Hydrogen Intensity and Real-time Analysis eXperiment - Overview, Status and Construction Updates

Hangzhou 21 cm Cosmology Workshop - 22.07.24

Devin Crichton - ETH Zürich

HIRAX Overview

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- Hydrogen Intensity and Real-time Analysis eXperiment
- Radio inteferometer with a compact, redundant layout
- Funded up to 256 dish deployment.
    - Plans to extend to 1024.
- 6m diameter monolithic dishes instrumented to operate between 400 – 800 MHz
    - Post-reionisation 21cm IM from z = 0.8 – 2.5
- To be co-located with the SKA-MID, MeerKAT, HERA at the SARAO Karoo site.
- Repointed driftscan survey of ~⅓ of the sky over 4 years
- Primary Science Goals:
    - Observationally probe the evolution of dark energy through intensity mapping
    - Survey the transient radio sky

Overview of HIRAX-256: Crichton et al. https://arxiv.org/abs/2109.13755

HIRAX Site

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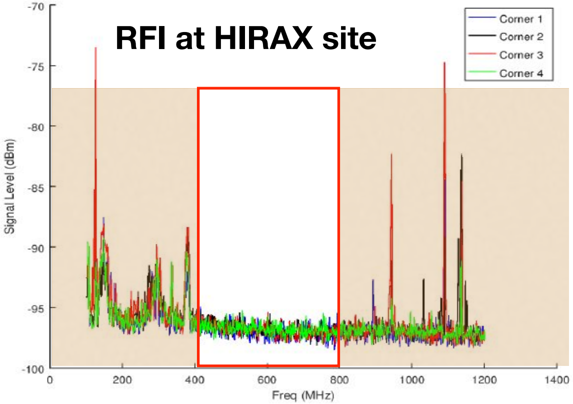
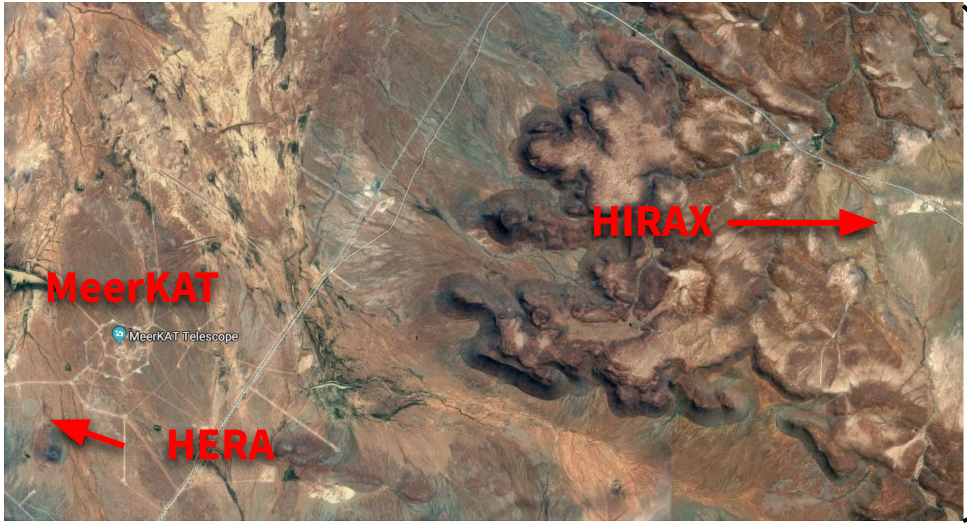
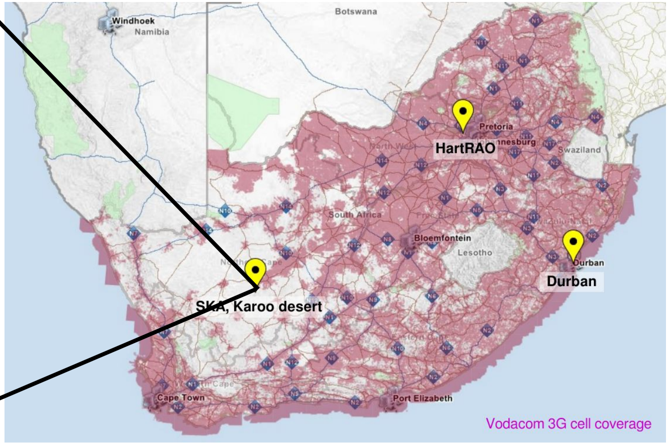
- Guest instrument on SARAO managed Karoo site
- Low RFI site - protected by government regulations
- Close to road for access, power and external network connection and SARAO infrastructure







HIRAX Science Goals

HI Intensity Mapping Tomography

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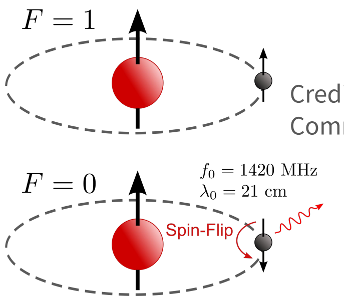
- Hyperfine Hydrogen transition line at 1420.4 MHz
- Efficiently and tomographically map cosmological volumes
  - Generally low angular resolution but redshift information cheap
  - Probe epoch of reionisation at low frequencies and large scale structure at high frequencies.



Credit: Wikimedia Commons

- Post-reionisation IM
  - ν > 200-300 MHz
  - Biased tracer of large scale structure
  - Large volumes achievable
  - Comparable to low angular resolution spectroscopic survey

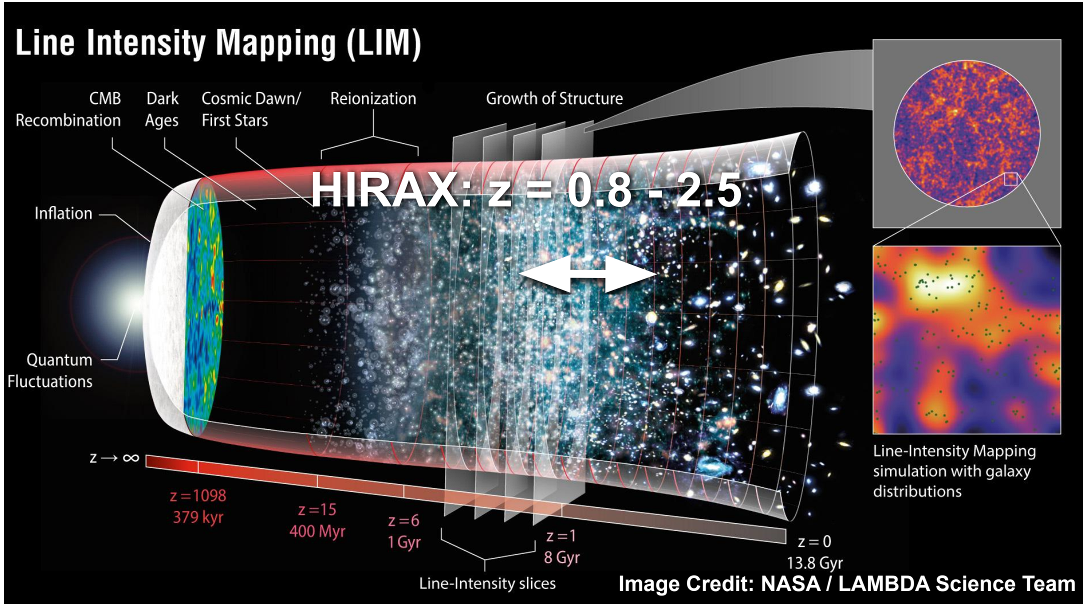


Image Credit: NASA / LAMBDA Science Team

HIRAX BAO Cosmology

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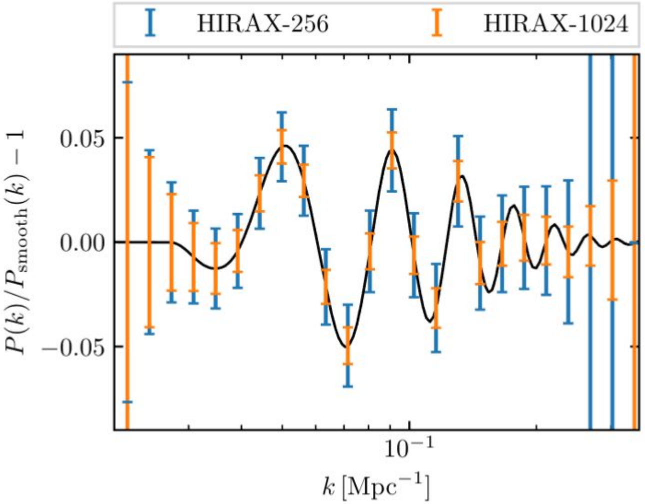
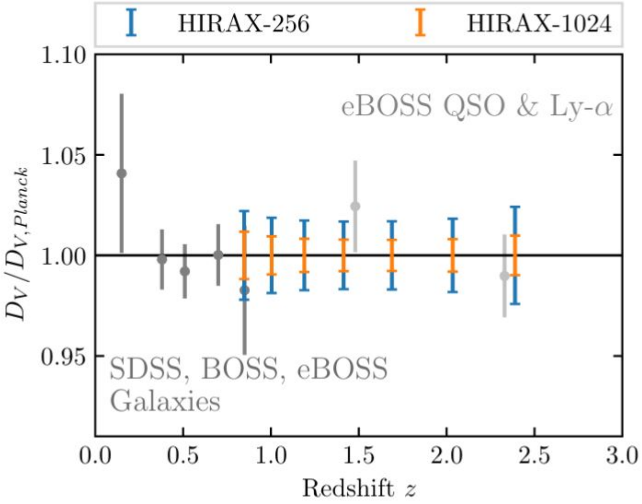
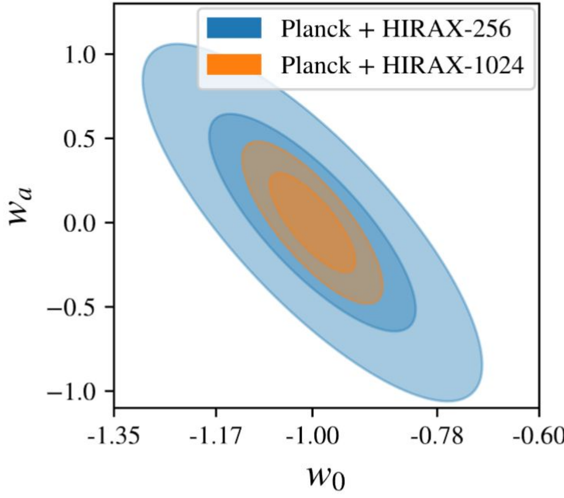
Parameter	Value
Number of dishes	256
Dish diameter	6 m
Dish focal ratio	~~0.23~~ **0.21**
Collecting area	7200 m^2
Frequency range	400–800 MHz
Frequency resolution	1024 channels, 390 kHz
Field of view	5°–10°
Resolution	0.2°–0.4°
Target system temperature	50 K

- BAO scales targeted with HIRAX array layout and frequency range - standard rules for geom. constraints
- Forecasted high significance P(k) measurement
- (More detailed simulation based, forecasting analysis in preparation - **Viraj Nistane**)







Transient and Additional Science Goals

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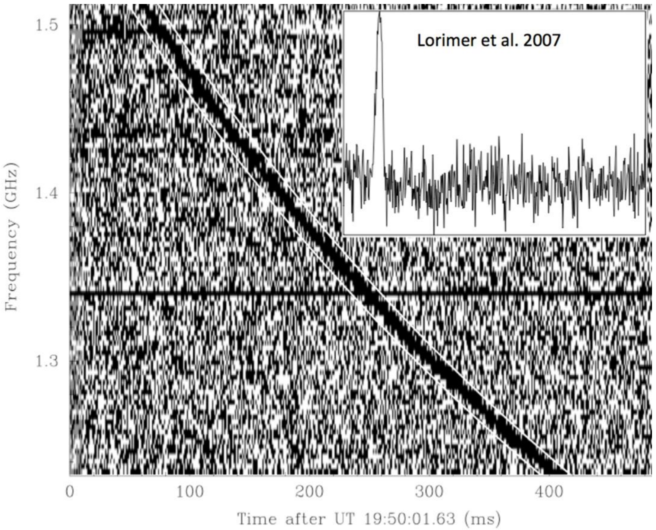
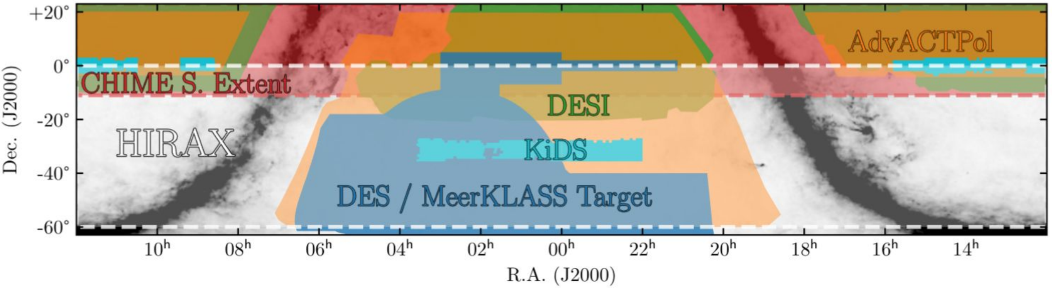


Real-time analysis of beamformed data

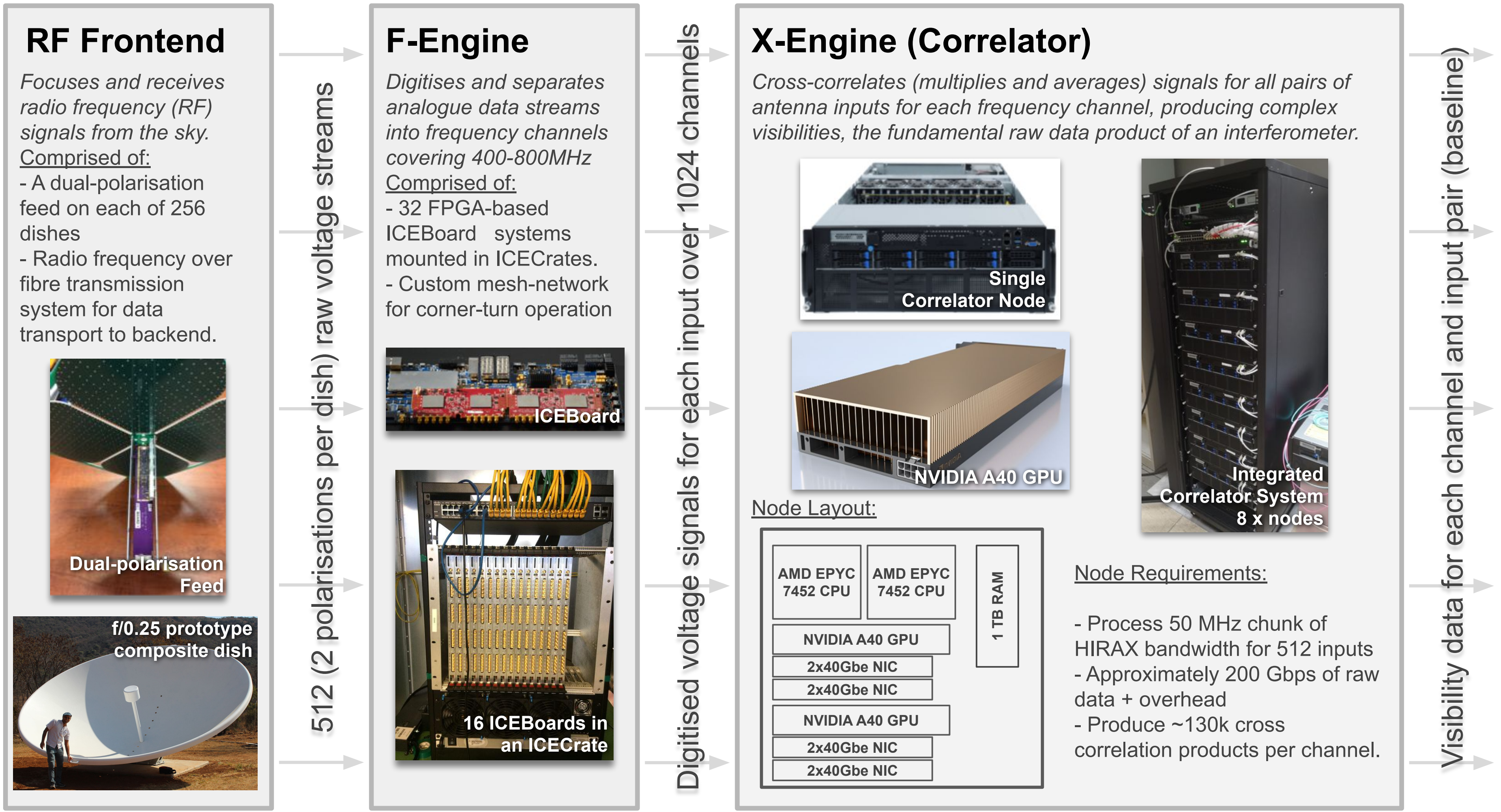
- **Fast Radio Burst Search**
  - Fast dedispersion algorithms over range of dispersion measures
  - Localisation with outriggers (e.g. BIUST Botswana)
- **Pulsar timing and search**
  - Timing and pulse profiles of known pulsars with coherent dedispersion
  - Incoherent search with high frequency and time sampling
- **HI Absorbers**
  - Blind and targeted absorption line search by long time integration on highly upchanneled beams



Cross-correlations with overlapping surveys

- DES, Rubin LSST, HSC, KiDS, DESI
- Euclid, Roman
- Ground based CMB (Lensing), ACT, SPT.

HIRAX Hardware Overview


RF Frontend
Focuses and receives radio frequency (RF) signals from the sky.
Comprised of:
- A dual-polarisation feed on each of 256 dishes
- Radio frequency over fibre transmission system for data transport to backend.
Dual-polarisation Feed
f/0.25 prototype composite dish
512 (2 polarisations per dish) raw voltage streams
F-Engine
Digitises and separates analogue data streams into frequency channels covering 400-800MHz
Comprised of:
- 32 FPGA-based ICEBoard systems mounted in ICECrates.
- Custom mesh-network for corner-turn operation
ICEBoard
16 ICEBoards in an ICECrate
Digitised voltage signals for each input over 1024 channels
X-Engine (Correlator)
Cross-correlates (multiplies and averages) signals for all pairs of antenna inputs for each frequency channel, producing complex visibilities, the fundamental raw data product of an interferometer.
Single Correlator Node
NVIDIA A40 GPU
Integrated Correlator System 8 x nodes
Node Layout:
AMD EPYC 7452 CPU
AMD EPYC 7452 CPU
1 TB RAM
NVIDIA A40 GPU
2x40Gbe NIC
2x40Gbe NIC
NVIDIA A40 GPU
2x40Gbe NIC
2x40Gbe NIC
Node Requirements:
- Process 50 MHz chunk of HIRAX bandwidth for 512 inputs
- Approximately 200 Gbps of raw data + overhead
- Produce ~130k cross correlation products per channel.
Visibility data for each channel and input pair (baseline)

HIRAX-256 Correlator

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HIRAX-256 correlator built and being tested at ETHZ/CE

- RFI measurements at CERN RF chamber.
  - Verified with SARAO
- Performance testing with `kotekan`

Approximate Performance (For 200Gbps/node, 1k chan)

HIRAX-256:

~54 TeraOp/s/node (N=512, 50 MHz, **U=13%**)

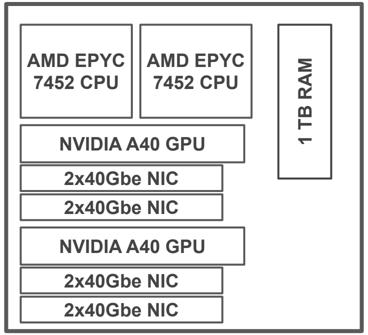
HIRAX-1024:

~211 TeraOp/s/node (N=2048, 12.5 MHz, **U=29%**)

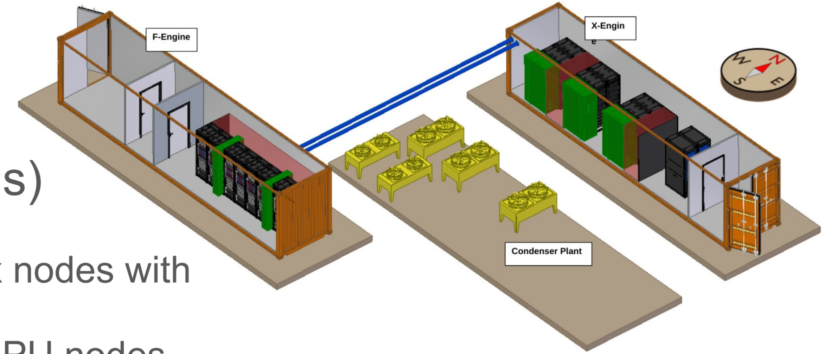
Lots of headroom for beamforming and other real-time analysis. Utilization likely to decrease.

Upcoming `kotekan` & HIRAX-256 correlator papers

Thierry Viant, Andre Renard, Keith Vanderlinde and others



Heterogenous Data Processing Backend



- On-site for real-time analysis and compression
- Beam-forming backends (nominal specifications)
  - **FRB**: O(100s) Beams @ 32k channels, 1ms sampling
    - GPU based incoherent dedispersion search, 5 x nodes with Nvidia A40s, 1TB RAM
  - **Pulsar Search/Timing**: ~6 full baseband beams 3 x GPU nodes
    - Coherent dedispersion for timing
    - Incoherent dedispersion at 1us, up to 16k channels for search
  - **Blind HI Abs. Search**: ~ FRB Beams @ 128k channels, accumulating ~30s.
- On-site analysis machines
  - On-site cosmology reduction/analysis / intake / storage
    - On-site calibration/visibility stacking for cosmological analysis
    - Daily pipeline tasks, data quality metric, housekeeping TOD-DBs

Thierry Viant, Andre Renard and others

Fiberglass Composite Deep Dishes

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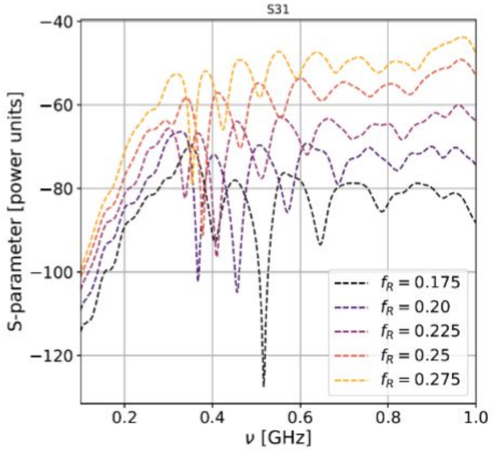
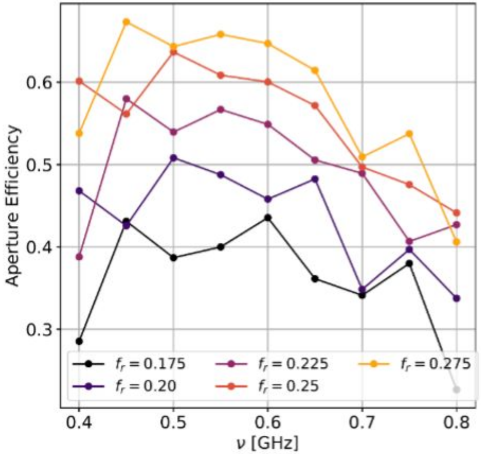
Dish design prioritising low cross-coupling

- Deep, f/0.21 dishes currently under construction: NRC design, AFF manufacture
- Low focal ratio reduces coupling effects as cost of aperture efficiency
- Monolithic design for main array
- Split design for outrigger





Analysis: Aaron Ewall-Wice


f/0.25 prototype dish in HartRAO


f/0.21 split outrigger dishes at AFF


f/0.21 plug for monolithic dishes at Carnarvon

Calibration and Characterisation Challenges

HIRAX Calibration Challenges

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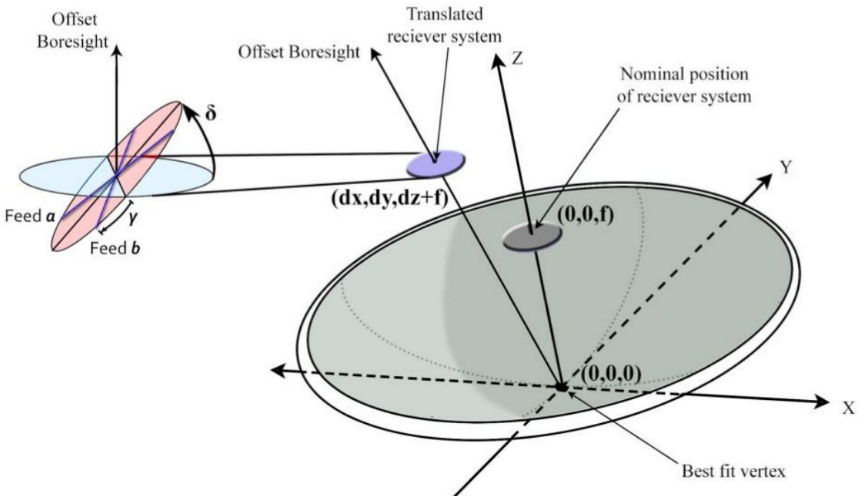
- Dishes fixed per elevation pointing
  - *Calibration options limited, pointing etc. needs external verification/measurement*
    - Informed by simulations and measurements
- Redundant interferometer
  - Calibration and on-site data compression relies on internal consistency
  - *HW Requirements on precision over accuracy*
- **Consistency needs to be verified across array**



Telescope mechanical parameter	Target precision (RMS)
Receiver position relative to focus	0.5 mm
Receiver orientation relative to boresight vector	2.5′ polar and azimuthal
Dish surface deviations	1 mm
Dish vertex position relative to elevation axis	1 mm
Orthogonality of boresight vector and elevation axis	1′
Elevation axis position within the array	0.5 mm in array plane 1 mm out of array plane
Elevation axis alignment within the array	1′
Elevation pointing angle	1′

~ λ/100 - λ/50

Telescope Mechanical Assembly Requirements

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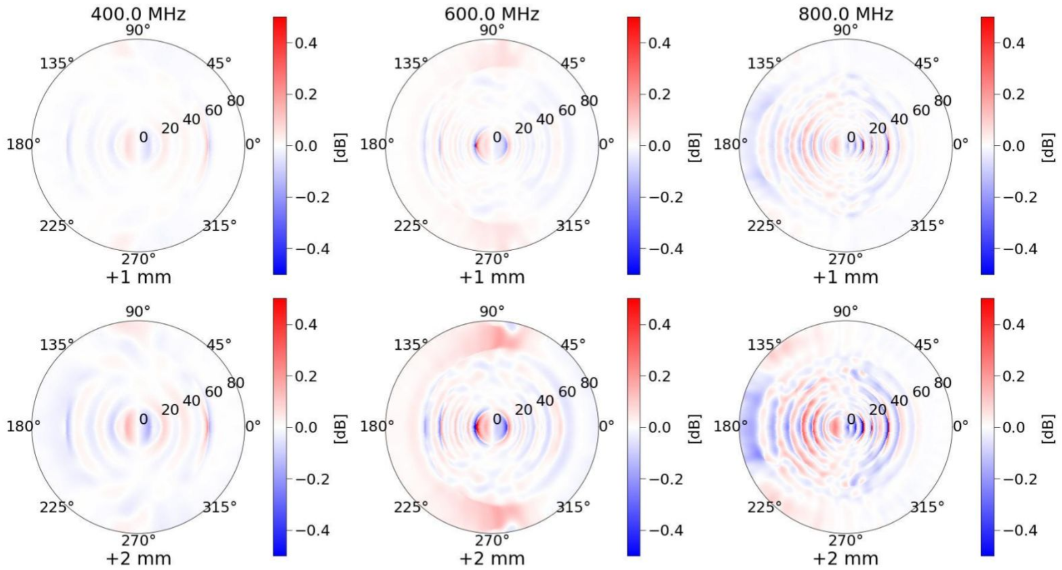


Requirements set with simulations

- λ/100 - λ/50 (< 1 mm)
  - Favour precision over accuracy
- Verified with metrology
  - Laser Tracker and Photogrammetry
  - During manufacture and operation

- Shifts beam centroid/effective pointing
  - Large systematic effect for physical tolerances
- Distribution of mis-pointing across the array is a large systematic concern

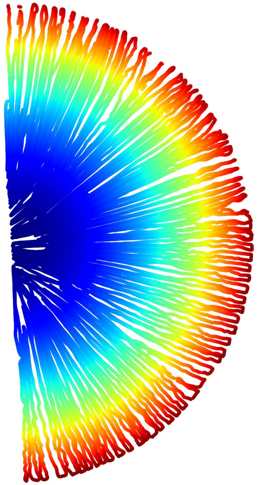
Beam Simulations: Kit Gerodias

Validation with On-site Metrology

- Laser Tracker
  - High point density and precise
  - Suitable for factory measurements of plug, moulds, jigs and reflectors
  - Requirements verification before deployment
- Photogrammetry
  - Once targets set, allows for multiple re-analyses of reflector surface
  - Field-ready for on-site measurements
  - Monitor dish shape over time, through repointings of the array
- Inform systematics analysis for early array:

Measurements and beam simulations → Array-level systematics → Power spectrum systematics

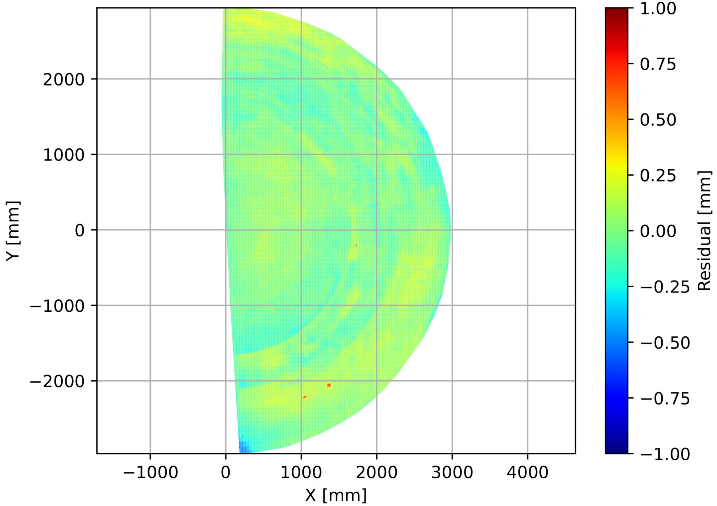
ETHZ: Jennifer Studer and Thierry Viant



Initial HIRAX Plug Surface Analysis

- Measurement directly after production

RMS residual **0.080 mm**
Fit **focal length** is **1259.8 mm**



Current Status and Construction

HIRAX-256 Status and Timeline

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- Many components e.g. correlator and SDP in final stages of testing
- Dish factory established in Carnarvon, site development plan in late stages
- Significant activity in developing dish construction tooling with Advanced Fiber Form, early 2023 to present:
    - First plug at Carnarvon, well characterised and refined after shipping
    - Process for pulling moulds being refined, temperature control challenging
- First non-monolithic reflectors for outriggers under QA
    - Further along than monolithic due to less strict requirements
- Commissioning two-element test array at adjacent at Klerefontein
    - Site in late stages, non-monolithic dishes to be deployed soon enabling full system test
- Once mould pulling process finalised dish production in full swing Q2-Q4 2024.

Recent Construction Updates ca. June 2024

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Two element Klerefontein prototype site,

- Late stages of site development
- Awaiting dishes
- Platform for drone beam analysis and other system characterisation steps

Recent Construction Updates ca. June 2024

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- Integrated split design outrigger dishes constructed and under QA
- Work on feed support and mount in late stages of testing and characterisation

Recent Construction Updates ca. June 2024

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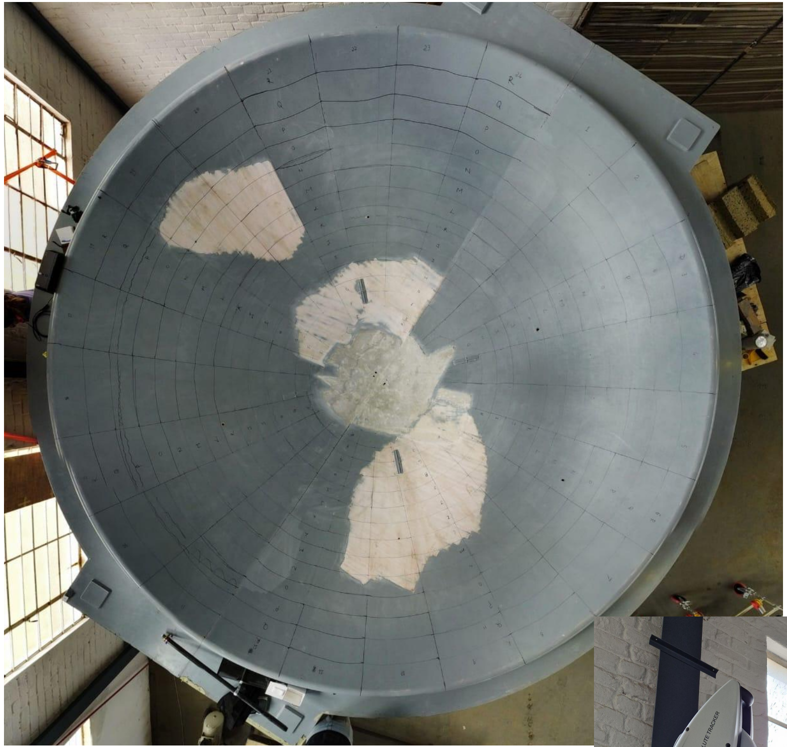
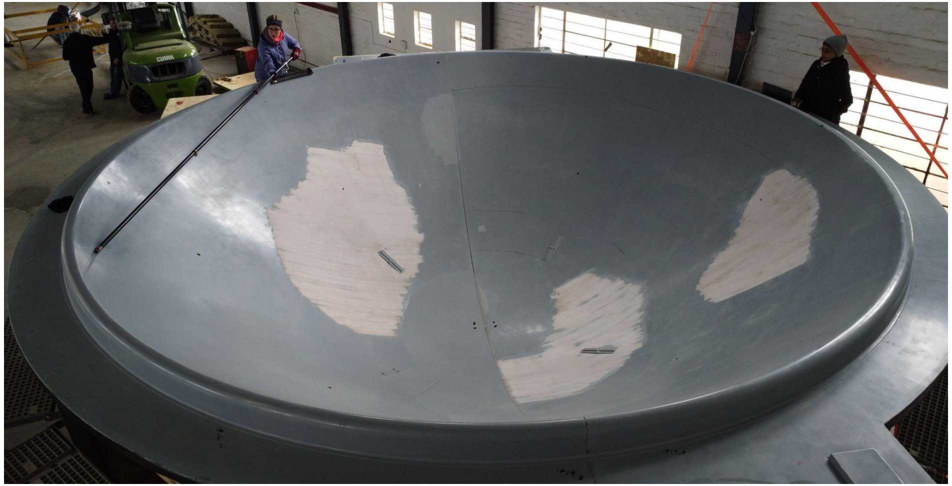


Plug for forming monolithic dish moulds in Carnarvon, refined and re-characterised after shipping

- Measurement and iteratively refined with laser tracker metrology
- Process for pulling moulds from the plug currently under refinement



Measurements:
Jennifer Studer, Tasmiya Papiah and Keshav Bechoo

Conclusions

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- 21cm intensity mapping provides access to large cosmological volumes over mostly linear scales - can be targeted with dedicated, compact interferometers.
- HIRAX has the statistical power for a compelling cosmological survey - BAO focused
- Platform for real-time analysis with significant on-site compute
- Overcoming systematics/foregrounds challenge is difficult and requires a controlled and well-characterised instrument model.
- Static dishes cannot be easily calibrated directly, requires reconstruction and verification with system measurements.
- Many subsystems close to completion. Dishes with final design to be constructed very soon and early science data expected with array build out to follow.
- Will learn a lot for early data! Klerefontein site in late stages of deployment.

Thanks!