The Hydrogen Intensity and Real-time Analysis eXperiment

Overview and Status

Devin Crichton, ETH Zürich

SKA Days Zürich — 06.09.23

HIRAX Overview

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- **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

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

HIRAX-256 Status and Timeline

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- ***Establishment of dish factory in Carnarvon in Feb-May 2023***
- ***Significant activity in developing dish tooling at Advanced Fiber Form, early 2023 to present***
- Commission 2-element qualification dishes at Klerefontein site in late 2023 - early 2024
- Commission continuing to Swartfontein site in early 2024

HI Intensity Mapping

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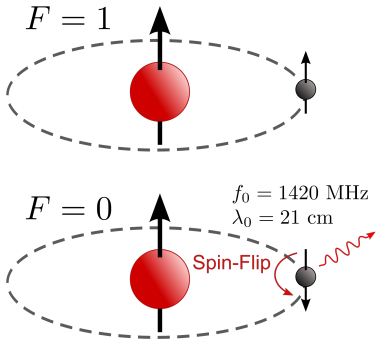
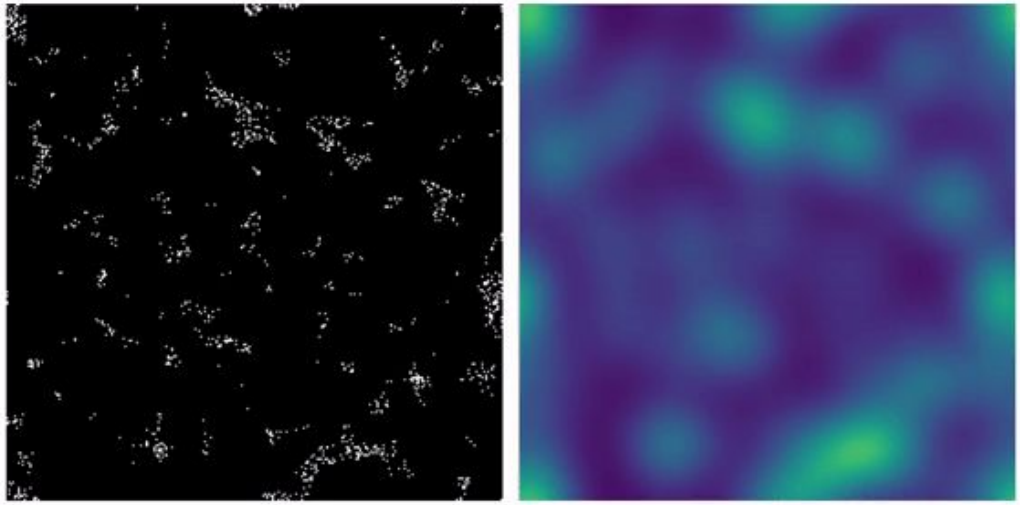


Credit: Wikimedia Commons

- 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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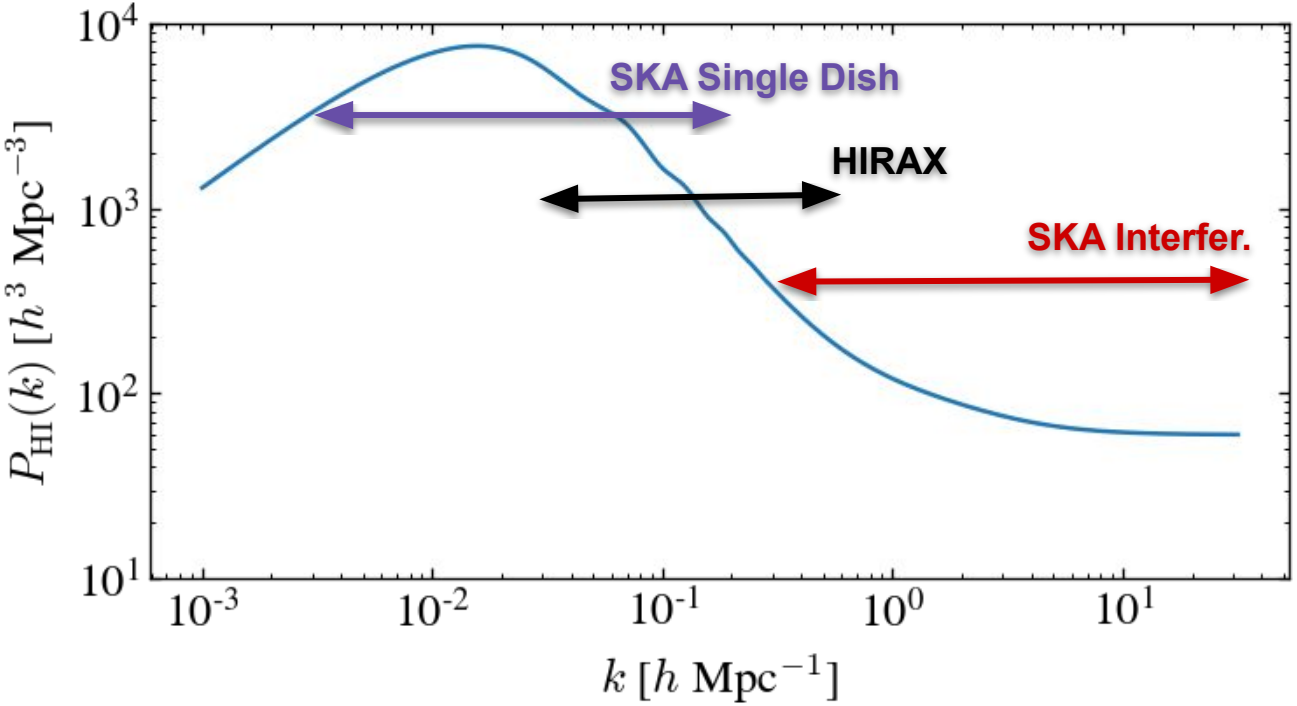

- Primordial non-gaussianity
- Modified gravity theories

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

- Non-linear dynamics
- HI content of galaxies

Science Goals - BAO Cosmology

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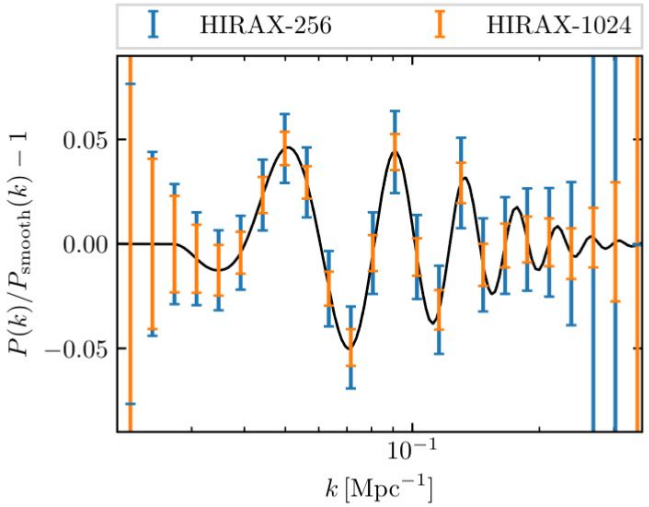
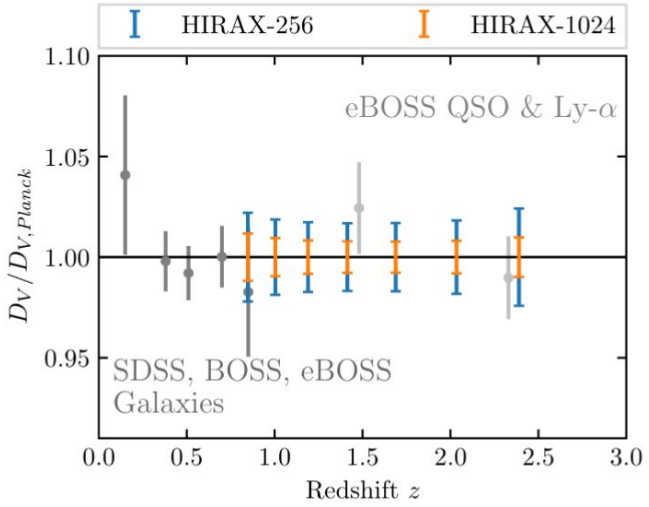
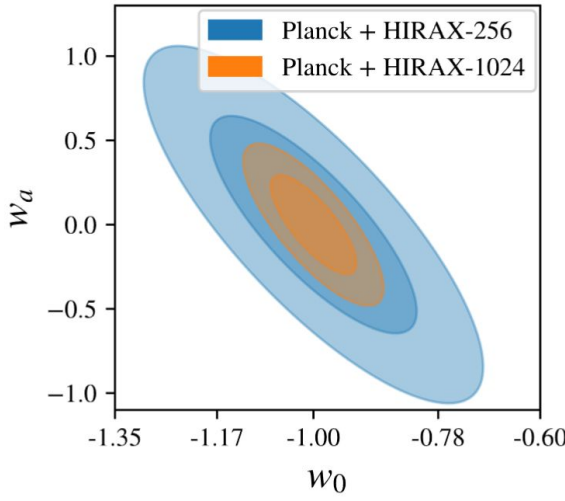
Parameter	Value
Number of dishes	256
Dish diameter	6 m
Dish focal ratio	0.23
Collecting area	7200 m^2
Frequency range	400–800 MHz
Frequency resolution	1024 channels, 390 kHz
Field of view	5°–10°
Resolution	0.2°–0.4°
Target system temperature	50 K

- 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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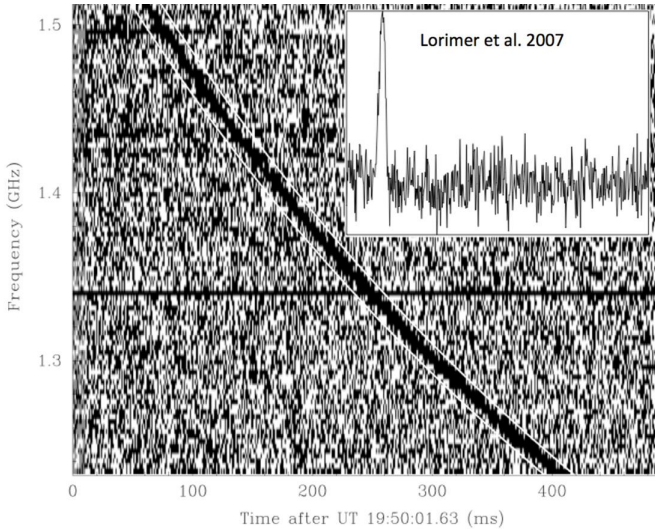
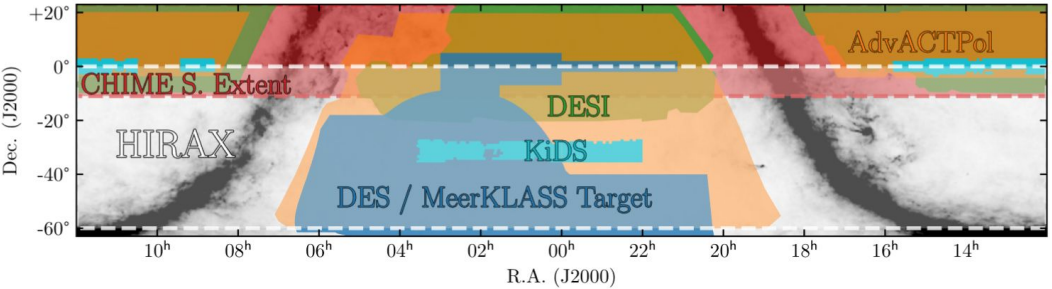


Real-time analysis of beamformed data

- 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

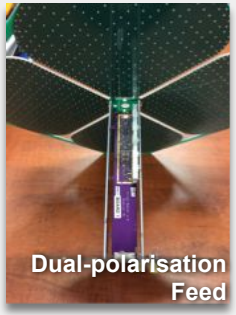
- DES, Rubin LSST, HSC, KiDS, DESI
- Euclid, Roman
- Ground based CMB (Lensing), ACT, SPT.

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.



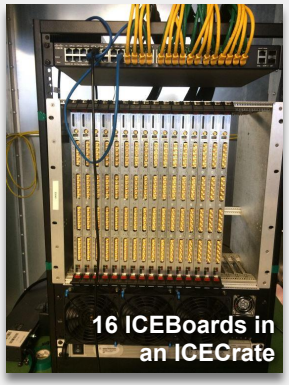
512 (2 polarisations per dish) raw voltage streams

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

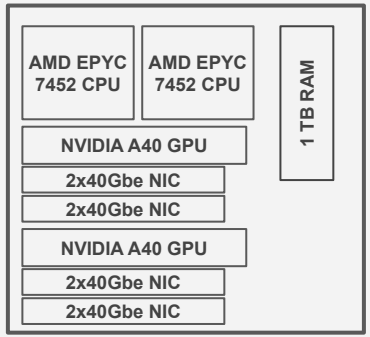


Digitised voltage signals for each input over 1024 channels

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:

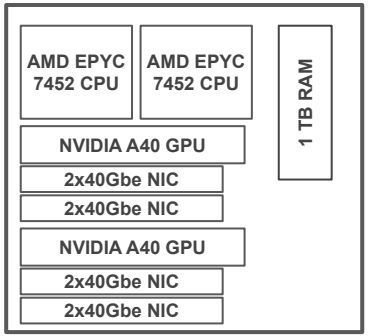
~54 TeraOp/s/node (N=512, 50 MHz, **U=13%**)

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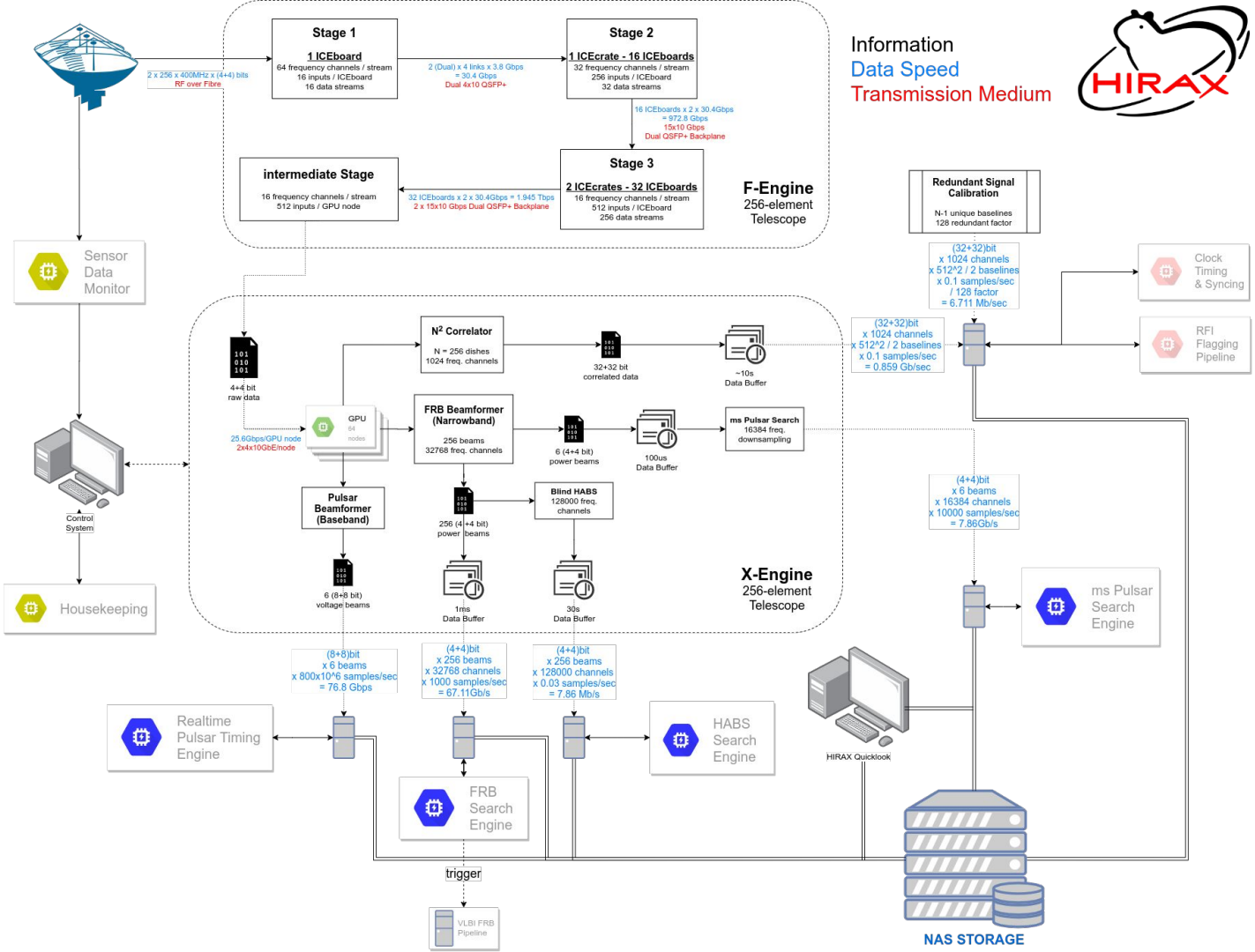
- Onsite compute/storage for FRB, Pulsar, HI Abs. and cosmology intake backends for HIRAX-256

- 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
- Bleien site upgrades
  - New feeds and a lot of misc. upgrades, supporting holography and drone beam measurement testing



Credit: Scott Eyono

Drone Beam Mapping at Bleien

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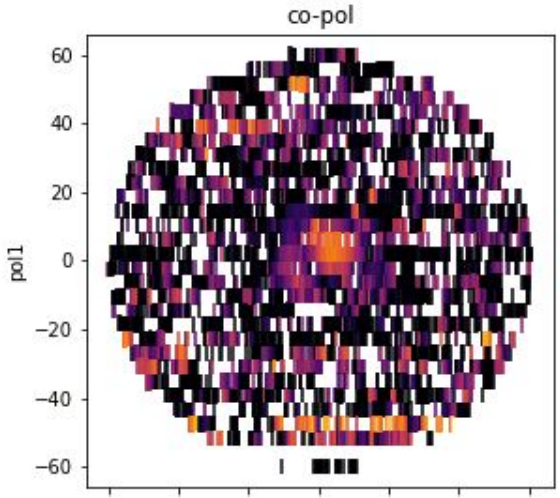
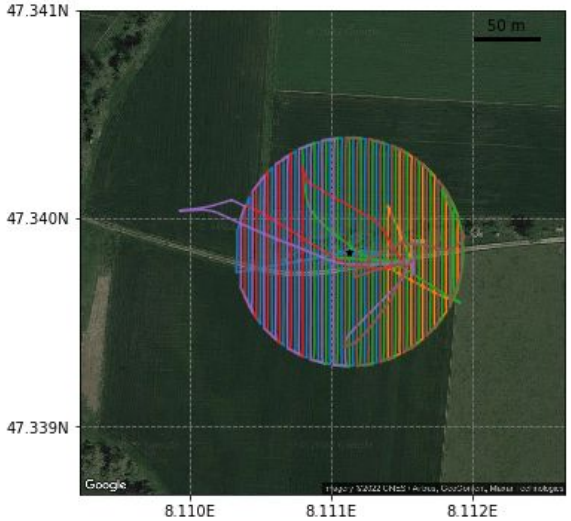
- Drone mounted transmitter for direct beam mapping of
- Test flights at Bleien Observatory in Switzerland
  - Also with other groups at Green Bank CHIME outrigger and DRAO
- Exploring feasibility of flights at Karoo site
  - RFI characterisation and testing
- Comparing with holography and photogrammetry reconstruction

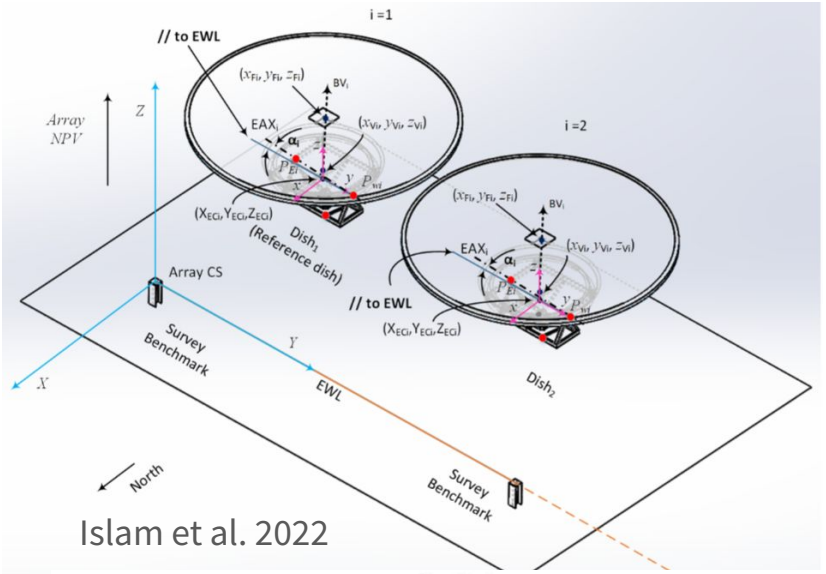




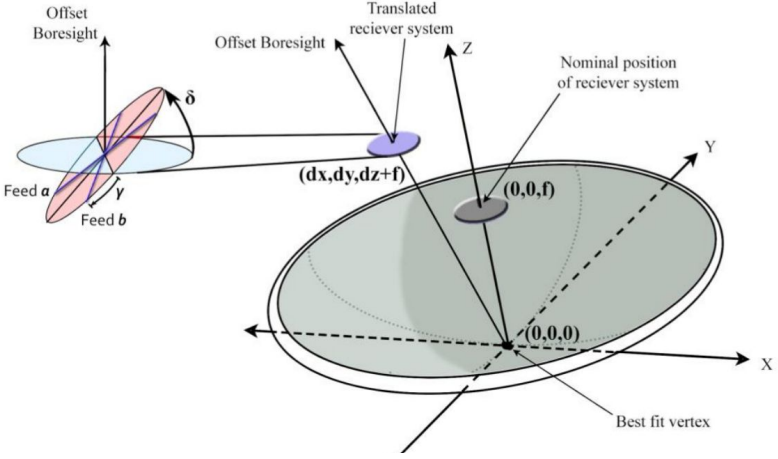
Christian Monstein, Thierry Viant, Tony Walters and others

On-site Metrology (FLARE-3)

- 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



Islam et al. 2022



On-site Metrology (FLARE-3)

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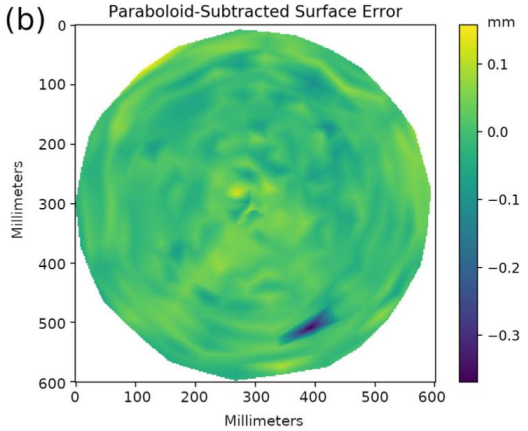
- Laser Tracker
  - Positioning and orientation of elevation axes and nominal pointing vectors across array
  - Verification of positioning of feed mount, and dish fabrication jigs during production
  - High precision over long distances but long setup/measurement time, require scanning with retroreflectors
- Photogrammetry
  - Once targets set, allows for quick re-analysis
  - Monitor dish shape over time, through repointings of the array

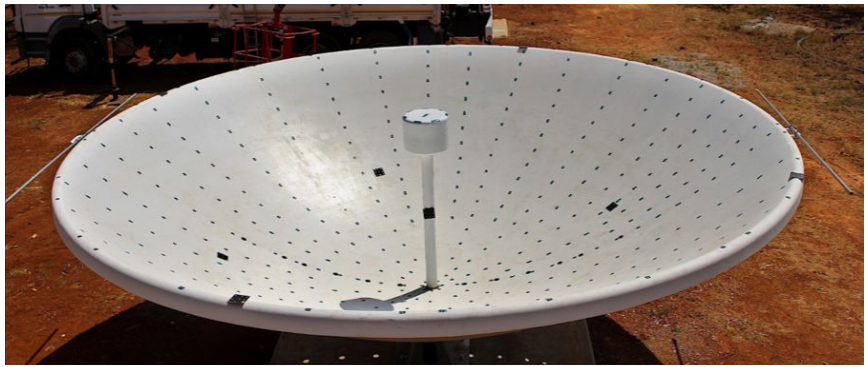


Measurements and beam simulations

→ Array-level systematics

→ Power spectrum systematics

ETHZ: Jennifer Studer and Thierry Viant



Systematics / Chromaticity and Foregrounds

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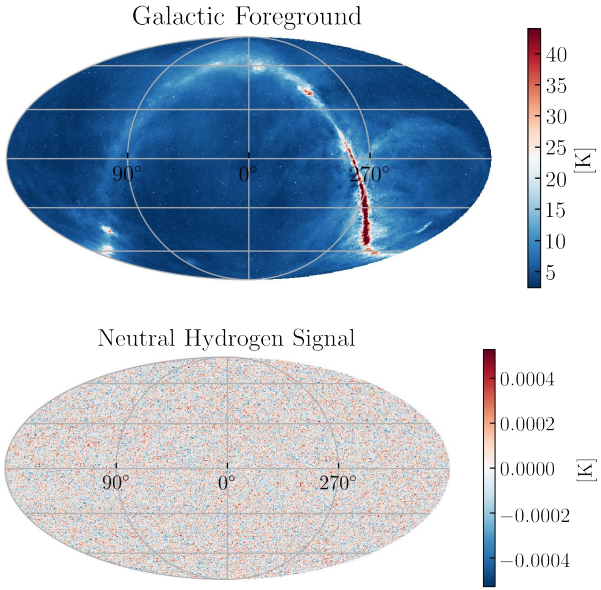
- Foregrounds are the primary challenge for 21cm cosmology
  - Galactic signal brighter by many orders of magnitude
- Signal and Foregrounds have different, *on-sky* properties
  - Galactic emission is:
    - Polarised
    - Strongly correlated over wide frequency bands
    - Structured on the sky in ~known way
  - In principle, there are not many mixed *on-sky* degrees of freedom
- Mode-mixing inherent in measurement is a major issue
  - Instrument has chromatic response *fundamentally* as well as arising from *systematics*
  - With perfect knowledge of the instrument, this can be accounted for, however the large contrast in signal strengths can make small reconstruction residuals a big problem
- **Instument simulation and characterisation is critical!**



Foreground Wedge

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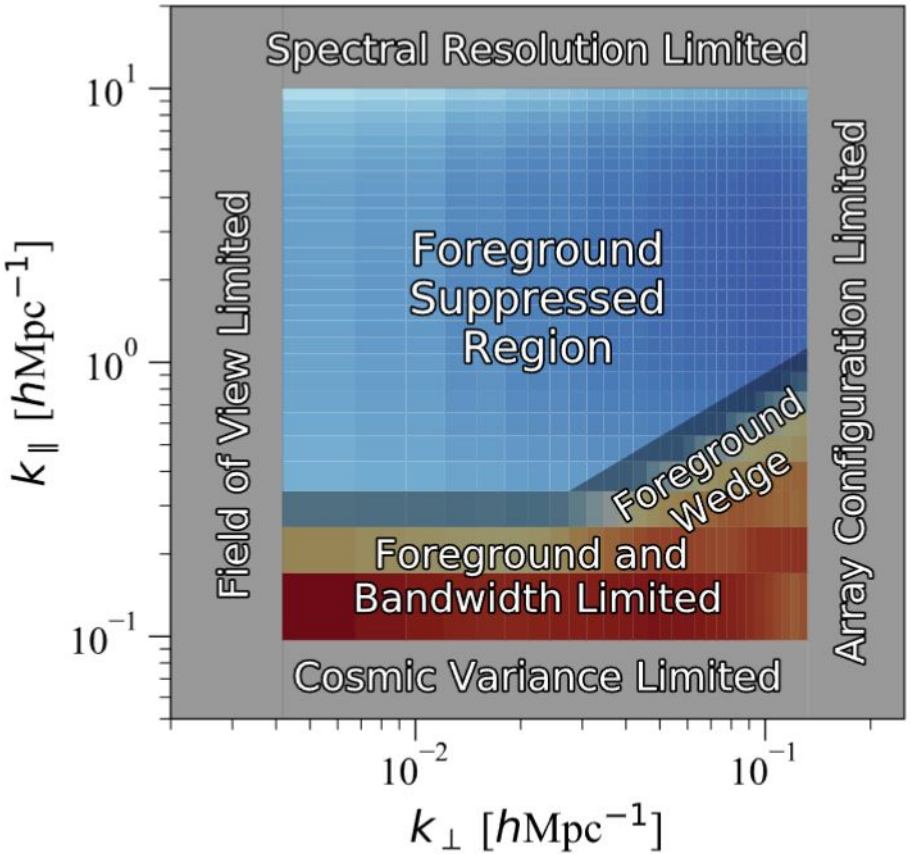
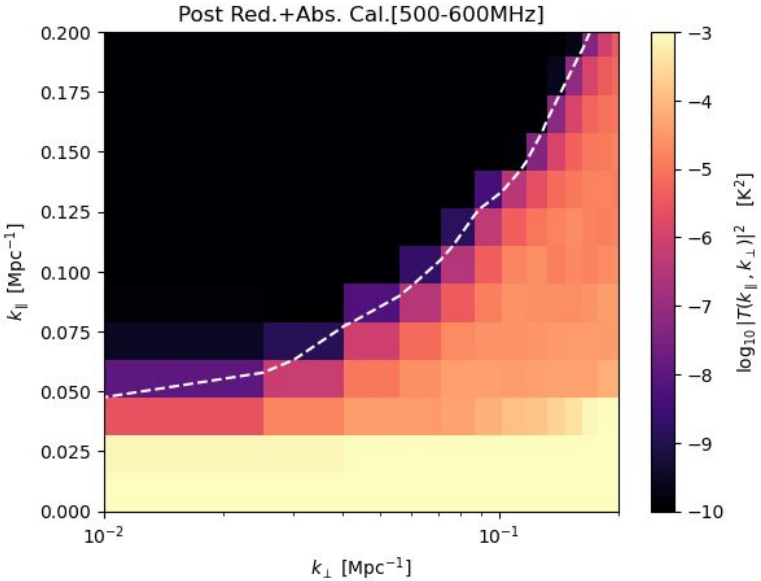
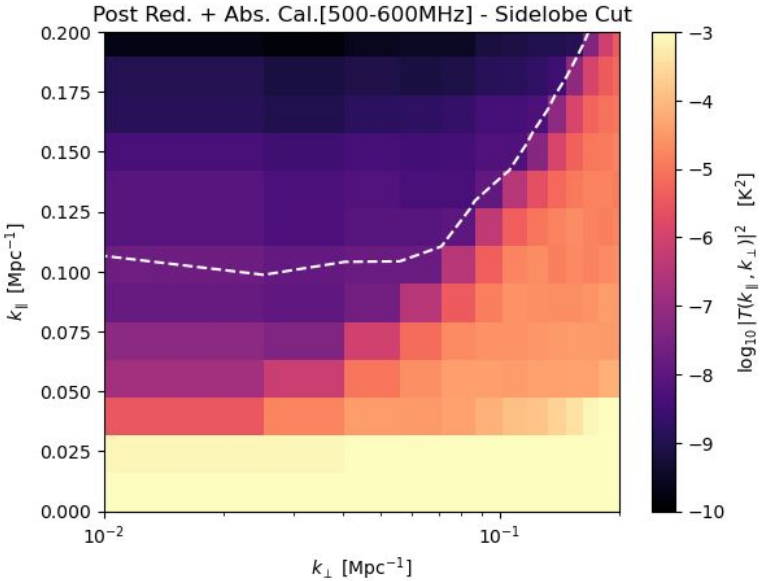
- Nominally clean region for cosmology
- Details of where the wedge is limited depend on instrument and, in particular, wide field response
- Many ways for foregrounds to leak out of the wedge
  - Miscalibration
  - Systematic reflections and correlations
  - etc.



Liu and Shaw 2020, arXiv:1907.08211

Foreground Wedge





Example: Mismodeling of primary beam during calibration using point source field

- Can cause significant leakage into cosmological modes
- Developing full pipeline for these kinds of simulations including calibration steps

Conclusions

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- HIRAX has the statistical power for a compelling cosmological intensity mapping survey
- Platform for real-time analysis with significant on-site compute requirements
- Overcoming foreground challenge is difficult and requires a controlled and well-characterised instrument model
- Systematics evaluated and controlled with design ↔ measure ↔ simulations loop
- Static dishes cannot be easily calibrated directly, requires reconstruction and verification with system measurements.
- Incorporating informed instrument model into forward model based analysis.
- Dishes with final design to be deployed late 2023 - early 2024 and early science data expected. Will learn a lot!

Thanks!