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

Cosmology in the Alps - 18.03.2024

Devin Crichton - ETH Zürich

HIRAX Overview

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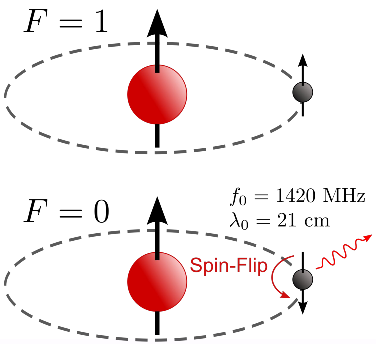
- **H**ydrogen **I**ntensity and **R**eal-time **A**nalysis e**X**periment
- Radio inteferometer with a compact, redundant layout
- Funded up to 256 element deployment.
  - Plans to extend to 1024.
- 6m diameter monolithic dishes instrumented to operate between 400–800 MHz.
- To be co-located with the SKA at the SARAO Karoo site.
- Intensity mapping survey of ~⅓ of the sky over 4 years
- Primary Science 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

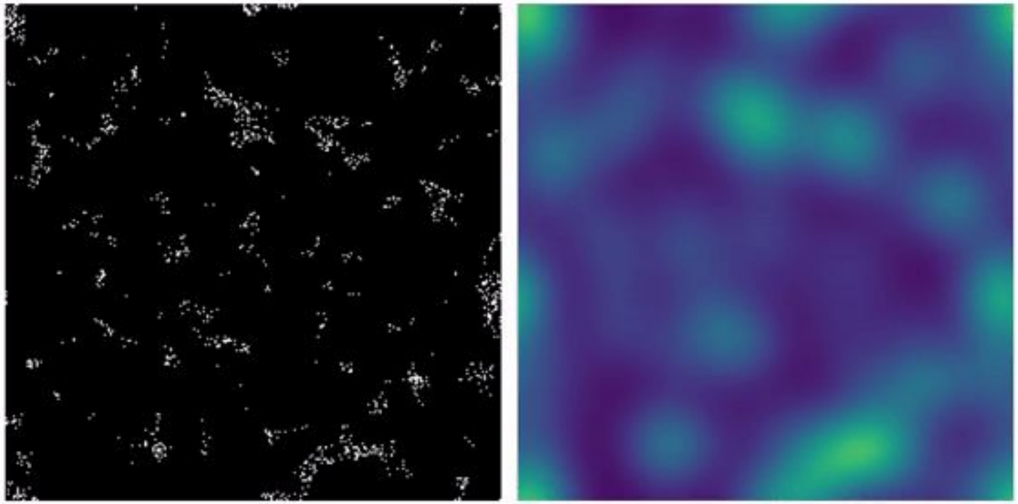
HI Intensity Mapping Tomography

- 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 spec. survey



Line Intensity Mapping (LIM)

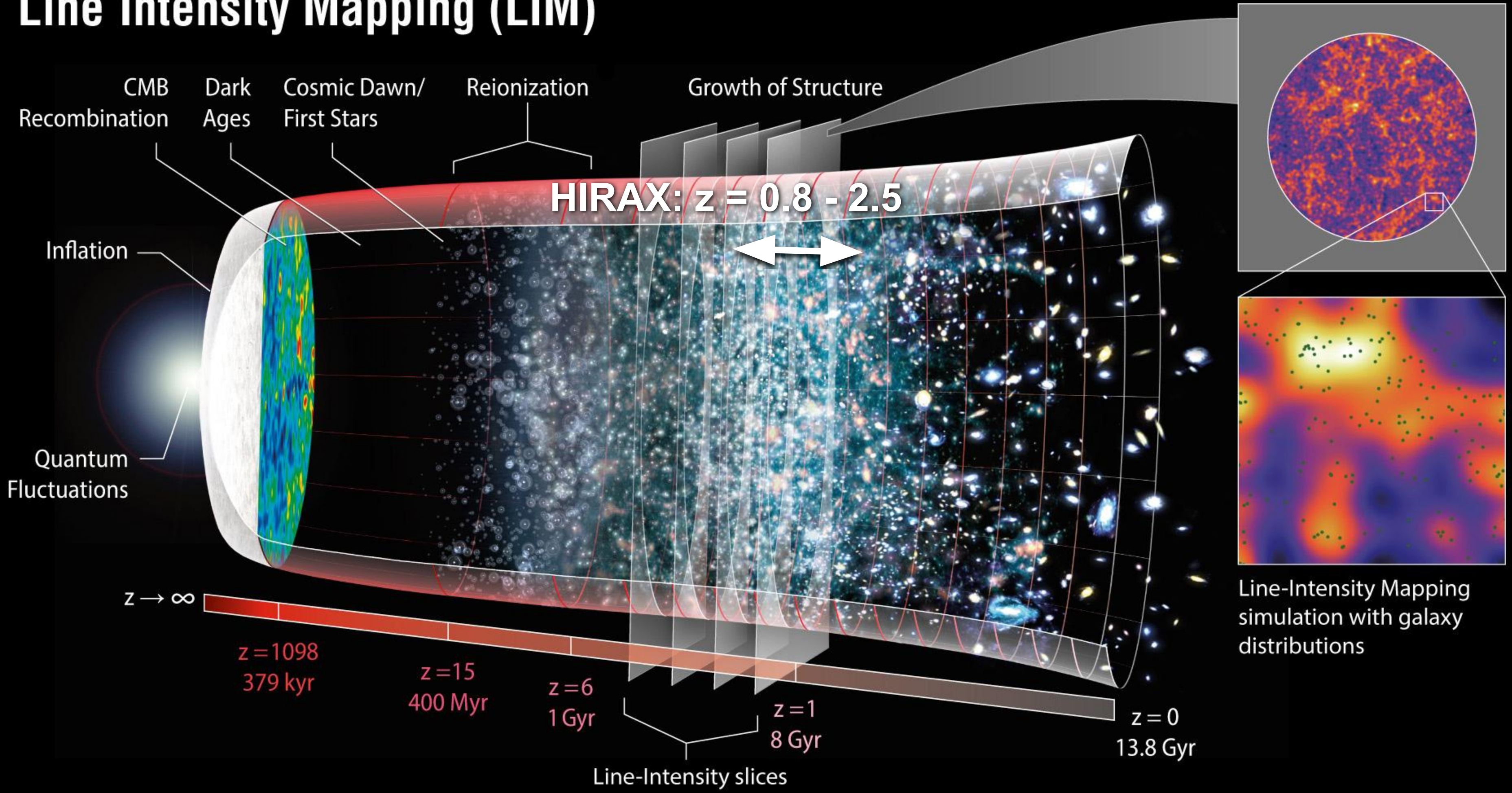


Image Credit: NASA / LAMBDA Science Team

21cm Cosmology in Context

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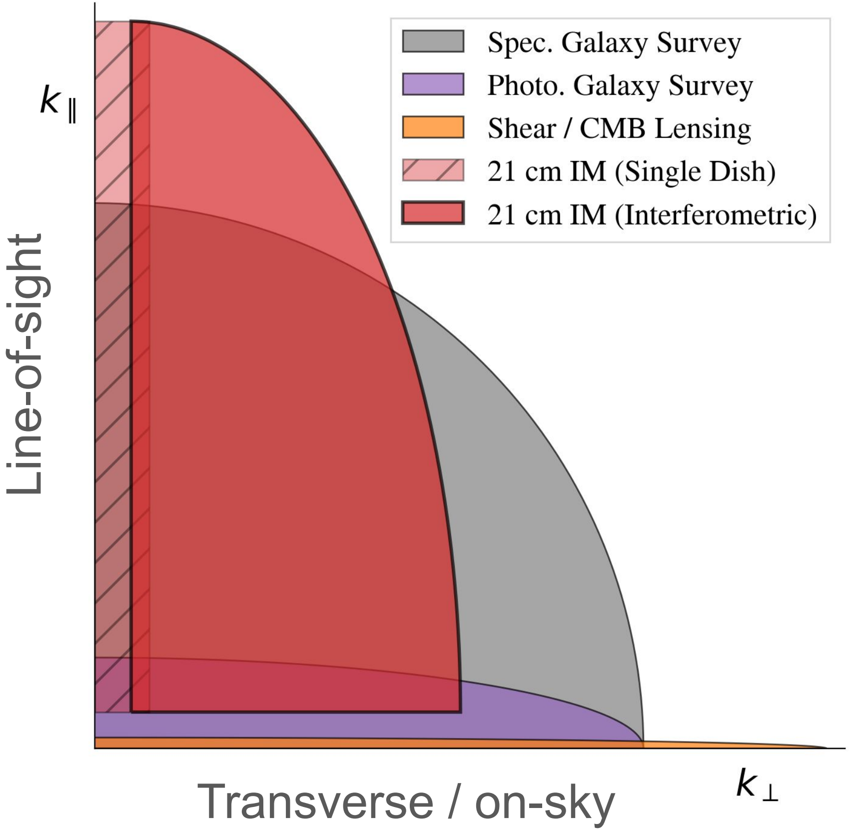
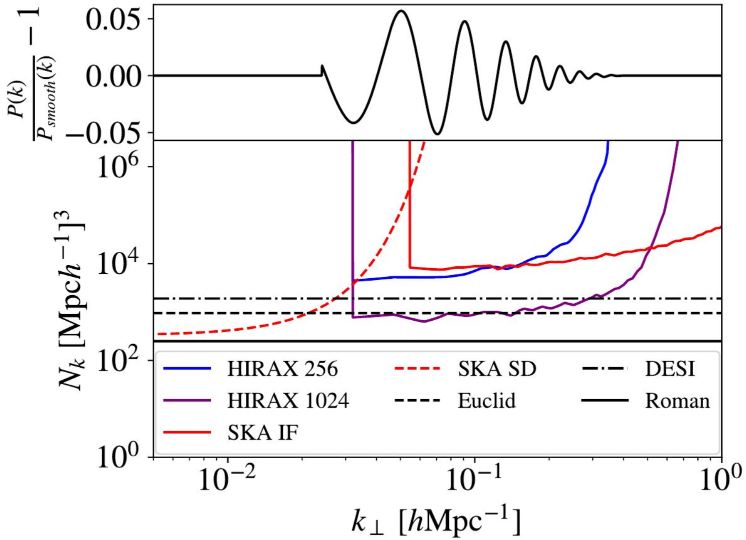


Figure adapted from A. Slosar

- Tomographic constraints comparable to spectroscopic large scale structure survey
- Large-scale LoS modes lost to smooth spectrum foregrounds
- Limited by resolution cutoff (small and large scales for interferometer array)



Motivation for Compact Redundant Arrays

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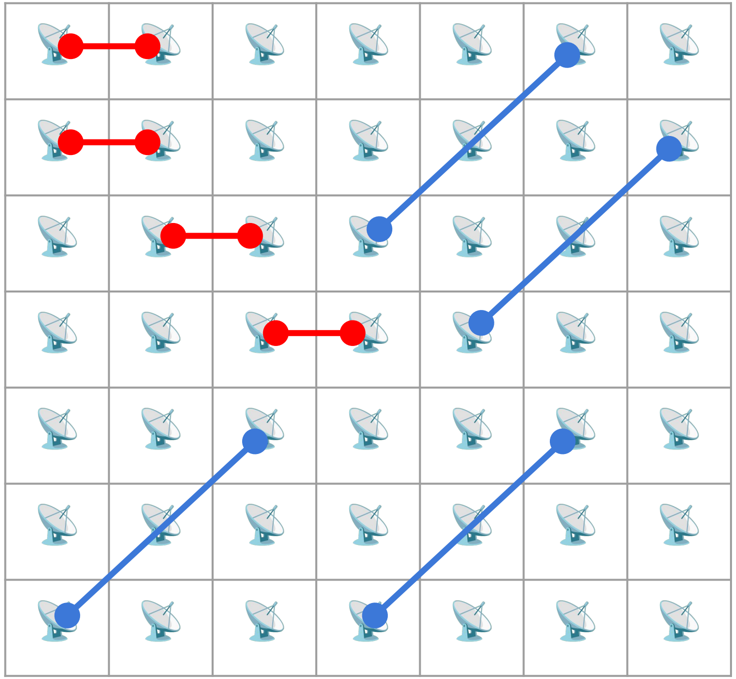
- Redundant array
  - Large N with many repeated baselines
    - Many independent measurements of same sky modes
  - Internal, redundant, calibration
  - Data compression depends on hardware-level redundancy
  - Large grating lobes leads to poor imaging capability
- Compact
  - Most weight on short baselines
  - Sensitivity to large (cosmol.) angular scales
  - Potential for cross-talk, reflections and impact from array-level effects

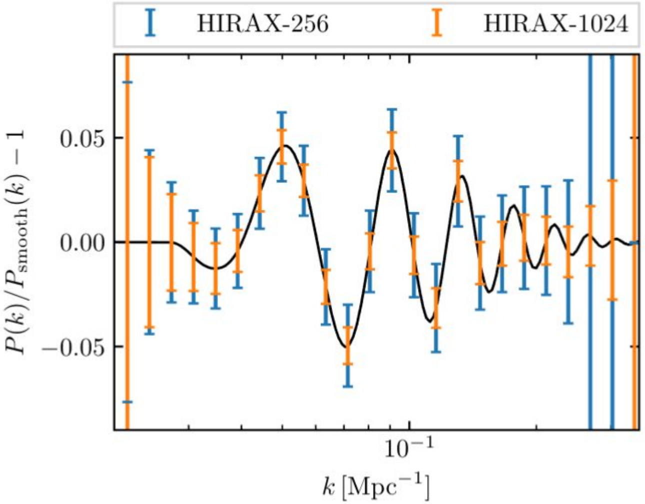
- E.g HIRAX, CHIME, CHORD, HERA, MWA

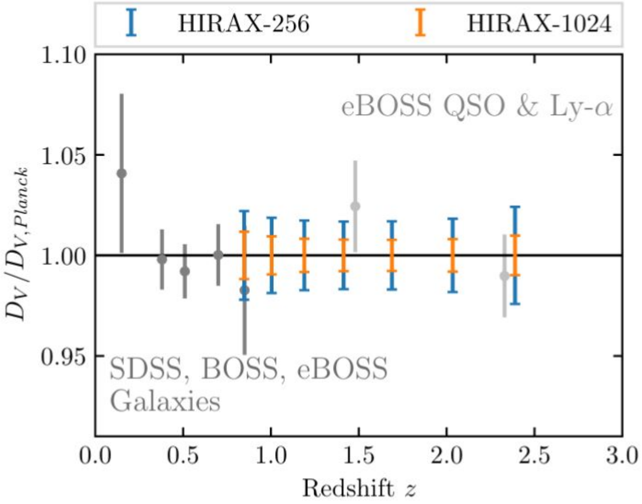


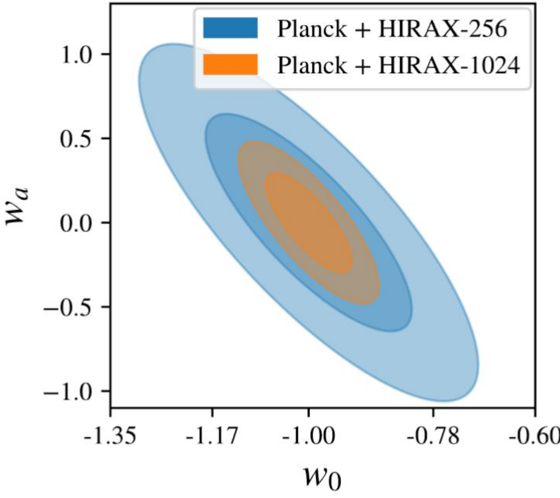
HIRAX BAO Cosmology

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**)
- Cosmological HI sky simulations (***Pascal Hitz, see poster***)







Transient and Additional Science Goals

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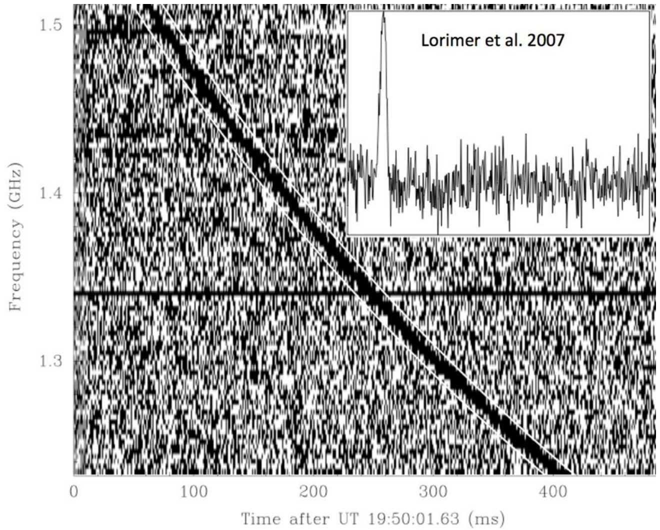
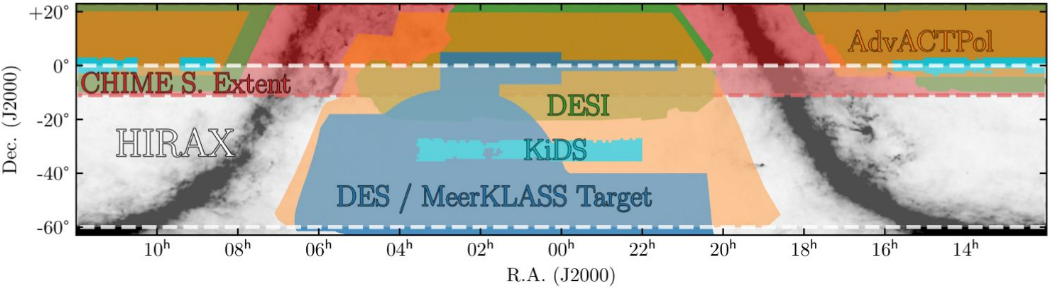


Real-time analysis of beamformed data

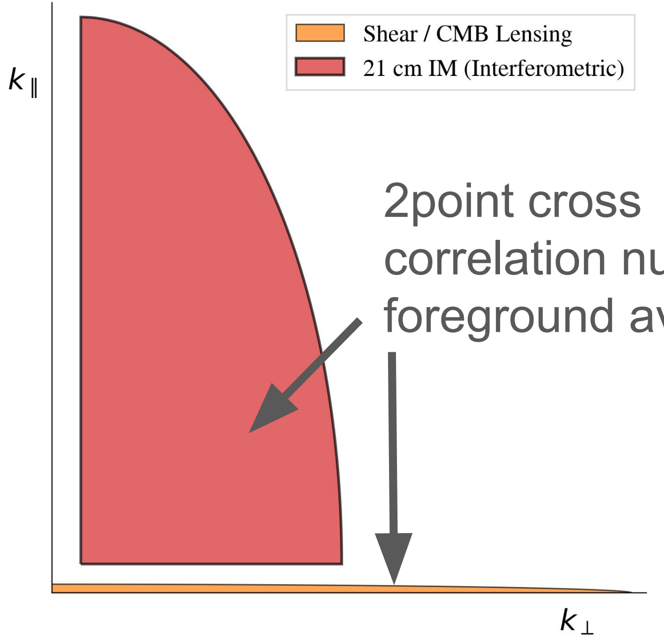
- Fast Radio Burst Search
  - Fast dedispersion algorithms over range of dispersion measures
  - Localisation with outriggers (e.g. BIUST Botswana)
- Pulsar timing and search
  - Timing and pulse profiles of known pulsars with coherent dedispersion
  - Incoherent search with high frequency and time sampling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



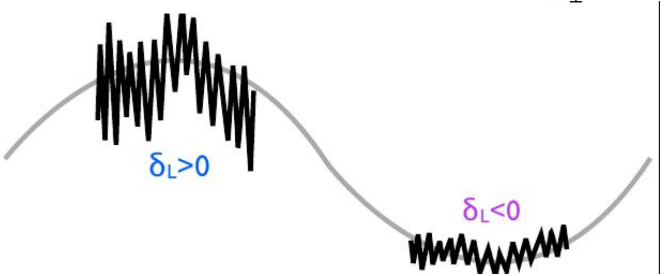
Cross-correlations with overlapping surveys

- DES, Rubin LSST, HSC, KiDS, DESI, 4MOST
- Euclid, Roman
- Ground based CMB (Lensing), ACT, SPT.

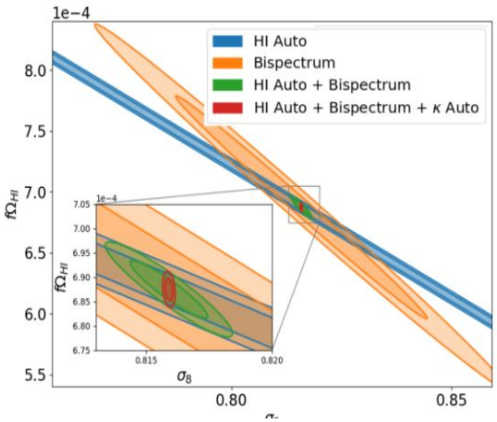
Higher order cross-correlations

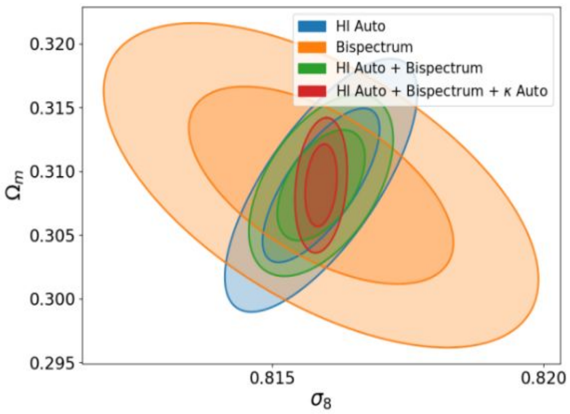


2point cross correlation nulled by foreground avoidance



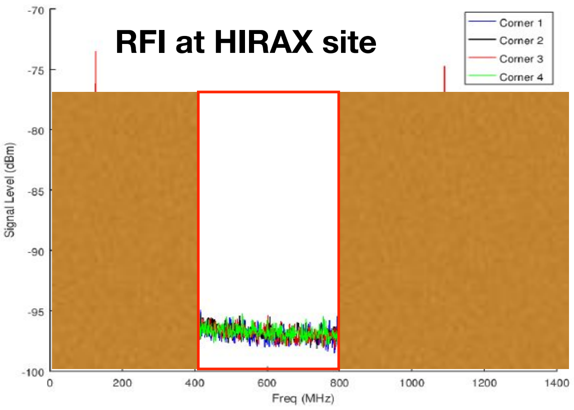
- CMB-21cm Cross Bispectrum: Low-k lensing modes cross with two high-k 21 cm modes.
- Forecast signal to noise promising using upcoming ground based lensing maps
- Detection strong enough to provide cosmological constraints - different degeneracy axis
- Moodley, Naidoo et al. arXiv: 2311.05904

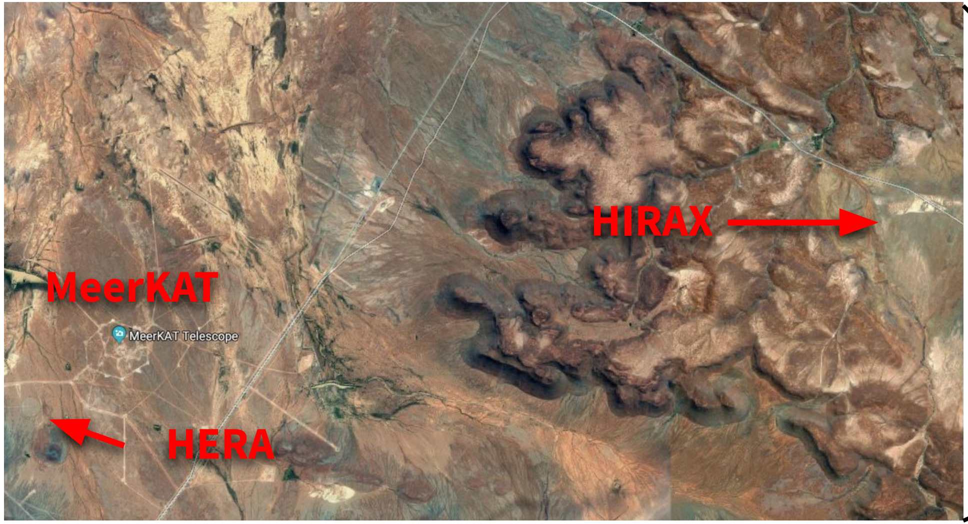


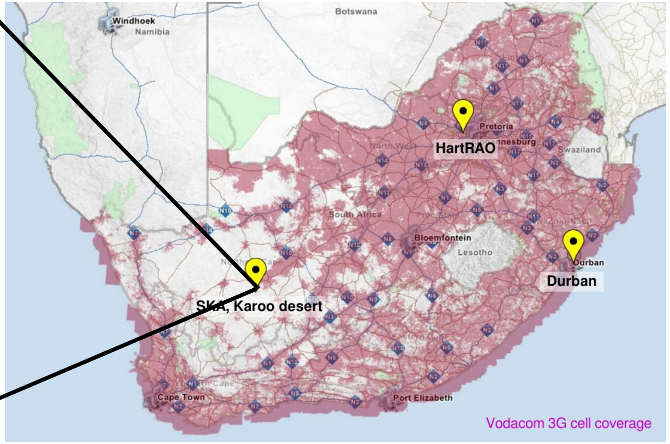


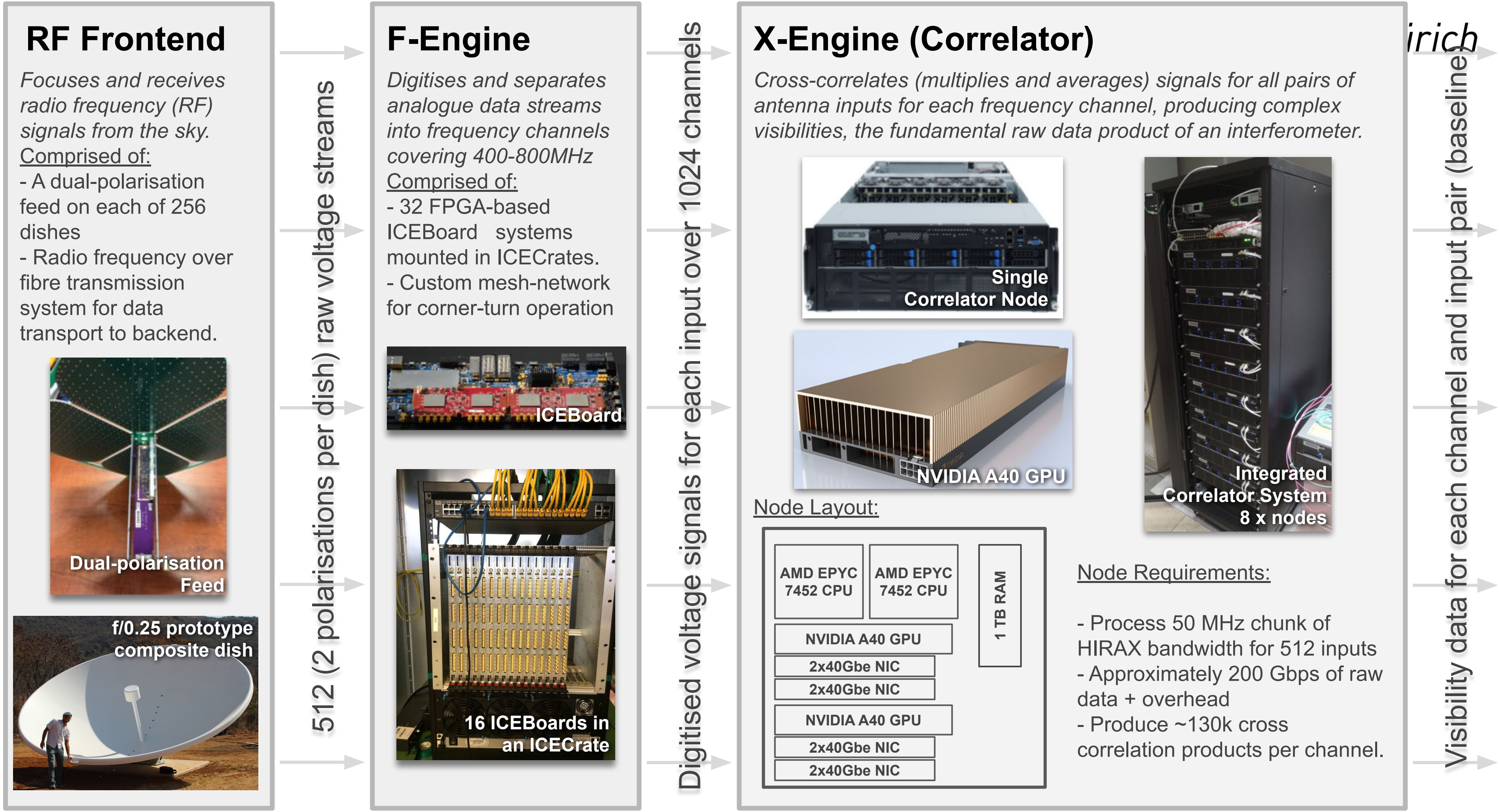
HIRAX Site

- 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








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

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

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

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

HIRAX-256:

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

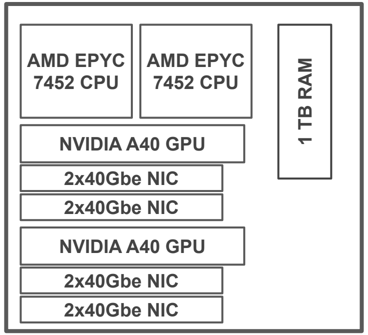
HIRAX-1024:

~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

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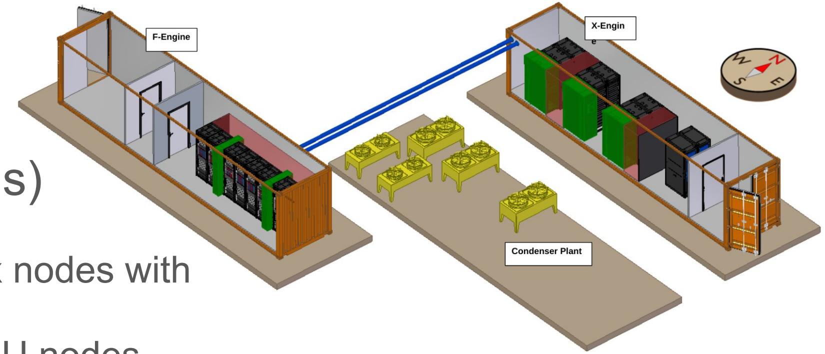

- On-site for real-time analysis and compresison
- Beam-forming backends (nominal specifications)
  - FRB: O(100s) Beams @ 32k channels, 1ms sampling
    - GPU based incoherent dedispersion search, 5 x nodes with Nvidia A40s, 1TB RAM
  - Pulsar Search/Timing: ~6 full baseband beams 3 x GPU nodes
    - 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 TODDBs

Systematics / Chromaticity and Foregrounds

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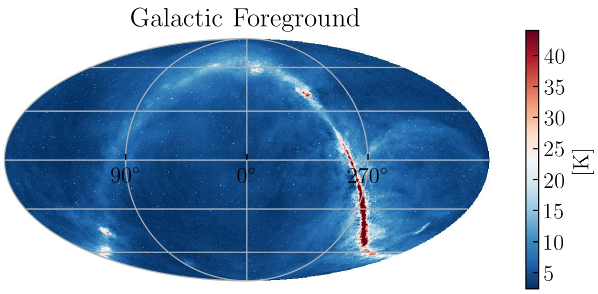
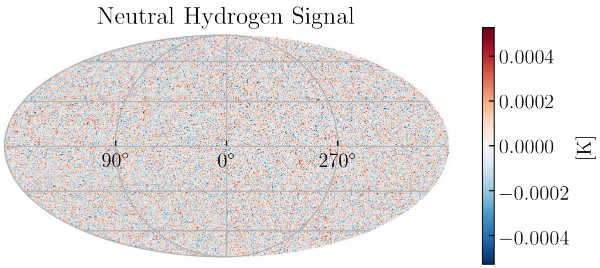
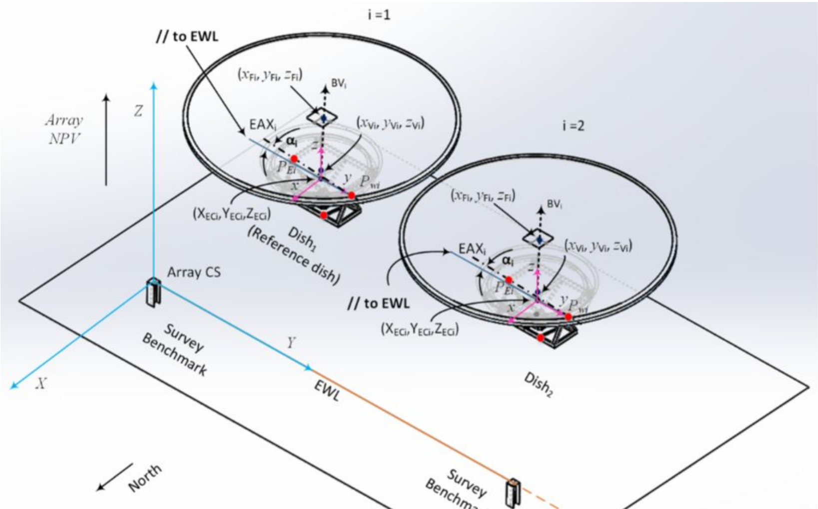
- Foregrounds are the primary challenge for 21cm cosmology
  - Galactic signal brighter by many orders of magnitude
- Signal and Foregrounds have different, *on-sky* properties
  - Galactic emission is:
    - Polarised
    - Strongly correlated over wide frequency bands
    - Structured on the sky in ~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!**



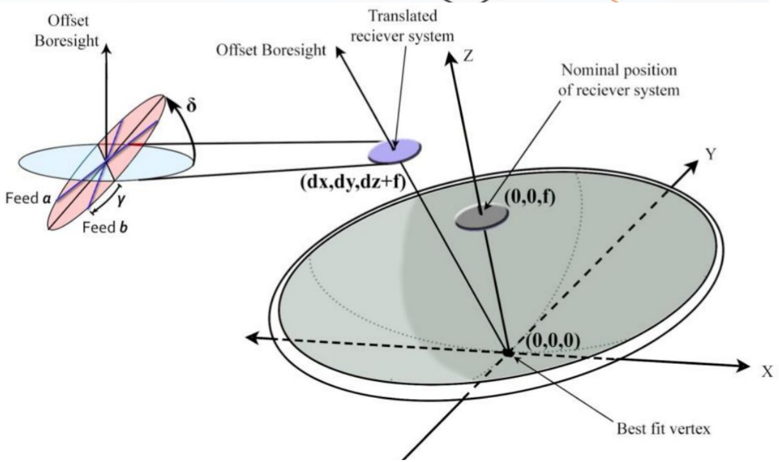


HIRAX Calibration Challenges

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



Telescope Mechanical Assembly - Focal Plane

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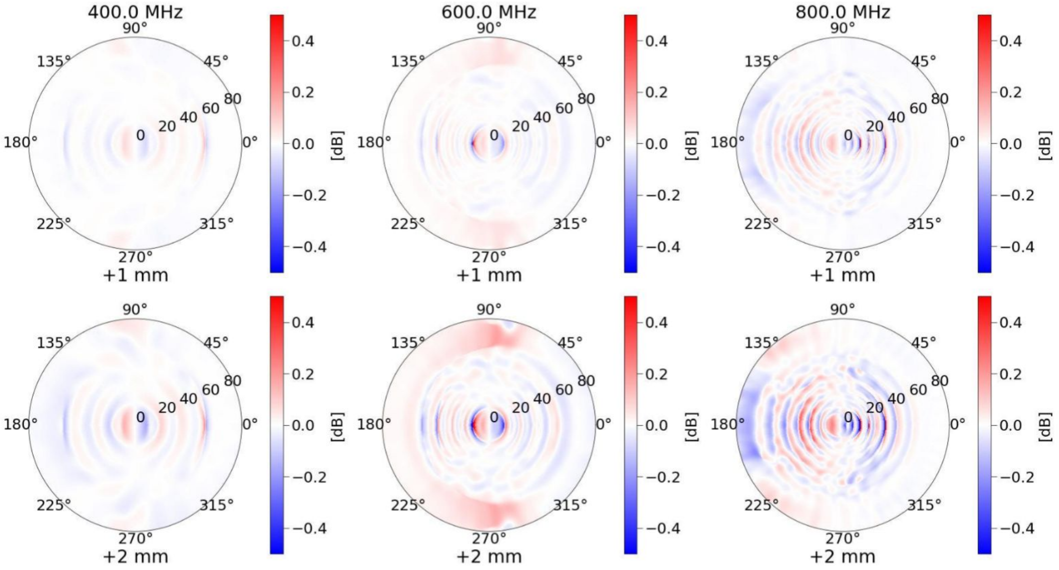
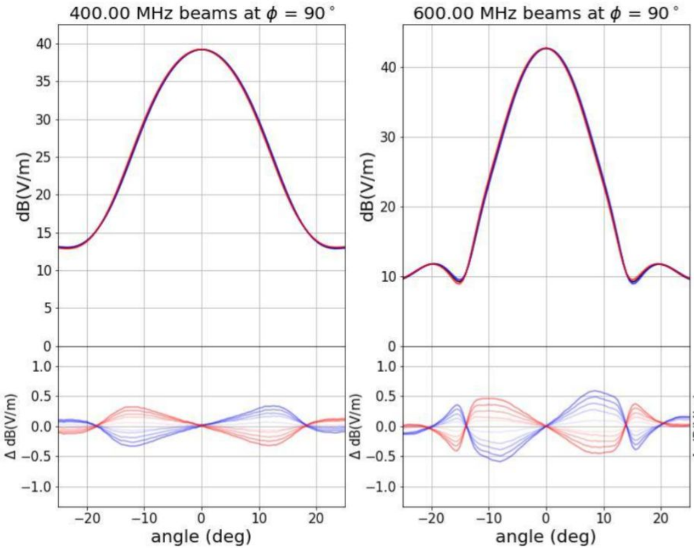
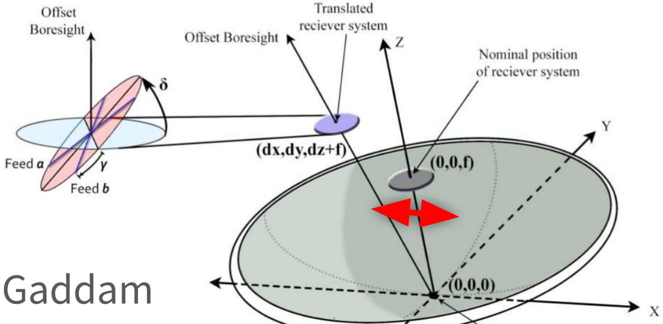




- Shifts beam centroid/effective pointing
  - Large systematic effect for tolerances feasible to design for
- Distribution of mis-pointing across the array is a large systematic concern



Beam Simulations: Kit Gerodias, Aditya Karigiri, Sindhu Gaddam

Validation with On-site Metrology

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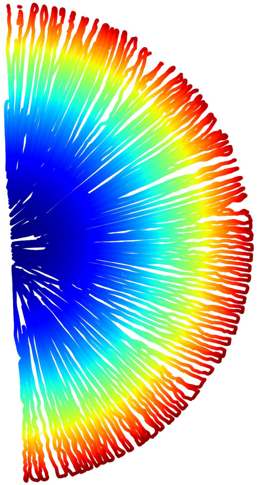
- Laser Tracker
  - High point density and precise
  - Suitable for factory measurements of plug, moulds, jigs and reflectors
  - Requirements verification before deployment
- Photogrammetry
  - Once targets set, allows for multiple re-analyses of reflector surface
  - Field-ready for on-site measurements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

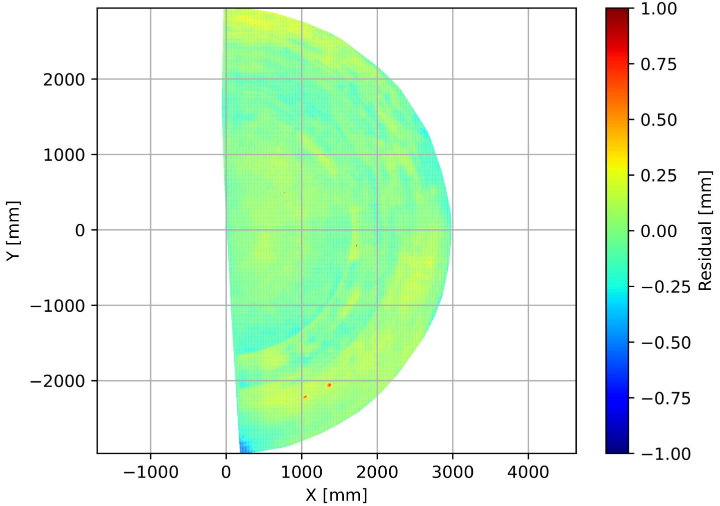
Measurements and beam simulations → Array-level systematics → Power spectrum systematics

ETHZ: Jennifer Studer and Thierry Viant



HIRAX Plug Surface Analysis (**Jennifer Studer, see poster**)

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



Drone Beam Mapping and Holography

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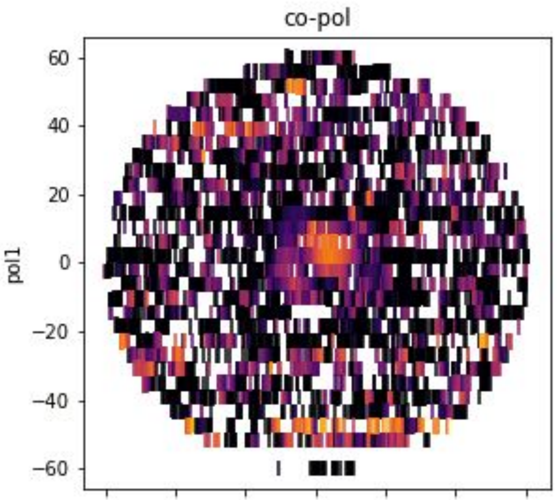
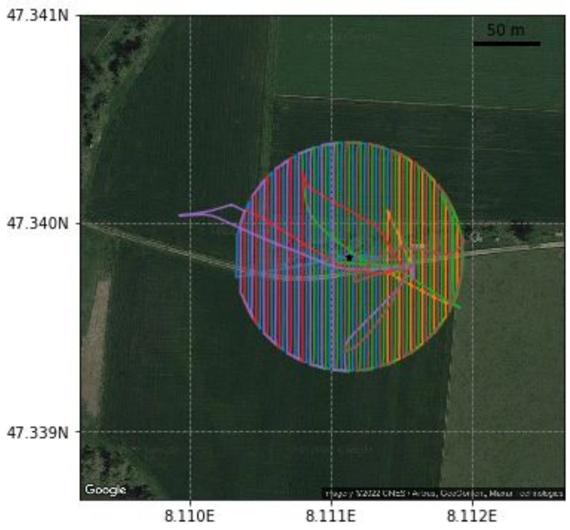
- Drone mounted transmitter for direct beam mapping of
- Test flights at Bleien Observatory in Switzerland
    - Also with other groups at Green Bank CHIME outrigger and DRAO
- Multiple parallel efforts
- Exploring feasibility of flights at Karoo site
    - RFI characterisation and testing
- Comparing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





Christian Monstein, Thierry Viant,
Tony Walters and others

HIRAX-256 Status and Timeline

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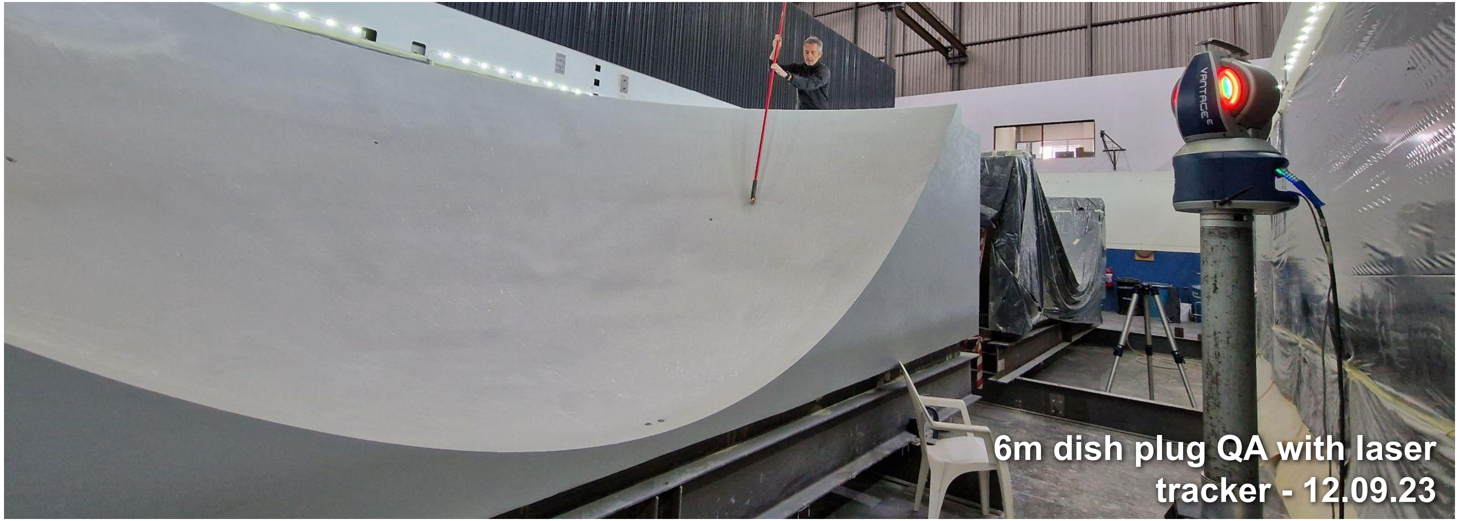
- **Establishment of dish factory in Carnarvon in Q1-Q2 2023**
- **Significant activity in developing dish tooling at Advanced Fiber Form, early 2023 to present, first plug at Carnarvon, moulds soon.**
- **Split dish reflector for outriggers under QA**
- Commission two-element qualification dishes at Klerefontein site mid 2024
- Dish production in full swing mid-late 2024



6m dish plug QA with laser tracker - 12.09.23

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.
- Systematics evaluated and controlled with design ↔ measure ↔ simulations loop
- Many subsystems close to completion. Dishes with final design to be deployed invery soon ~Q2 2024 and early science data expected with array build out to follow.
- Will learn a lot for early data!

Thanks!