National Research Foundation

SARAO
South African Radio Astronomy Observatory

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Developing a VLBI Observation Mode for MeerKAT

21 October 2024

Brief MeerKAT Overview

- SKA precursor in Northern Cape of South Africa.
- 64 dishes, equivalent 13.5 m diameter.
- Bands (linear polarization, H and V):
  - UHF: 544 – 1088 MHz
  - L-band: 856 – 1712 MHz
  - S-band: 1750 – 3500 MHz
- Baselines: min 29 m, max 7700.
- Sensitivity: ~ 400 m^2/K
- Correlator / Beamformer modes:
  - 1K, 4K, 32K coarse channelisation
  - 32K narrowband 'zoom' mode: 107 MHz and 53.5 MHz (L-band)
- MeerKAT Extension: 14 new dishes, GPU correlator

MeerKAT VLBI mode

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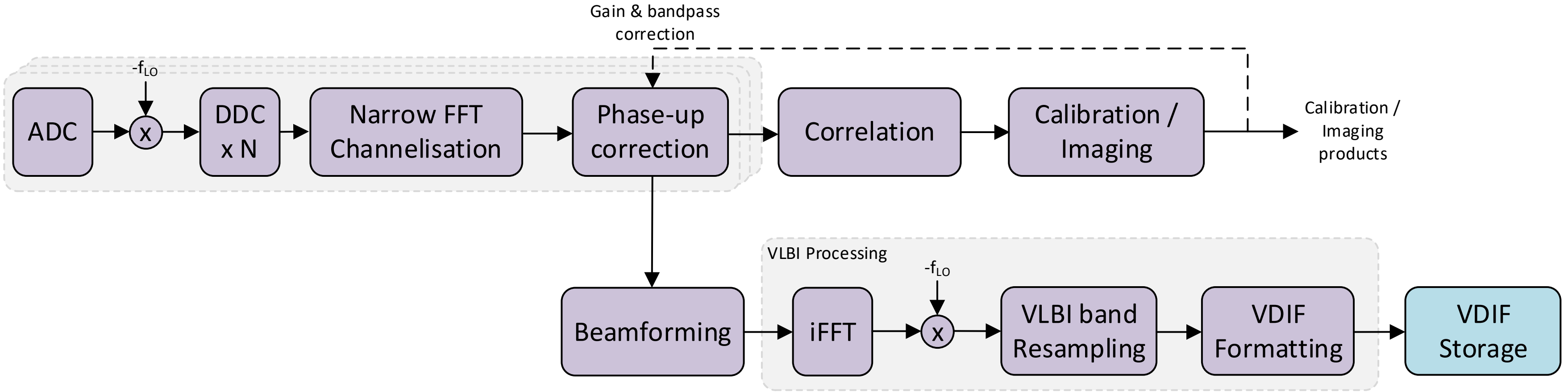
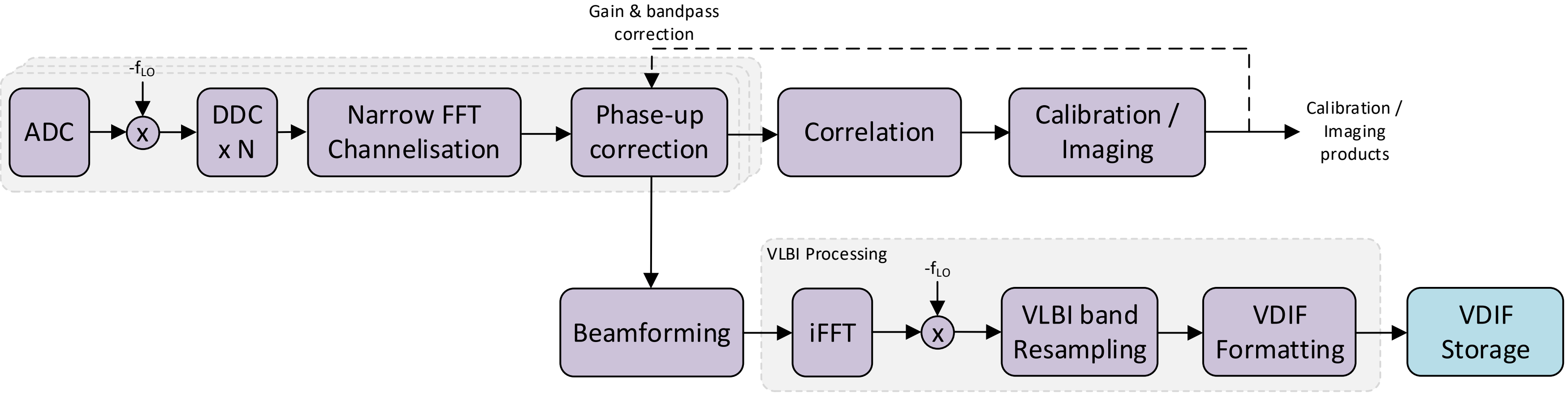
- Long-standing goal & cooperation with JIVE
  - Initial fringes with EVN in 2018!
- High sensitivity baseline within EVN, Australian LBA.
- Limited frequency overlap:
  - L-band: 21 cm, 18 cm (partial: ~80 MHz overlap)
  - S-band: 13 cm (LBA only)
- Design decisions:
  - No new hardware.
  - VLBI channels: min 2 x 32 MHz (goal: 2 x 64 MHz / 4 x 32 MHz)
  - Bands: L-band (goal: L-band and S-band)
  - Beams: Single coherent boresight beam (goal: 4x steerable)
  - E-shipping only, for now.
  - Prototype: offline processing; final: real-time.
- Aiming for completion of first-iteration architecture early 2025.

Signal Path Design



- Digital front-end:
  - Sample and DDC to lower bandwidth (adjustable center frequency)
  - FFT channelization for ease of reconstruction
  - Coarse / fine correction of geometric delays.
  - Application of bandpass (per-channel) correction coefficients
- Correlation, Online Calibration Pipeline, Imaging pipeline
  - Provides cal solutions for computing phase-up corrections.
- Coherent beamforming: channelized beam voltage

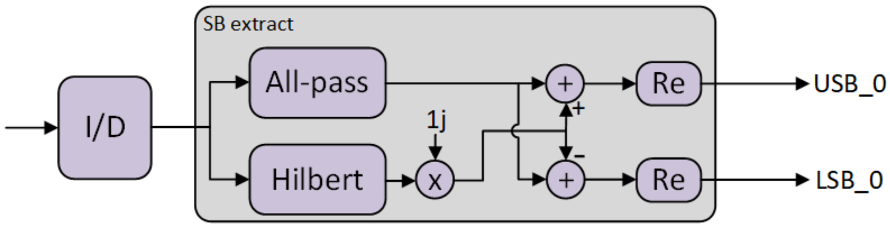
Signal Path Design

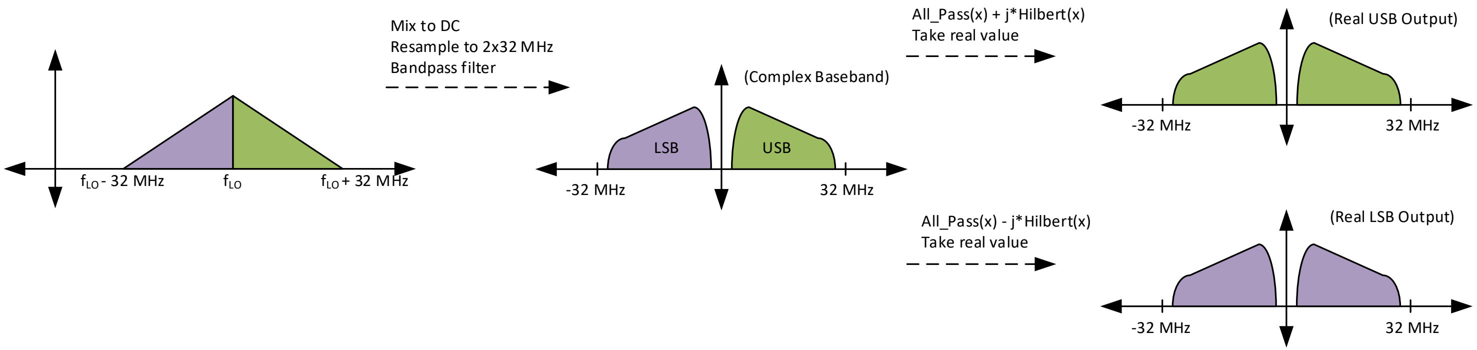


- VLBI Backend: Convert channelized voltages to VDIF:
  - Reconstruction via FFT
  - Downconvert to desired center frequency
  - Resample to desired VLBI channels
  - Compute / store channel power (used for station calibration)
  - Normalise and re-quantise: 2 bits (symmetric 4-level)
  - Write VDIF file to storage (FlexBuff format)
  - VDIF files transferred to server hosting jive5ab

Channelisation

- 2 x 32 MHx, 2 x 64 MHz: Simple LSB / USB extraction
- I/D interpolation to 2 x channel bandwidth (bandpass rather than low-pass filter to shape VLBI channels)
- Hilbert / All-pass filter to split channels





Channelisation

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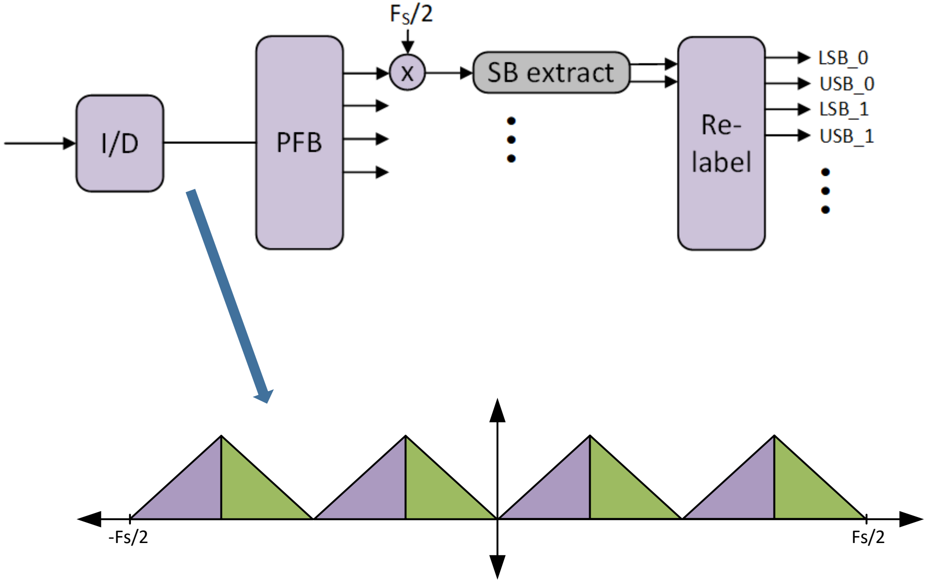
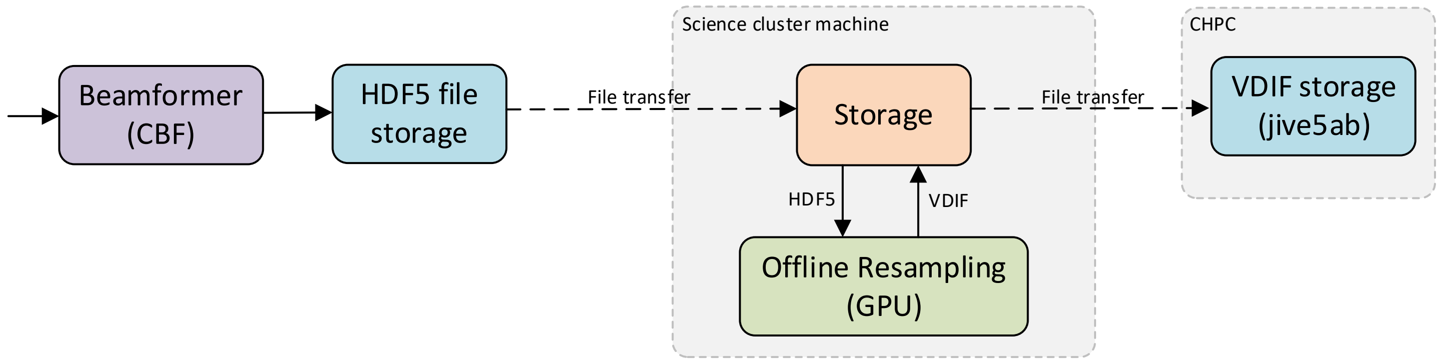
- 4 x 32 MHz or more channels: employ PFB.
- I/D interpolation to desired total bandwidth
- PFB channelize to 2 x VLBI channel bandwidth (prototype filter is bandpass to shape VLBI channels)
- Flip PFB channels
- Extract LSB / USB per PFB channel
- Label output channels correctly



Prototype (interim) Architecture



Interim architecture:

- Existing mode on MeerKAT SKARAB correlator
  - Modified 107 MHz ‘zoom’ mode with 32k FFT channelization
  - Beamforming enabled
  - Limited to 2 x 32 MHz channels, L-band, 1 beam.
- Beam channelised voltages streamed to server with SSD array, stored as HDF5 file.
- HDF5 converted to VDIF offline on science cluster
- VDIF files transferred to “jive5ab” server.

Real-time Architecture

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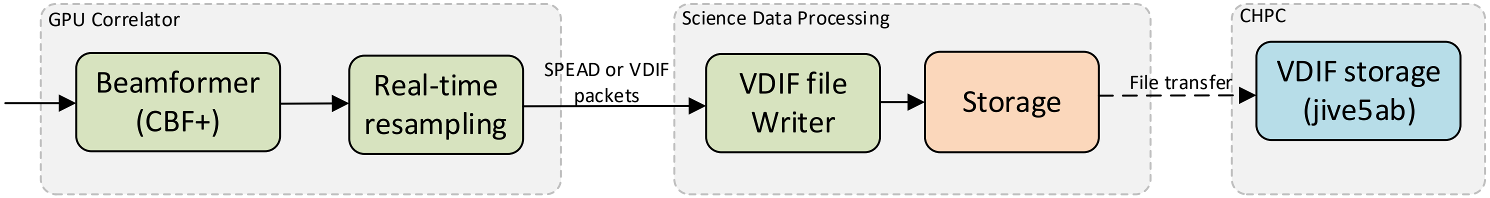

Real-time architecture:

- New mode on MeerKAT Extension GPU correlator
  - DDC by x8 or x16 with FFT channelisation
  - Beamforming enabled
  - Feasible to get 2 x 64 MHz channels, L-band and S-band.
- Beam voltages resampled and formatted for VDIF in real-time.
- VDIF-formatted data streamed to SDP subsystem; written to VDIF file.
- VDIF files transferred to “jive5ab” server.

Data Storage and Transport

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Modest transfer / storage requirements:

- Low VDIF data generation rate (512 to 1024 Mbps; 4096 Mbps for multiple beams)
- Given limited frequency overlap, don't participate in all observations.
- Ball-park storage estimate at 1024 Mbps for 2 x EVN, LBA sessions: 100 GB.

VDIF data handled per existing network / storage architecture:

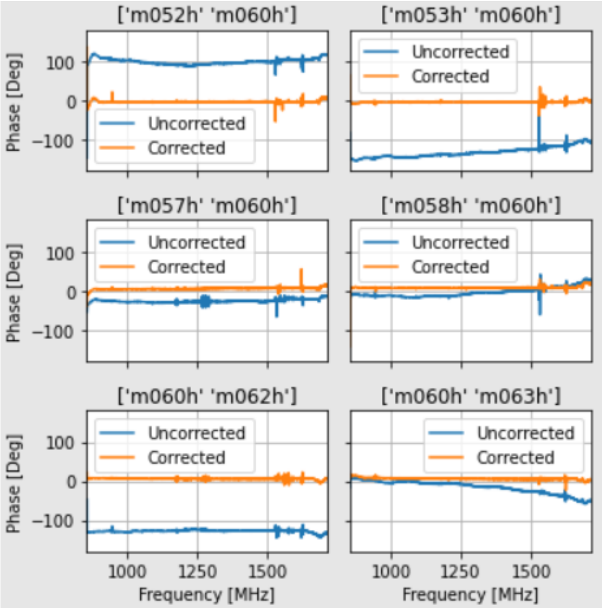
- MeerKAT data products stored temporarily on SDP subsystem on site (Karoo) network
- Data products transferred to MeerKAT archive (CHPC, Cape Town) for permanent storage

"VLBI server" for MeerKAT:

- jive5ab hosted on VM on existing MeerKAT Ceph storage cluster.
- Generated VDIF files generated / stored temporarily on SDP subsystem (Karoo network); then transferred to server at CHPC.
- User ssh onto VM for data download.
- VDIF data conforms to FlexBuff standard.

Array phase-up

- Standard phase-up, run prior to beamformer observation:
  - Short scan on primary calibrator, firing noise diode.
  - Wait for pipeline solutions.
  - Compute and apply per-channel corrections (at channeliser output)
- Cal solutions / corrections include:
  - K, G, B
  - Cross-pol: K_cross, B_cross (in two components: before/after noise diode)
  - Cross-coupling assumed negligible on boresight (offset-Gregorian antennas)
- Phase-up correction effectively performs online array calibration



Array phase-up

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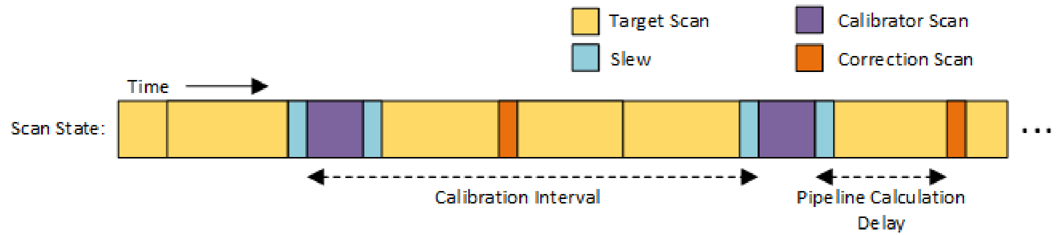
- For VLBI: (a) Phase-up at start of observation, (b) re-phase / phase-up corrections at regular intervals.

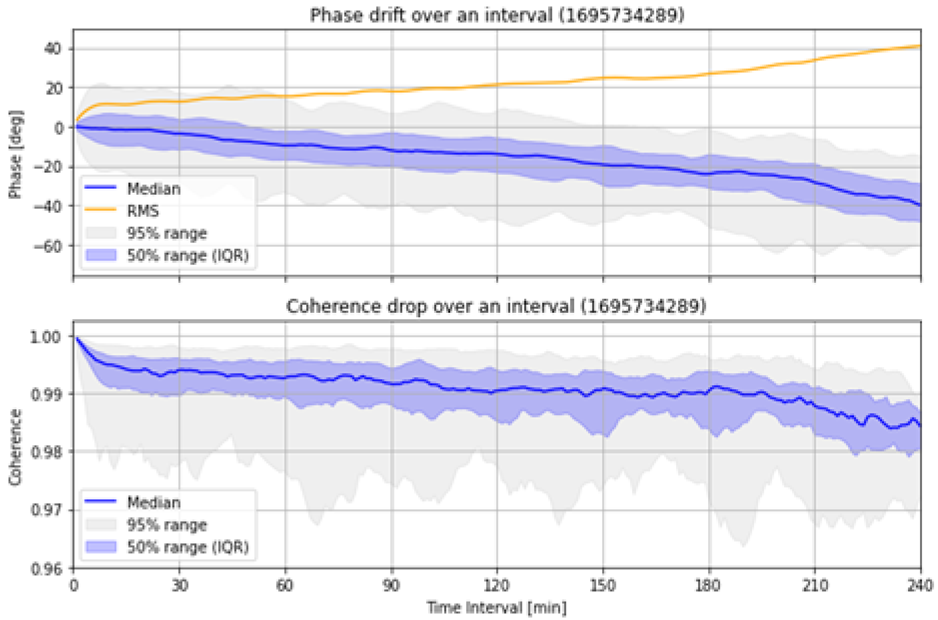
- Apply bandpass corrections (B, B_cross)?
  - Fully calibrated array allows for pol conversion: L to C (optional!)
  - However, introduces reconstruction error

- Regular phase-up corrections:
  - Interrupt VLBI observation for scan on calibrator + “correction scan” to apply solutions when available.
  - Currently checks if correction required after each VLBI scan
  - Calibration can fail: requires automated QA
  - TBC: limit corrections to K, G only (quicker, easier QA)
  - TBC: rules to minimize impact



Array phase-up

- How often to perform corrections?
  - L-band: every 2 hours
  - S-band: more often, TBC.



Station Calibration

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- Standard single-dish flux cal methods:
  - Maintain Tcal and Gain [K/Jy]: DFPU and gain curve. [RXG file]
  - Measure Tsys during observation using Tcal [ANTAB file]
  - … not directly applicable to coherent beam flux calibration
- Beam flux cal depends on coherence of antennas, number of antennas, which antennas.
- Proposed approach:
  - Use cal solutions from phase-ups / phase-up corrections: $g_i b_i$ per channel
  - Relates power in Counts to Jy directly
  - Beam power [Counts]:

$$P_{TAB} = k_{DSP}^2 \sum_{i=1}^{N} |g_i b_i|^2 S_i^{SYS} + k_{DSP}^2 \left| \sum_{i=1}^{N} g_i b_i \right|^2 S_{TGT}$$

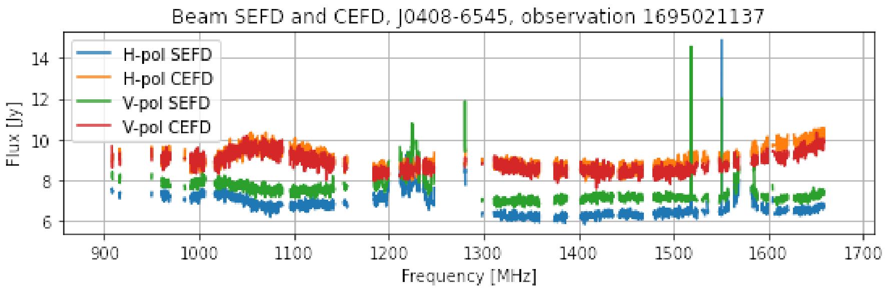
  - Beam gain [Counts / Jy] (mean over VLBI channel bandwidth):

$$G_{TAB} = k_{DSP}^2 \left| \sum_{i=1}^{N} g_i b_i \right|^2$$

Station Calibration

Proposed procedure:

- Store VLBI channel power vs time: $P_{TAB}(t)$
- Update G [Counts / Jy] on every phase-up correction. (requires verification scan)
- Compute $S_{TOT} = P_{TAB}(t) / G$; store in ANTAB file.
- Set DFPU=1.0. Alternately provide modelled beam G in [K/Jy] to convert Jy to temperature.
- Gain curve vs elevation: small effect for MeerKAT antennas. Ignore on first iteration.



Time and Frequency Reference

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- Clock reference: TFR subsystem using Hydrogen Masers (Allen dev. <= 2e-15)
  - Establishes Karoo Telescope Time (KTT), steered within 1 us of UTC(ZA) via GPS common view.
  - Provides reference 10 MHz for ADC clock signal generation
  - Provides 1 PPS signal for digitizer time synchronization

- Precise time manager:
  - Reference signal timestamps (in KTT) to array phase center
  - Increase accuracy by compensating for (a) sync signal delays and (b) signal path delays.
  - Round-trip measurement system estimates PPS propagation delay to digitiser.
  - Keep track of signal path delays: propagation through receivers electronics, PFB group delay, etc.
  - …needs to be updated for VLBI instrument!

Observation Execution

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- Parsing of VEX file for specified station to yield:
  - MeerKAT katpoint catalogue of targets
  - Array configuration parameters
  - VLBI processing configuration parameters

- Custom observation script:
  - Observations align with specified UTC scan times.
  - Adjusts scan times to accommodate local horizon
  - Checks if a scan is feasible given modelled slew time.
  - Implements periodic phase-up corrections at specified interval.

- Auxiliary files generated after completion from sensor data:
  - ANTAB file (contents to be agreed upon)
  - UVFLG file
  - LOG file: observation status; maser-gps jumps

Progress and Status (Oct 2024)

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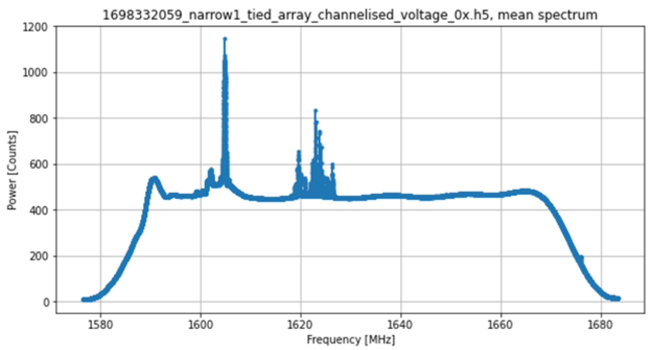
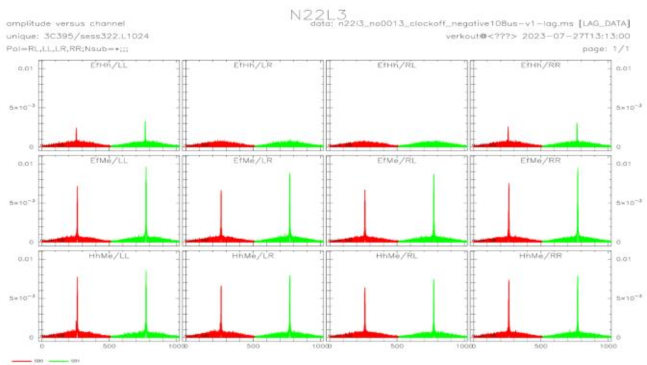
Complete:

- Interim 107 MHz SKARAB signal path
- Beamforming and initial phase-up
- Offline reprocessing to VDIF
- VEX-file parsing and observation execution (except phase-up corrections)
- Fringe-finding against EVN with short captures. Clock offset: 32 us, 6 us with preliminary precise time correction.

In progress:

- Integrating GPU accelerated offline processing.
- jive5ab test server up-and-running for internal testing.
- Station cal and auxiliary files
- Optimising speed and RFI resilience of phase-up.





THANK YOU

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