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MeerKAT as a VLBI station: EVN integration and new developments

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MeerKAT Overview

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- SKA-Mid precursor in Northern Cape of South Africa operating since 2018
- 64 dishes of 13.5 m diameter, baselines from 29 to 7700 m.
- Linear polarization receivers (H and V) in UHF, L-band and S-band.
- Developments in progress:
  - Adding 12 SKA-Mid dishes
  - GPU-based correlator
  - Band 5B expansion (8.3 – 15.4 GHz)
  - New observation modes – including VLBI

VLBI developments:

- Original MeerKAT specification to join EVN and LBA
- Experiments with JIVE back to 2018, project started 2023, VLBI mode commissioned 2025.
- Joined EVN since October 2025 Call for Proposals.
- Development of GPU-based mode in progress.

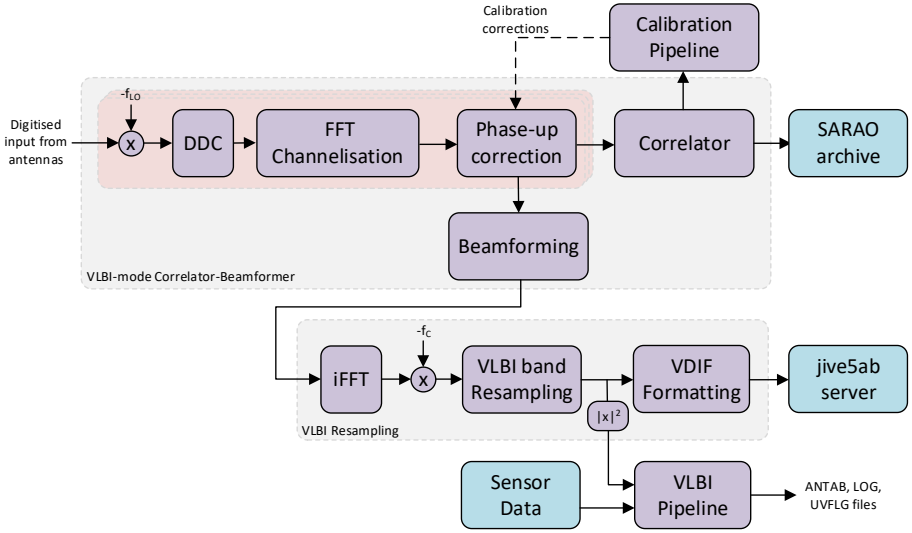
MeerKAT VLBI Design

Constraints on initial design:

- Single phased beam at boresight
- Only L-band receiver: 21 cm and 18 cm bands.
- VLBI channels: 2 x 32 MHz at 512 Mbps

Signal path design:

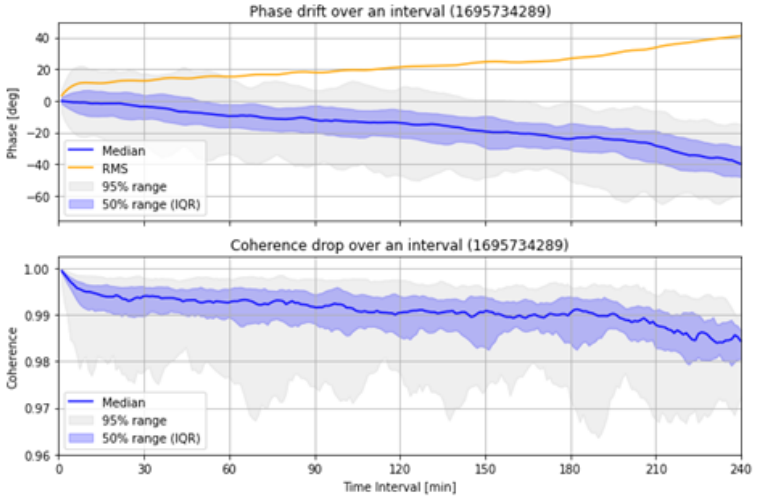
- Standard narrowband ‘zoom mode’ correlator, modified for FFT channelization.
- Coherent beamforming, phasing using online calibration pipeline.
- Reconstruct channelised voltages via iFFT, resample to VLBI channels, format to VDIF.
  - Staged approach: (i) offline processing, (ii) real-time processing on GPU correlator
  - Linear polarisation or optional conversion to circular.
- Internet-facing `jive5ab` server for hosting VLBI observation (VDIF) data
- Pipeline for VLBI metadata: antab, uvflg files.



MeerKAT VLBI Design

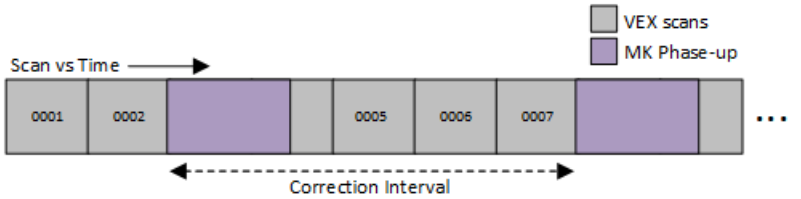
VLBI beamforming / phase-up:

- Selected core antennas included in beam (default: 43 antennas within 1 km core); longer baseline antennas added for calibration performance.
- 'Phase-up' process: calibrator scan, wait for pipeline solutions, apply corrections.
- Phase-up prior to observation; repeat at regular intervals: every ~2 hours for L-band.
- Two types:
  - Correction using bandpass calibrator: single and cross-pol KGB corrections, except cross-pol leakage.
  - Phase correction on gain calibrator. (TBC!)



VLBI observation execution:

- VEX-file parsing to get observation parameters.
- Observe on UTC-based schedule; including decision-making on whether source track is feasible.
- Insertion of phase-up events: overrides VLBI schedule except for specified sources.



MeerKAT VLBI Design

Station calibration / ANTAB file

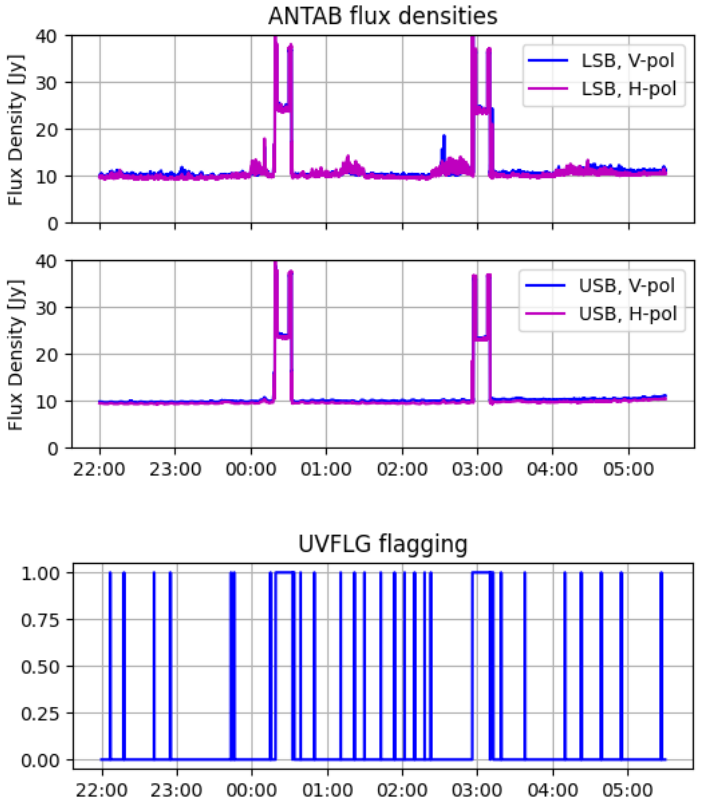
- Using interferometric gain calibration rather than noise diodes; flux density rather than temperature
  - Add flux calibrator scan to start / end observation.
  - Also use phase-up corrections scans
- Yields complex $g_i b_i$ for each antenna; compute beam gain [Counts to Jy]:

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

- Compute $S_{TOT}(t) = P_{TAB}(t) / G_{TAB}$ [Jy] (sets DPFU=1.0)
- Gain updated on every flux calibrator scan
- Gain curve vs. elevation: small effect for MeerKAT antennas. Ignoring on first iteration.

Other metadata:

- UVFLG file: flag when not pointing at source
- Custom observation log file (not FS format).



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VLBI data storage and transfer:

- 'VLBI server' at CHPC in Cape Town: VM hosting `jive5ab`
- Storage allocated from existing MeerKAT archive Ceph cluster.
- VDIF files stored according to FlexBuff conventions
- VDIF data transfer via `jive5ab` over UDT; typical speeds ~ 500 Mbps.

Ongoing improvements:

- Reducing impact of "phase-ups" during observation:
  - Shortening phase-up duration
  - Considering improved scheduling via VEX-file.
- Timestamp accuracy: typically off 20 to 30 us from UTC.
  - Due to propagation delays in signal path and ADC sync signals.
  - Existing system developed for pulsar instruments corrects timing errors: to be integrated with VLBI mode.
  - Will generate corrected timestamps referenced to array phase center.

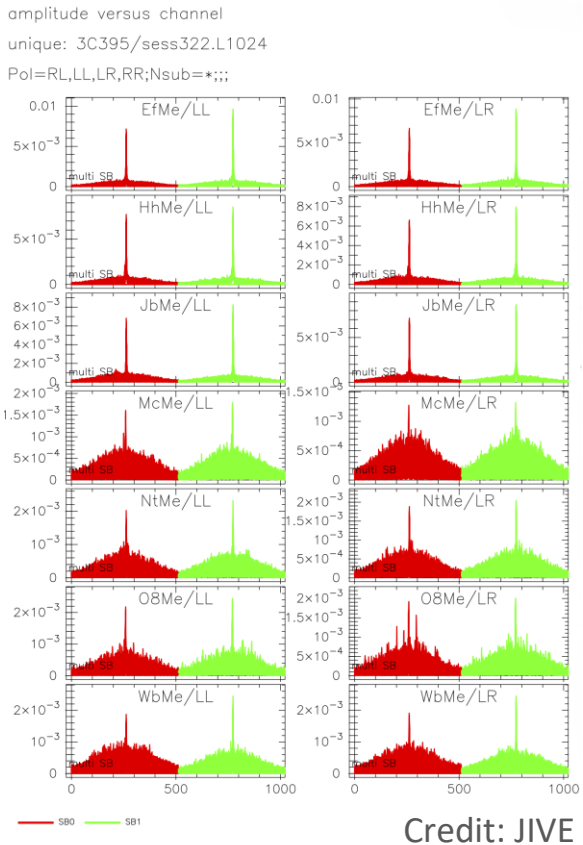
Progress & status

EVN integration:

- Early tests by observing Network Monitoring Experiments
- Participated in selected observations for commissioning / early science starting early 2025.
- Joined EVN on best effort basis:
  - Since October 2025 call-for-proposals; 9 experiments observed to date.
  - L-band (18 and 21 cm), 2 x 32 MHz
  - Users can request access to visibilities in MeerKAT archive.
  - Correlator products available: 107 MHz at 32K channels (FFT channelisation); 856 MHz at 4K channels.
  - EVN proposals are checked for overlap with existing MeerKAT proposals.

LBA integration:

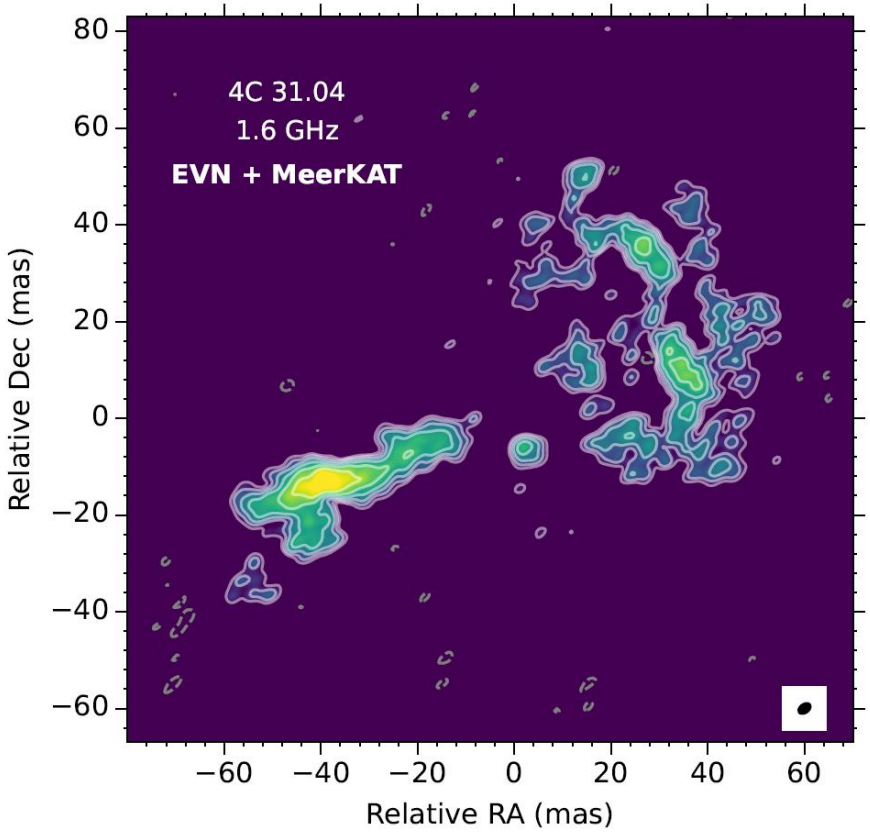
- Successful integration and initial test observation / fringes



Credit: JIVE

Early science results

S. Murthy (ALMA) and Z. Paragi (JIVE)

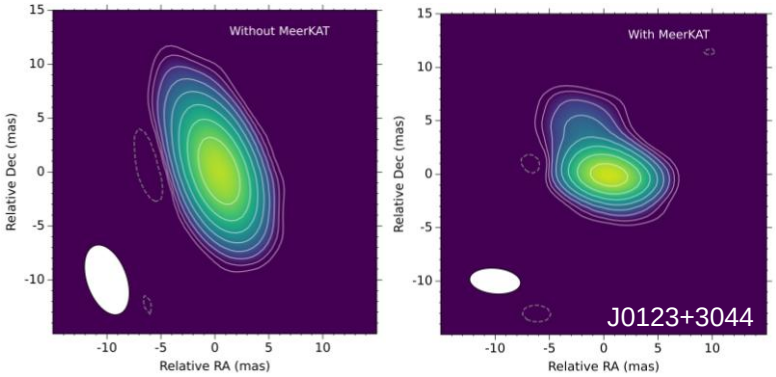


EM181A (preliminary):

- Traditional CLEAN, experimenting with weighting.
- Resolution with MeerKAT: 3x2 mas at 1.6 GHz
- Start resolving lobe hotspots where HI absorption previously observed.

Including MeerKAT increases EVN resolving power:

- Adds significant sensitivity in N-S baselines
- Accurate calibration on long baselines due to short MeerKAT – Hartebeesthoek spacing.



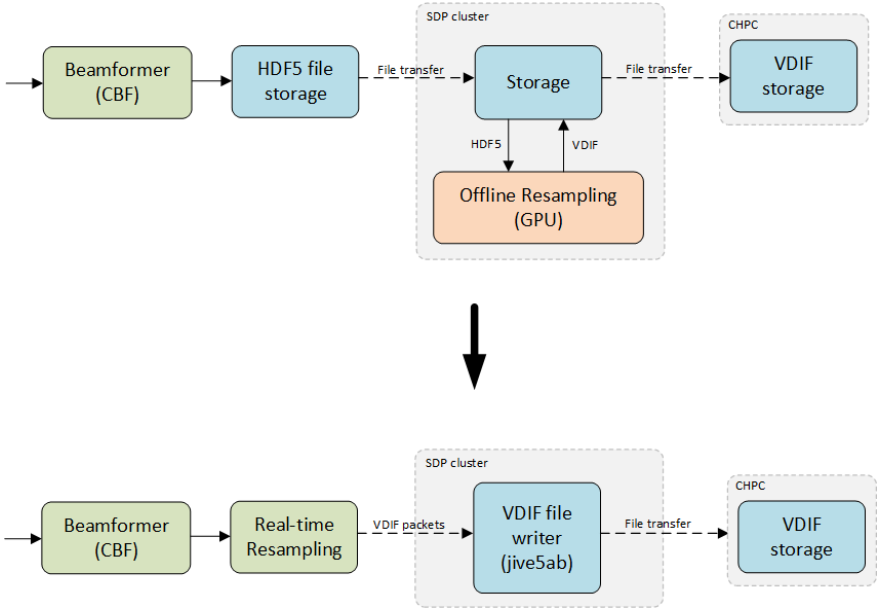
VLBI mode update

Limitations of current VLBI mode:

- Beam data stored and resampled offline.
- Operational limits from finite disk space (24 hours worth); takes time to finalise processing.
- No new development on SKARAB-based correlator:
  - Only supports L-band, 2 x 32 MHz.

New VLBI mode for next-gen GPU correlator:

- Real-time resampling to VDIF packets in correlator; written to file using `jive5ab` on SDP cluster.
- Design goals: 2 x 64 MHz channels, observe for multiple station IDs concurrently in distinct subarrays.
- Commissioning early 2027.
- Possible future expansions, TBC:
  - 4 x steerable beams.
  - New bands: S-band and/or Band 5b.



Summary

- MeerKAT has an operational VLBI mode
- Joined EVN as VLBI station
  - See October 2026 call for proposals!
  - Can request access to visibilities.
- Early science results are promising
- Updated VLBI mode coming early 2027:
  - Addresses existing shortcomings.
  - Platform for further expansion: multiple beams; other bands.

Special thanks to JIVE for great support!

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THANK YOU

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