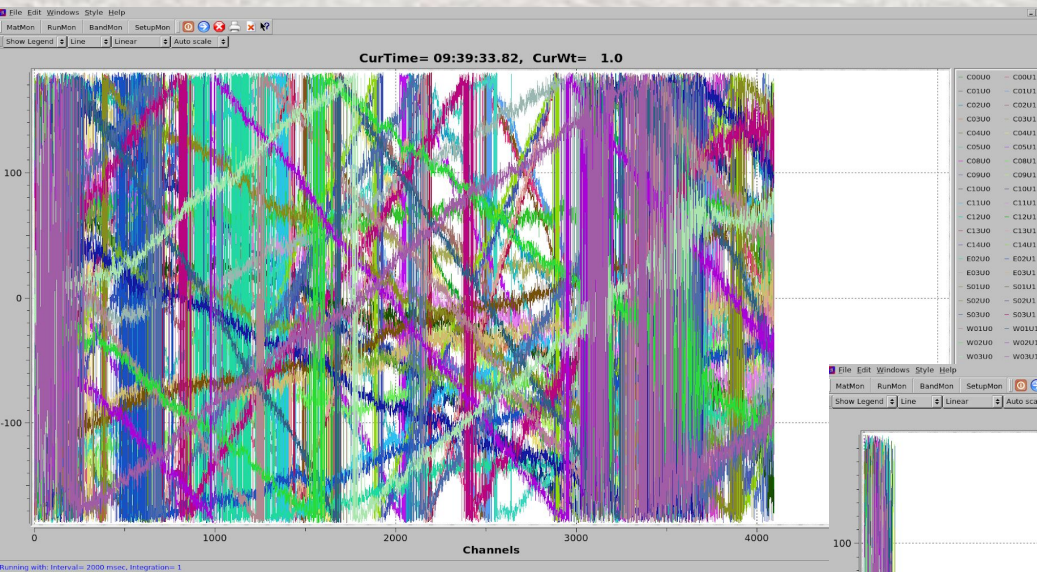
- Fully automatic operation of the SPOTLIGHT in passive mode with the existing GMRT operation.
- TGC -> Source and calibration code information (e.g., band-pass, phase calibrator, etc.) -> GWB -> SPOTLIGHT controller -> SPOTLIGHT -> Phasing.
- Phasing -> bad antennas list -> SPOTLIGHT correlator -> Beam simulation package

Independent Backend

- Fully automated commensal operation of the SPOTLIGHT as a real-time discovery machine.
- TGC -> Metadata information -> SPOTLIGHT controller

Monitoring

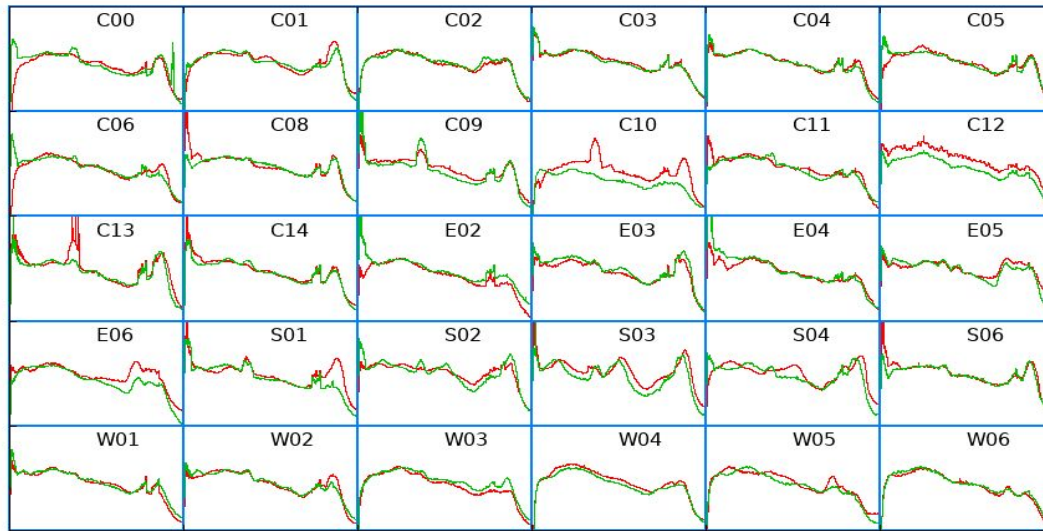
- Real-time monitoring of visibility and phasing quality checks.
- Fetch real-time self and cross-visibilitys from shared memory -> web-based monitor tools



Sample plots showing cross phase spectrum before and after phasing on a calibrator

Spotlight Self Band - Prj: T10DEC, Obj: 3C147 (10Dec2024 21:26:55)

Self Power (0-100000)

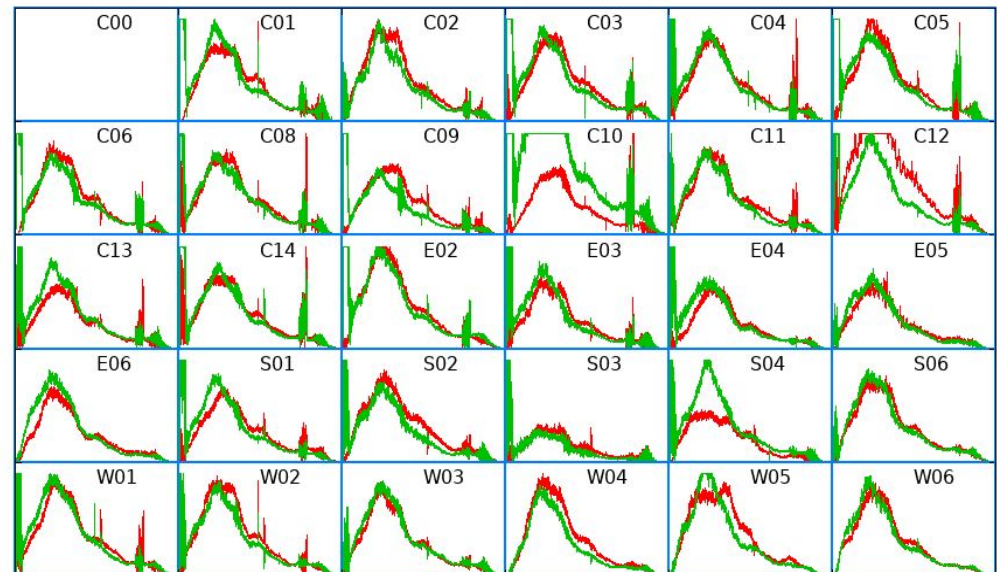


Frequency (550 - 750 MHz), Channel (4096)

Real-time self bandshape monitoring

Spotlight Visibility Band - Prj: T10DEC, Obj: 3C147, RefAnt: C00 (10Dec2024 21:57:56)

Visibility

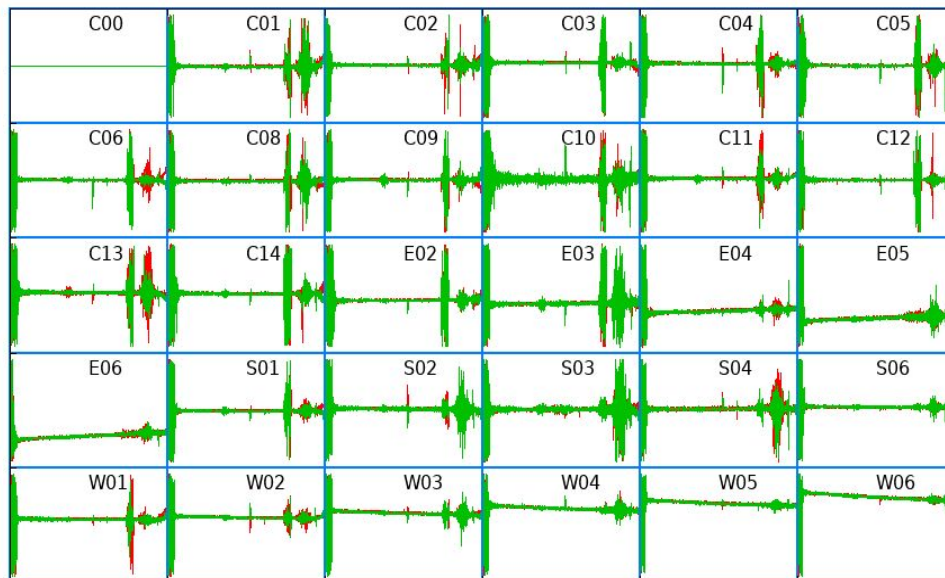


Frequency (550 - 750 MHz), Channel (4096)

Real-time cross spectrum monitoring

Spotlight Phase Band - Prj: T10DEC, Obj: 3C147, RefAnt: C00 (10Dec2024 21:43:57)

Phase (+/- 180 Deg)



Frequency (550 - 750 MHz), Channel (4096)

Real-time cross phase spectrum after phasing

Spotlight Visibility Matrix - Prj: 48_093, Obj: PGC2081790, Frequency: 1450 - 1350 MHz (4Aug2025 16:51:55)

ANT	C00	C01	C02	C03	C04	C05	C06	C08	C09	C10	C11	C12	C13	C14	E02	E03	E04	E05	E06	S01	S02	S03	S04	S06	W01	W02	W03	W04	W05	W06	P-1
C00	+	22	21	18	20	18	19	17	19	20	20	19	22	18	22	22	19	21	19	20	19	21	20	20	18	20	20	18	21	20	C00
C01	19	+	25	21	24	22	23	21	23	24	24	23	26	21	26	26	22	24	24	25	24	26	24	24	22	24	24	22	25	24	C01
C02	21	21	+	19	22	20	21	19	21	21	22	21	23	20	24	24	20	22	22	21	23	22	22	20	22	22	20	22	20	23	C02
C03	22	21	24	+	20	17	18	17	18	19	19	19	22	17	22	21	17	20	19	20	18	21	20	19	18	20	19	18	20	19	C03
C04	22	21	25	26	+	20	21	19	20	22	22	21	24	20	24	24	21	23	22	23	21	23	22	22	20	21	22	20	22	22	C04
C05	20	19	22	22	23	+	19	18	19	20	20	19	22	17	22	22	18	20	20	21	19	21	20	20	18	20	20	18	21	20	C05
C06	21	20	23	23	25	22	+	19	19	20	21	20	23	19	22	23	19	21	21	20	22	21	21	18	21	20	19	21	21	21	C06
C08	20	20	22	23	23	21	22	+	18	18	19	18	21	17	20	21	17	19	19	20	18	20	19	19	17	19	17	20	19	19	C08
C09	21	20	23	24	24	22	23	22	+	20	20	19	22	18	22	23	19	21	20	21	20	22	20	21	18	20	20	18	21	20	C09
C10	22	21	24	26	26	23	24	24	25	+	22	21	24	19	23	24	20	23	22	23	21	24	21	22	21	22	22	20	23	22	C10
C11	21	20	23	23	24	21	22	22	23	24	+	21	24	20	24	24	20	23	22	23	21	24	22	22	20	23	22	20	23	22	C11
C12	20	19	22	22	23	20	22	21	21	23	21	+	23	18	22	22	20	21	20	22	20	23	21	21	19	21	21	19	22	21	C12
C13	21	20	23	24	24	21	23	21	23	24	23	21	+	21	26	27	22	25	23	25	23	25	24	24	22	24	24	22	25	24	C13
C14	18	17	20	21	21	19	20	19	20	21	19	20	+	21	22	19	20	20	21	19	21	20	20	18	20	20	19	21	20	21	C14
E02	20	19	22	23	23	21	21	21	22	23	21	20	22	19	+	26	22	24	23	25	23	25	25	24	22	24	24	22	25	24	E02
E03	19	19	22	22	22	20	21	20	22	22	21	20	21	19	20	+	23	26	24	24	23	26	24	24	22	25	25	22	25	25	E03
E04	23	21	24	25	26	23	24	23	24	26	24	23	25	21	24	22	+	21	21	19	22	21	21	18	20	21	19	22	20	22	E04
E05	18	17	20	21	21	18	20	19	20	21	19	19	20	17	19	19	21	+	23	23	22	25	23	20	22	23	20	22	24	23	E05
E06	21	20	23	24	25	21	23	21	23	24	22	21	23	19	21	21	24	20	+	22	21	23	22	22	19	22	22	20	23	22	E06
S01	20	20	22	23	24	20	22	21	22	24	22	21	21	19	21	21	23	19	22	+	22	25	23	22	21	24	23	21	24	23	S01
S02	19	19	22	22	23	20	22	21	22	23	22	20	22	19	20	20	23	19	22	21	+	23	21	21	19	22	21	19	22	21	S02
S03	20	20	23	23	24	20	23	21	23	24	22	21	23	19	21	21	23	20	22	21	22	+	24	24	21	23	23	22	25	23	S03
S04	18	17	20	21	21	18	19	19	20	21	20	18	20	17	19	18	22	17	20	19	20	+	23	21	22	22	20	23	22	22	S04
S06	19	17	20	21	22	19	20	19	20	22	20	18	20	18	20	19	22	17	21	19	19	20	18	+	20	22	22	20	24	22	S06
W01	21	19	23	23	24	21	22	21	22	23	21	20	22	20	21	21	24	19	22	21	21	22	19	19	+	21	20	18	21	20	W01
W02	21	20	23	23	24	21	23	22	23	24	22	21	23	20	22	21	24	20	23	22	22	22	20	20	22	+	22	21	22	22	W02
W03	19	18	21	21	22	19	21	20	21	22	20	20	21	18	20	19	22	18	21	20	20	18	18	21	21	+	21	23	22	22	W03
W04	21	20	23	24	24	22	23	22	22	24	23	21	23	20	22	21	24	20	23	22	21	23	20	22	23	21	+	22	21	22	W04
W05	21	20	23	23	24	21	22	21	23	24	22	21	23	20	21	21	24	20	23	22	22	22	19	20	22	22	21	23	+	23	W05
W06	17	16	20	20	20	18	19	19	20	19	17	19	17	18	18	21	17	19	18	19	16	17	19	18	19	19	+	19	19	19	W06
P-2	C00	C01	C02	C03	C04	C05	C06	C08	C09	C10	C11	C12	C13	C14	E02	E03	E04	E05	E06	S01	S02	S03	S04	S06	W01	W02	W03	W04	W05	W06	ANT

Real-time cross counts monitoring

Ongoing developments

- Offline correlator to process raw voltage data
Full polar visibility data at 1.3 ms resolution
Full polar beams
- Real-time correlator and beamformer supporting up to 2000 beams

Summary

- SPOTLIGHT - Petaflop system for real-time commensal search for transients
- 2000 post correlation beams
- Records raw voltages and visibility @ 1.3 ms time resolution upon detection

Acknowledgement

- C-DAC, Pune
- Digital Back-end Group, GMRT
- Control Room, GMRT

Thank You