The Hydrogen Intensity and Real-time Analysis eXperiment

Overview and Status

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SKACH Summer Meeting

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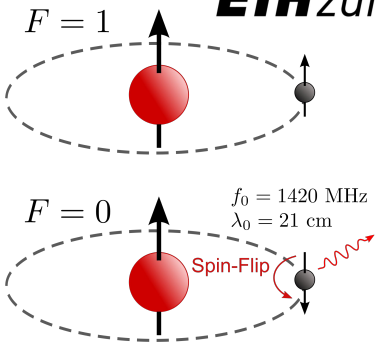
HIRAX Overview

ETH zürich

- **H**ydrogen **I**ntensity and **R**eal-time **A**nalysis e**X**periment
- Radio inteferometer with a compact, redundant layout
- Funded up to 256 element deployment.
- 6m diameter dishes instrumented to operate between 400–800 MHz. Plans to extend to 1024.
- To be co-located with the SKA in the Karoo (Low RFI, Southern Surveys)
- Will survey ~⅓ of the sky over 4 years
- Primary Goals:
  - Observationally probe the evolution of dark energy
  - Survey the transient radio sky

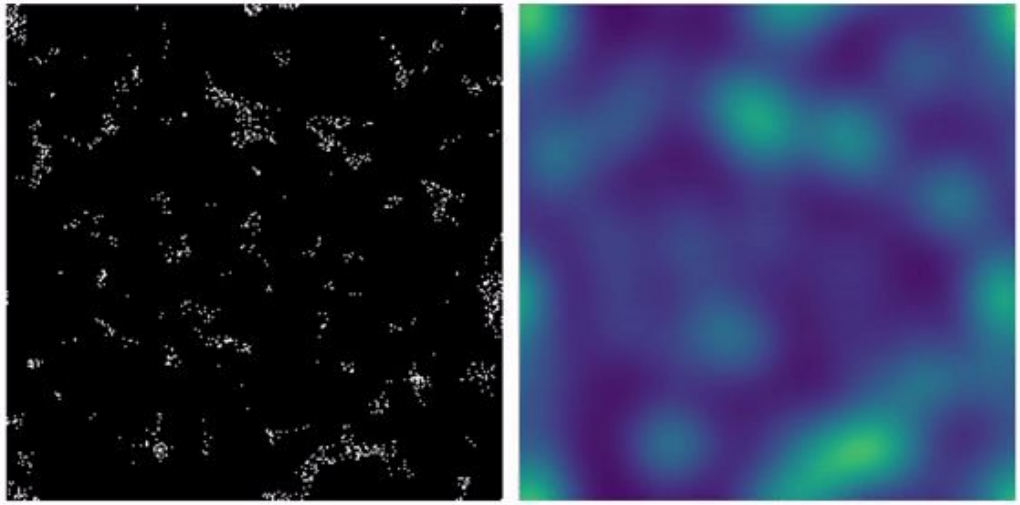
Recent overview of HIRAX-256
Crichton et al.
https://arxiv.org/abs/2109.13755

HI Intensity Mapping



Credit: Wikimedia Commons

- 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.
- Post-reionisation IM
  - ν > 200-300MHz
  - Biased tracer of large scale structure
  - Cosmological constraints from HI power spectrum
  - Large volumes achievable



HI Power Spectrum

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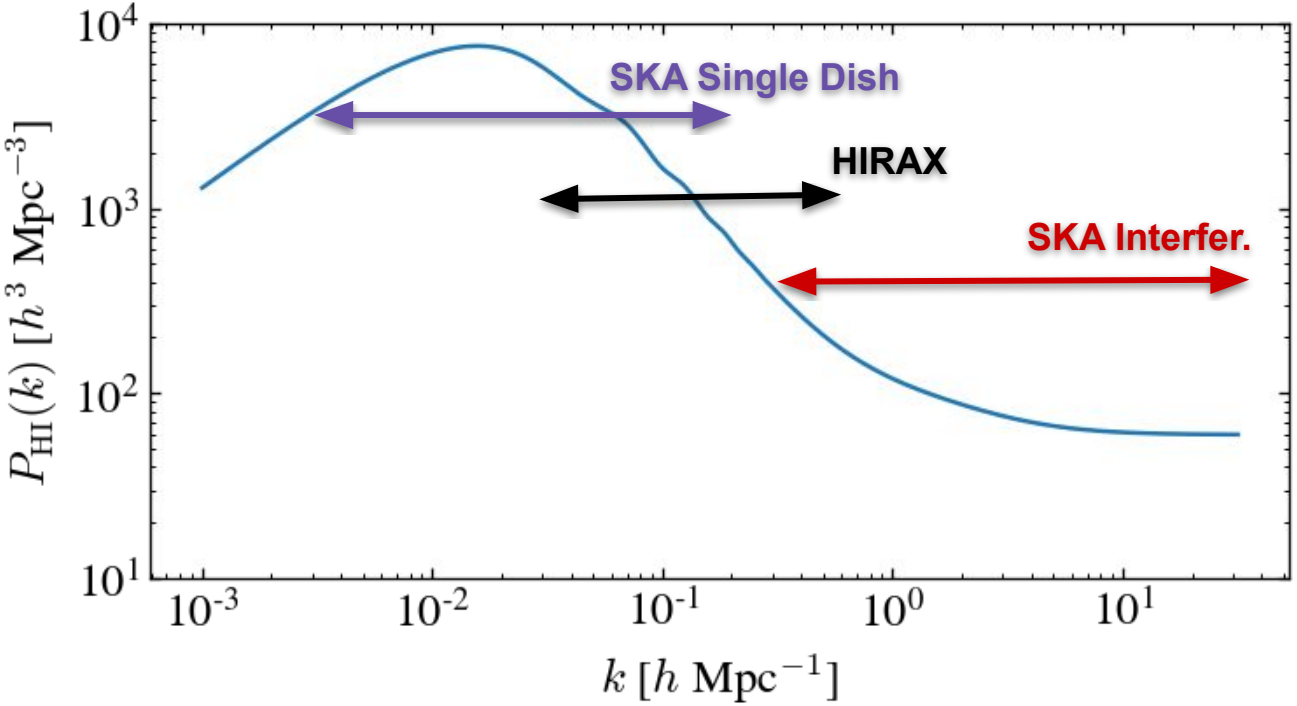

- Primordial non-gaussianity
- Modified gravity theories

- Growth of structure
- Geometric Constraints
- Expansion rate
- Dark energy

- Non-linear dynamics
- HI content of galaxies

Science Goals - BAO Cosmology

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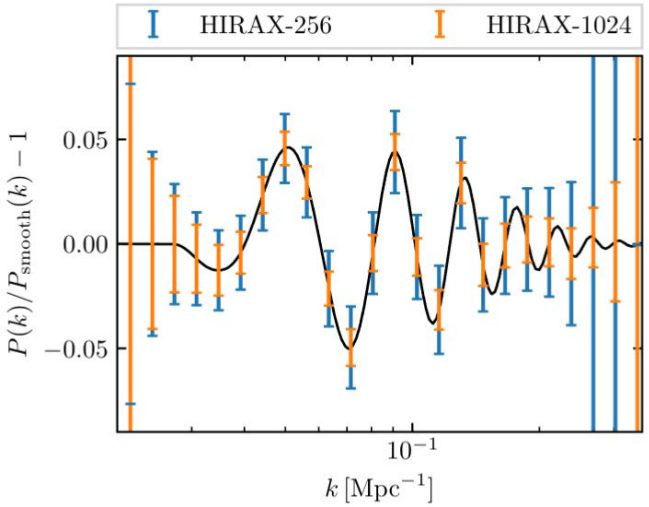
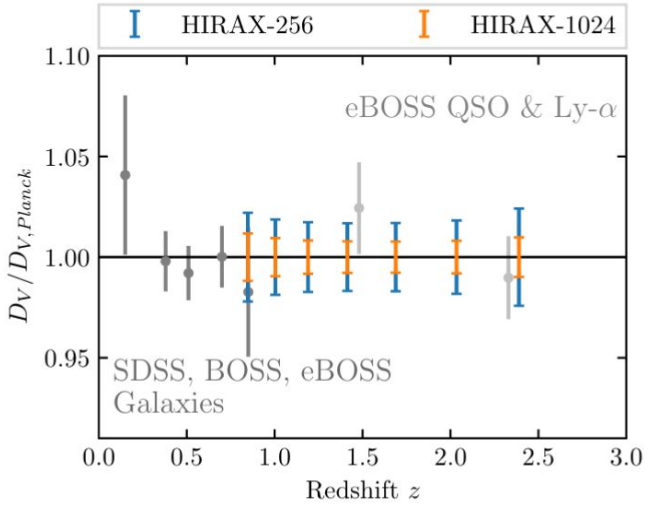
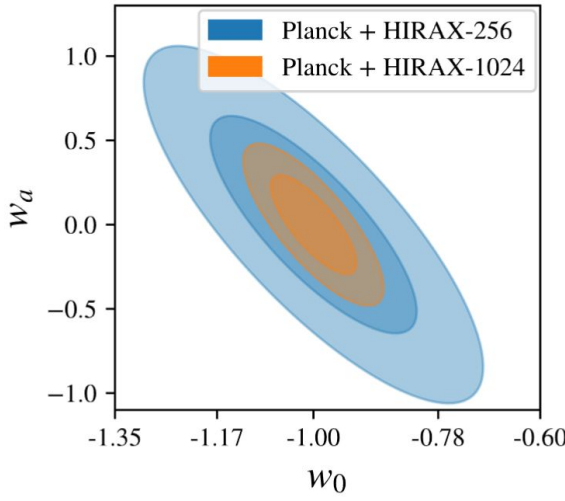
Parameter	Value
Number of dishes	256
Dish diameter	6 m
Dish focal ratio	0.23
Collecting area	7200 m^2
Frequency range	400–800 MHz
Frequency resolution	1024 channels, 390 kHz
Field of view	5°–10°
Resolution	0.2°–0.4°
Target system temperature	50 K

- Survey has statistical power to significantly constrain parameters, even at 256 element stage .
- Requires careful control of systematics
- More detailed, beyond Fisher, forecasting analysis in preparation (Viraj Nistane)







Transient and Other Science Goals

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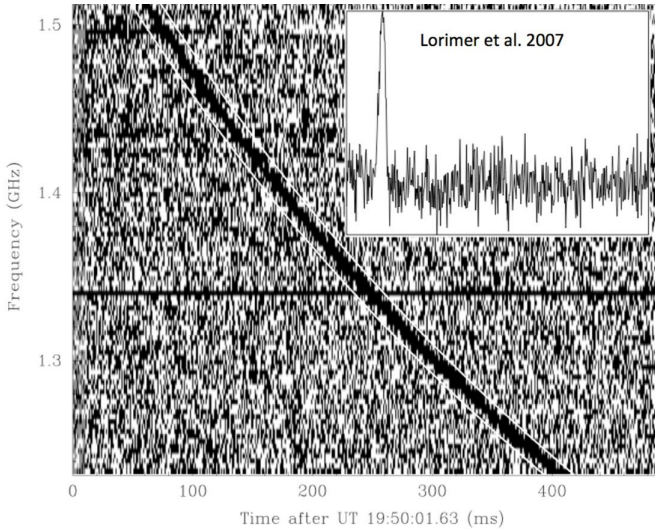
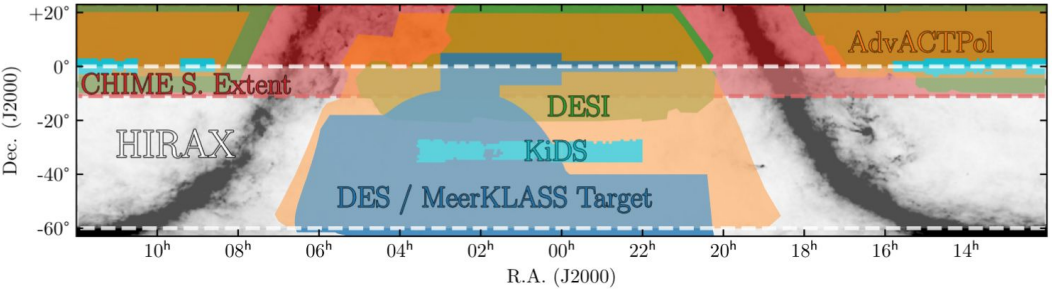


Real-time analysis of beamformed data

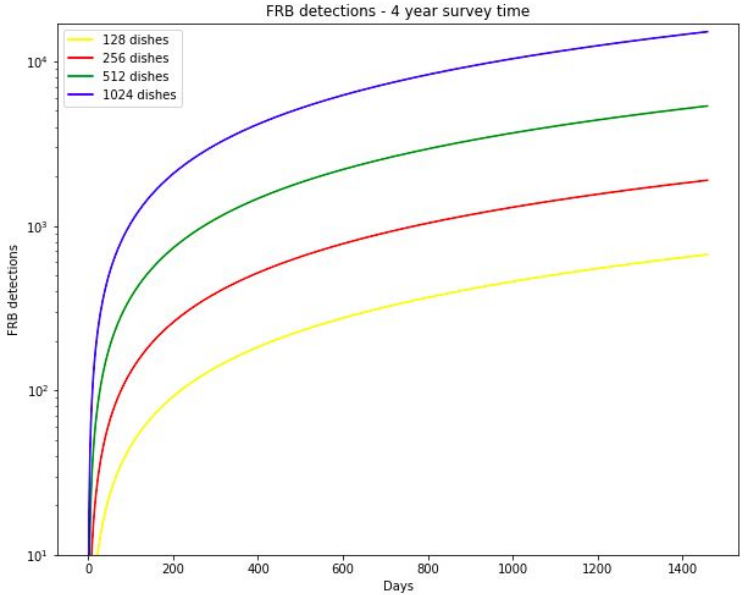
- Fast Radio Burst Search
  - Fast dedispersion algorithms over range of dispersion measures
- Pulsar timing and search
  - Timing and pulse profiles of known pulsars with coherent dedispersion
  - Incoherent search with high frequency and time sampling
- HI Absorbers
  - Blind and targeted absorption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

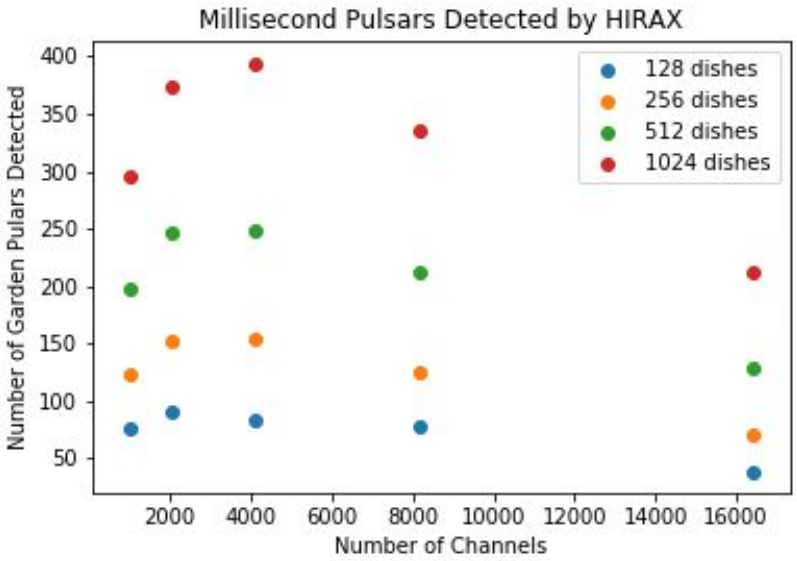


Cross-correlations with overlapping surveys

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

Forecasts: Transient Searches





At all scales, HIRAX will provide a sophisticated platform for pulsar and FRB searches, greatly adding to southern sky detection rates.

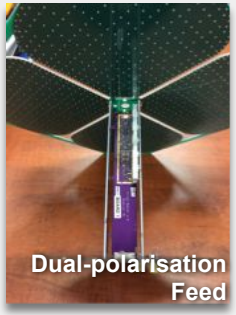
- Detection rates scale approximately with collecting area, and therefore number of dishes
- At 256 elements, HIRAX will have a similar collecting area to CHIME

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.



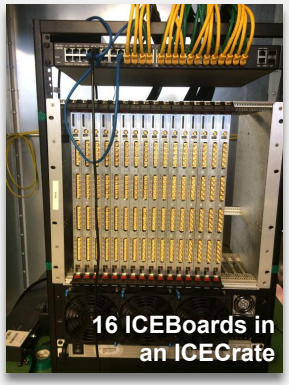
512 (2 polarisations per dish) raw voltage streams

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

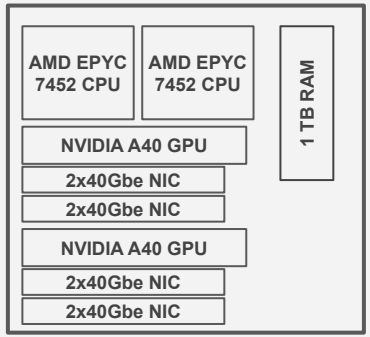


Digitised voltage signals for each input over 1024 channels

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.

Node Layout:



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 (FLARE-1)

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HIRAX-256 correlator built and being tested at ETHZ

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

Correlation Performance (For 200 Gbps/node)

HIRAX-256:

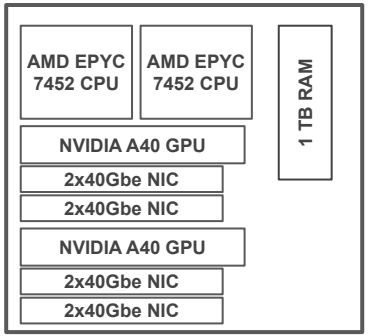
~54 TeraOp/s/node (N=512, 50 MHz, **U=13%**)

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 as implementation matures.

Upcoming `kotekan`, HIRAX-256 correlator papers



Thierry Viant, Andre Renard, Keith Vanderlinde and others

SDP Hardware (FLARE-2)

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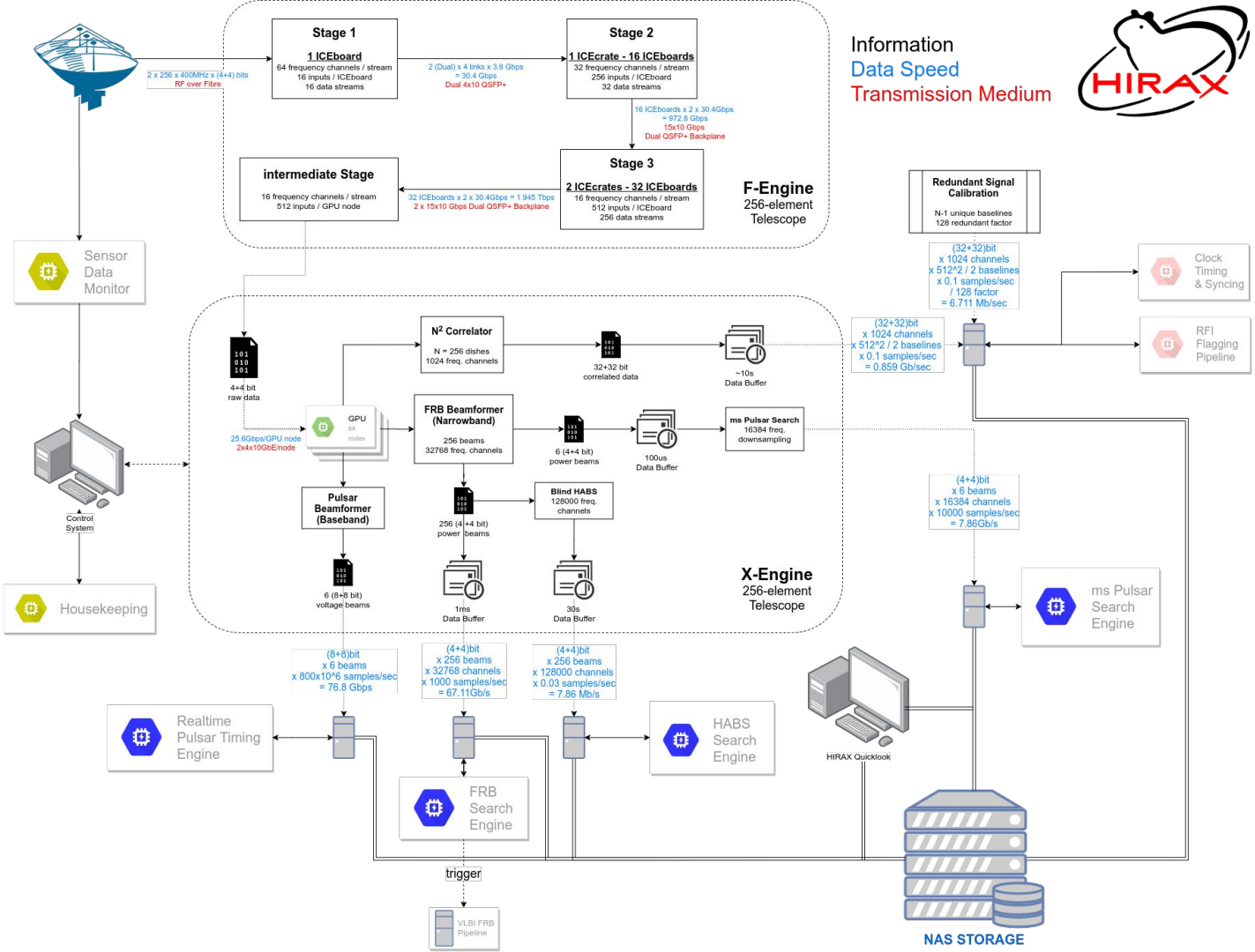
- Onsite compute/storage for FRB, Pulsar, HI Abs. and cosmology intake backends for HIRAX-256

- Beam-forming backends (nominal specifications)
  - FRB: ~ 256 Beams @ 32k channels, 1ms sampling
    - GPU based incoherent dedispersion search, 3(+) x nodes with Nvidia A40s, 1TB RAM
  - Pulsar Search/Timing: ~6 full baseband beams 2 x GPU nodes
    - Coherent dedispersion for timing
    - Incoherent dedispersion at 1us, up to 16k channels for search
  - Blind HI Abs. Search: ~ 256 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 TODDBs



Credit: Scott Eyono

SDP System Integration in Progress

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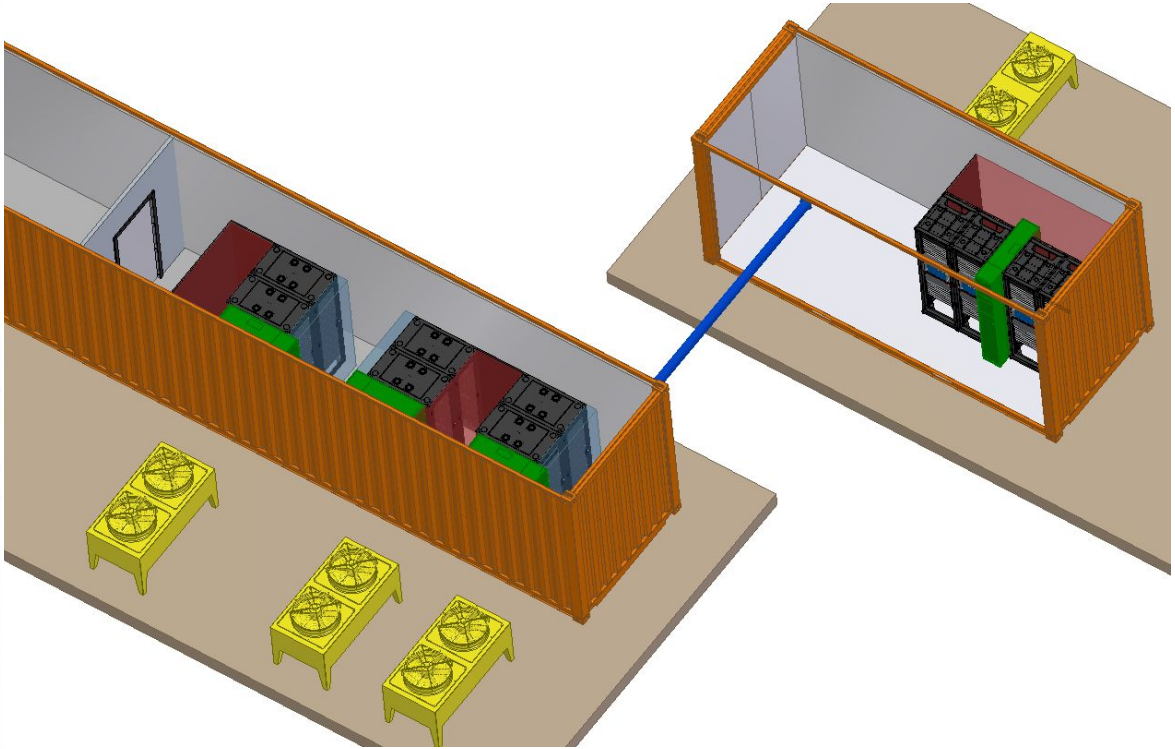
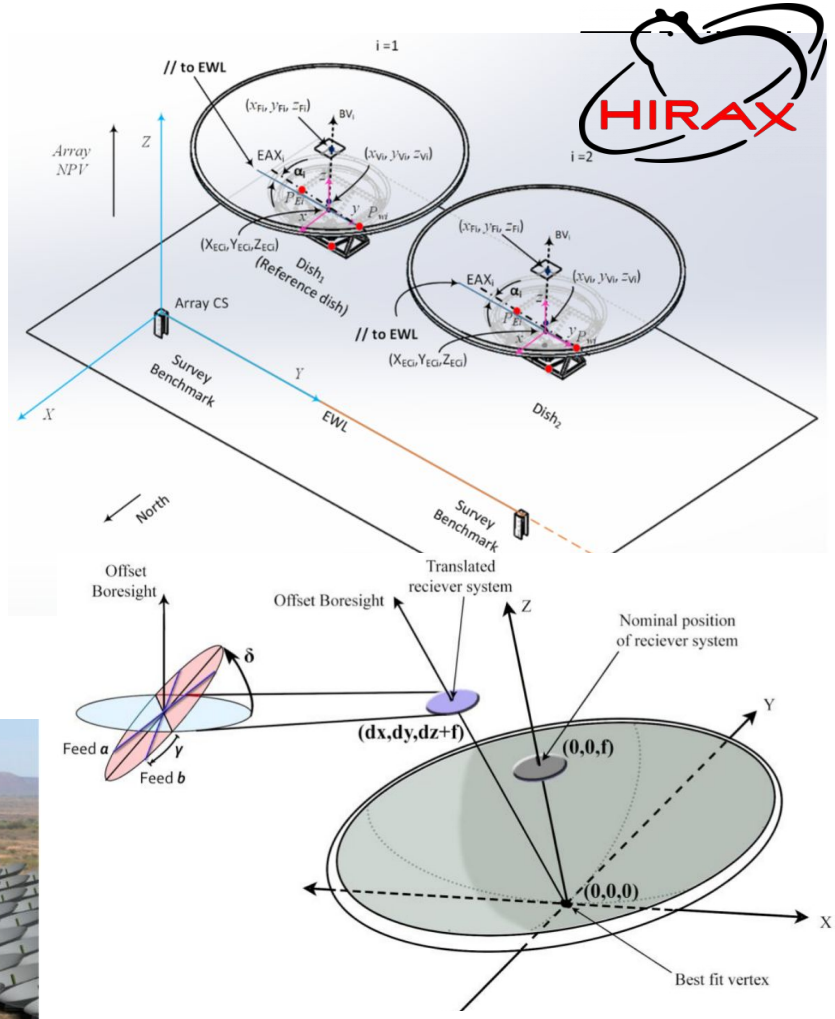
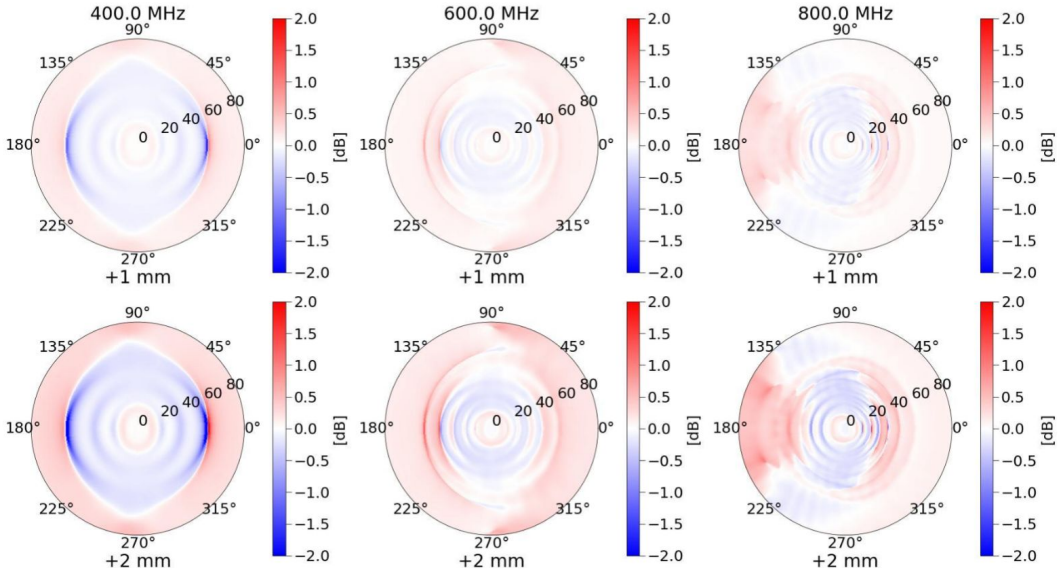


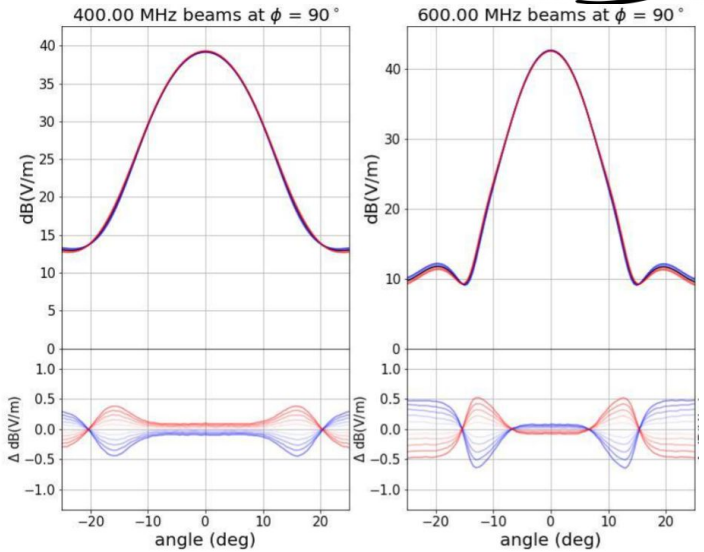
HIRAX Metrology

- Dishes fixed per elevation pointing
  - Calibration options limited, pointing etc. needs external verification/measurement
- 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

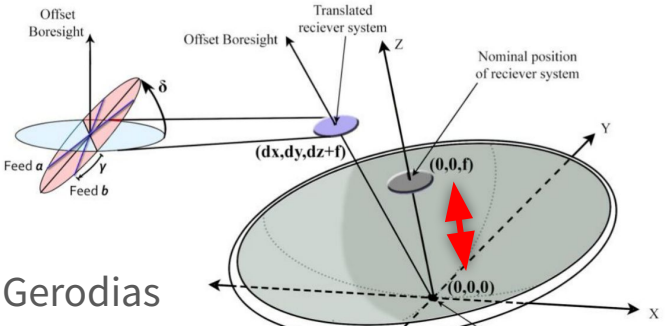


Telescope Mechanical Assembly - Focal Axis



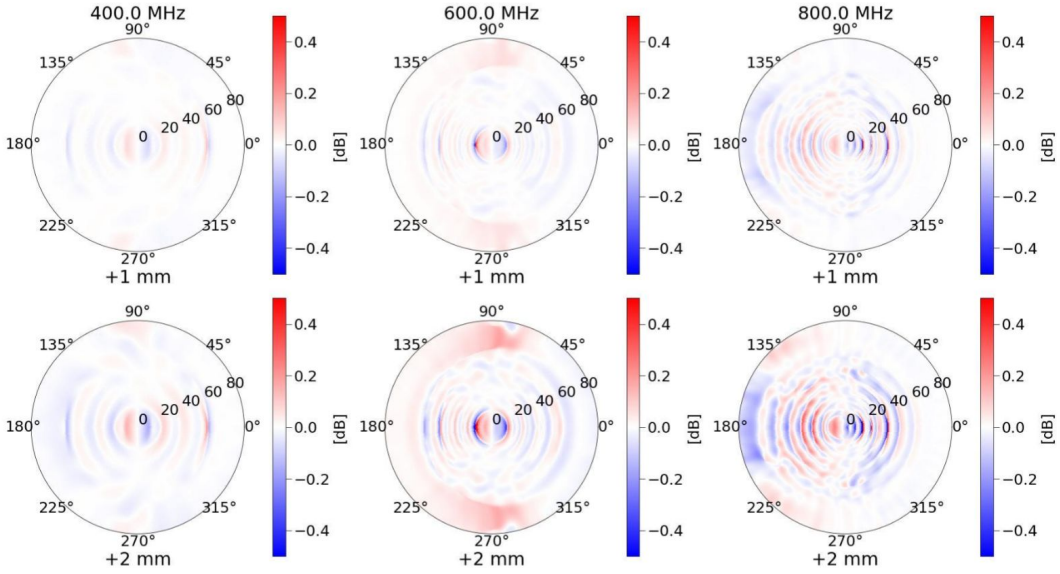


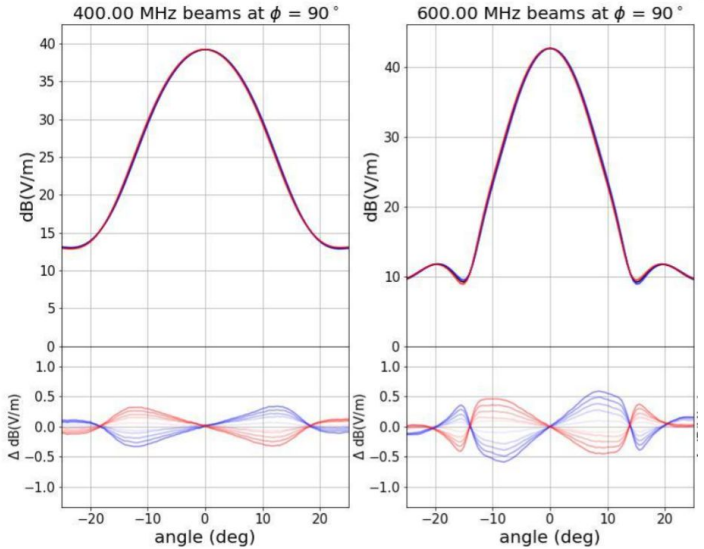
- Primarily effects sidelode structure



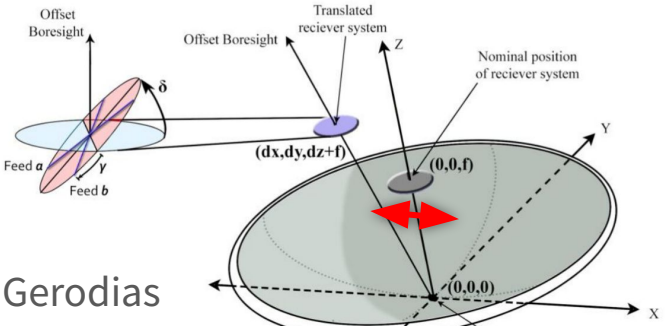
Beam Simulations: Kit Gerodias

Telescope Mechanical Assembly - Focal Plane





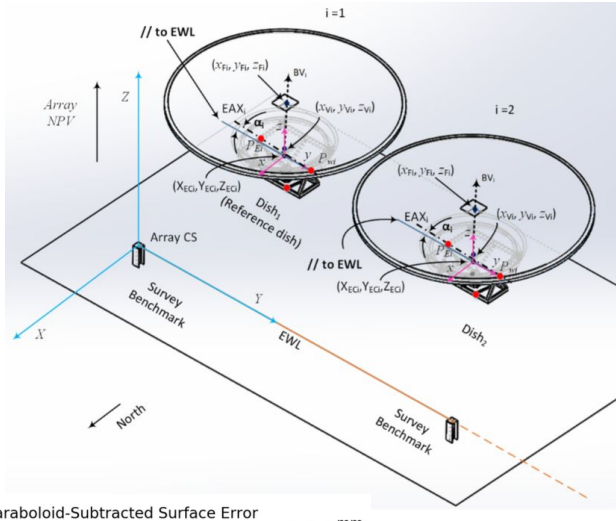
- Shifts beam centroid/effective pointing
  - Large systematic effect for tolerances feasible to design for
- **Distribution of mis-pointing across the array is a large systematic concern**

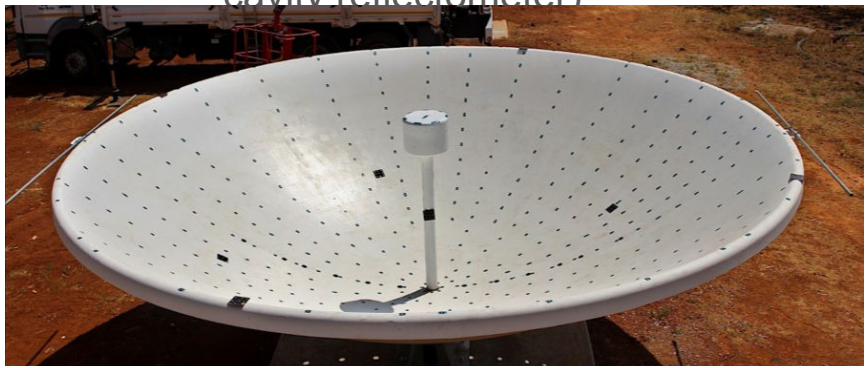


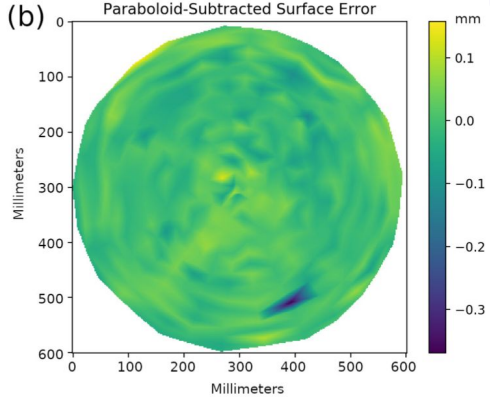
Beam Simulations: Kit Gerodias

On-site Metrology (FLARE-3)

- Laser Tracker
  - Positioning and orientation of elevation axes and nominal pointing vectors across array
  - Verification of positioning of feed mount, and dish fabrication jigs during production
  - High precision over large areas but long setup/measurment time, issues with reflective surfaces
- Photogrammetry
  - Once targets set, allows for quick re-analysis
  - Monitor dish shape over time, through repointings of the array
- (Also field-ready vector network analyzers and cavity reflectometer)







HIRAX-256 Status and Timeline

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- ***Establishment of dish factory in Carnarvon in Feb-May 2023***
- Develop HIRAX Karoo Klerefontein testbed site in June 2023
- Commission 2-element qualification dishes at Klerefontein site in September 2023
- Commission 8-element array at Swartfontein site in Q1 2024
- Commission 128-element array at Swartfontein site in Q2 2024

Thanks