HIRAX: Instrument Characterisation and Systematics

SKAO Cosmology SWG Meeting — 18.01.23

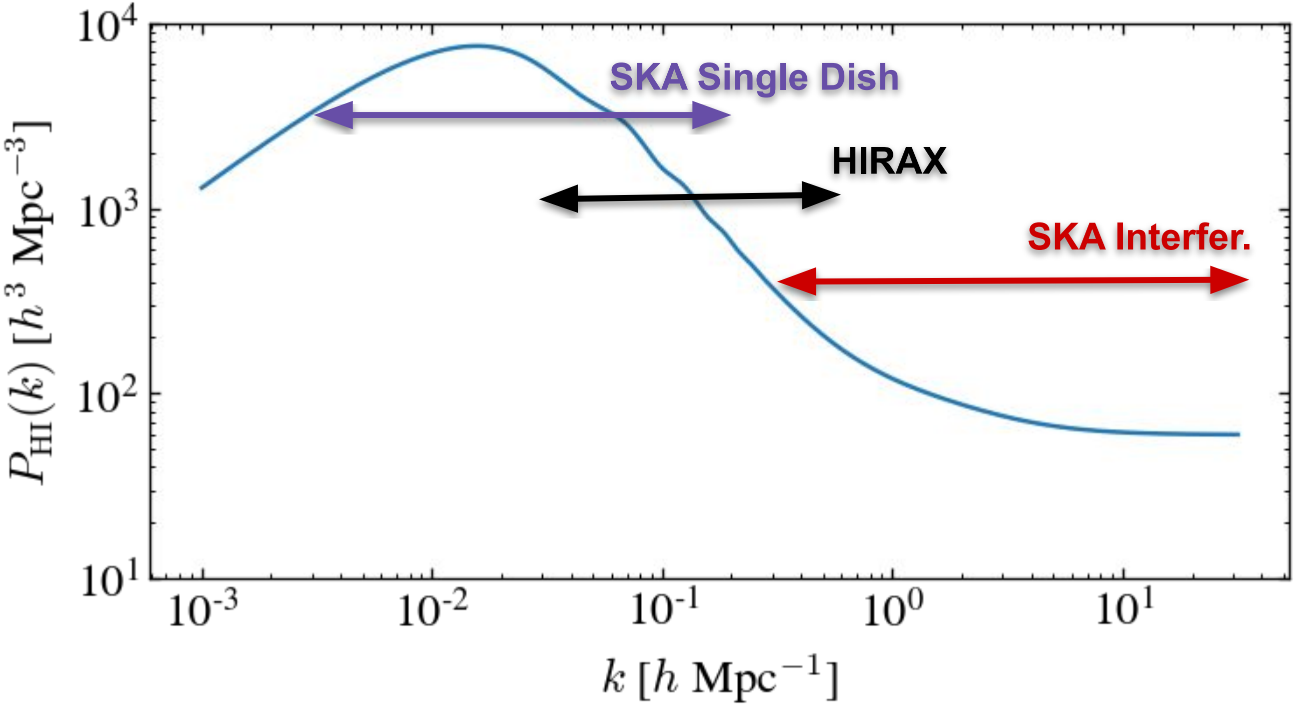
Devin Crichton - ETH Zürich

HIRAX Overview

- **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

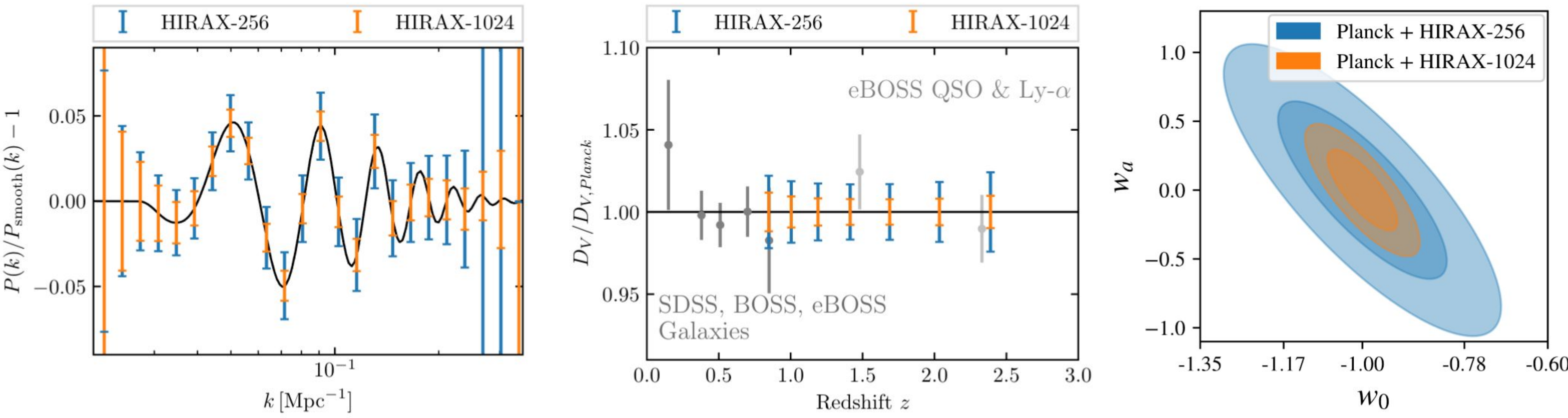
HI Power Spectrum



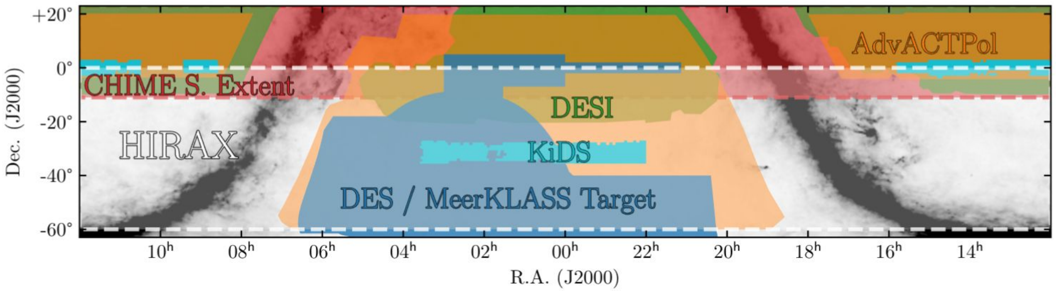
Science Goals - BAO Cosmology

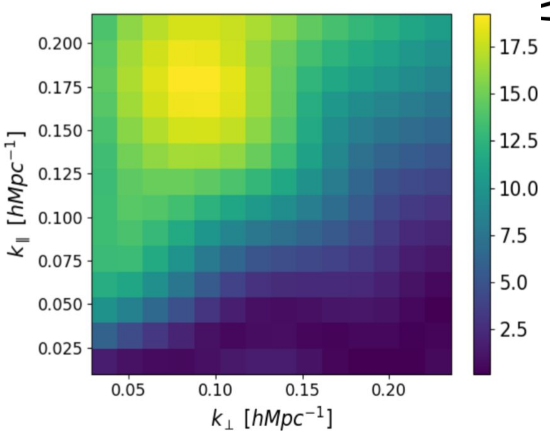
Parameter	Value
Number of dishes	256
Dish diameter	6 m
Dish focal ratio	0.23
Collecting area	7200 m^2
Frequency range	400–800 MHz
Frequency resolution	1024 channels, 390 kHz
Field of view	5°–10°
Resolution	0.2°–0.4°
Target system temperature	50 K

- 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)



Science Goals - Cross-Correlations

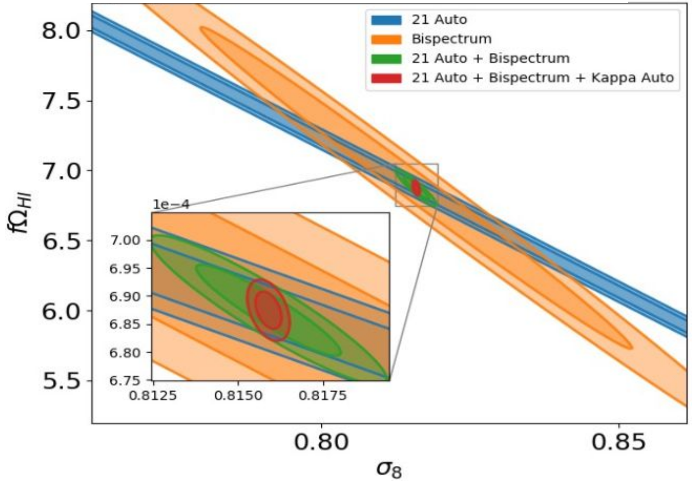




CMB-lensing Cross-bispectrum SNR

HIRAX has significant overlap with other surveys

- DES, Rubin LSST, HSC, KiDS, DESI
- Euclid, Roman



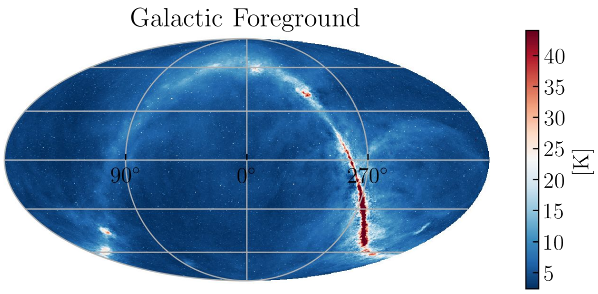
Potential for cross-correlation with CMB Lensing Surveys (Moodley, Naidoo et al. in prep.)

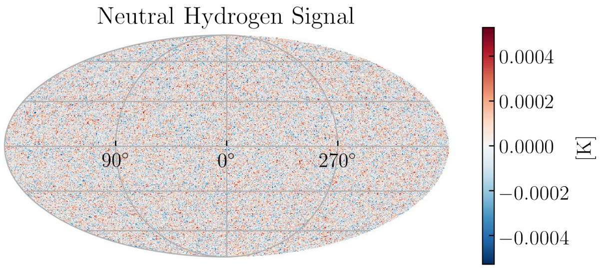
- Overlap with ACT, SPT and Simons Observatory
- Requires cross-bispectrum as long LoS modes likely lost due to FG filtering.

Warren Naidoo, Moumita Aich, Kavilan Moodley

Systematics / Chromaticity and Foregrounds

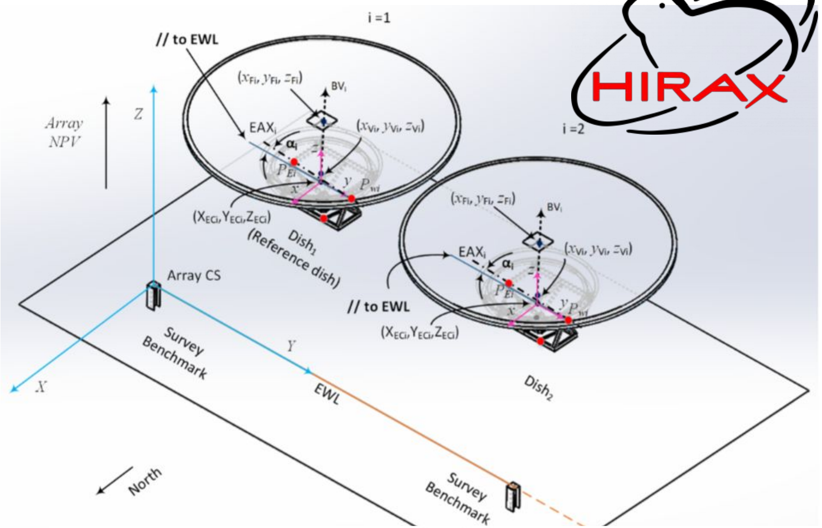
- Foregrounds are the primary challenge for 21cm cosmology
  - Galactic signal brighter by many orders of magnitude
- Signal and Foregrounds have different, *on-sky* properties
  - Galactic emission is:
    - Polarised
    - Strongly correlated over wide frequency bands
    - Structured on the sky in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

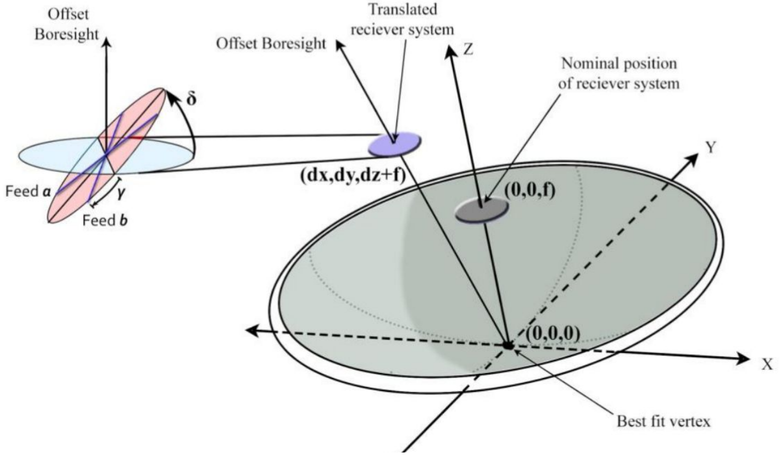




Design Considerations

- Dishes fixed per elevation pointing
  - Calibration options limited
- Compact array
  - Cross-talk between neighbouring feeds and array level effects
- Redundant interferometer
  - Calibration and on-site data compression relies on internal consistency
  - HW Requirements on precision over accuracy.





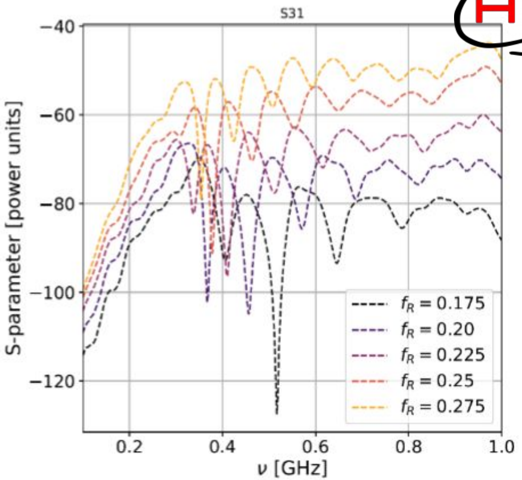
Dish Focal Ratio - Cross-talk

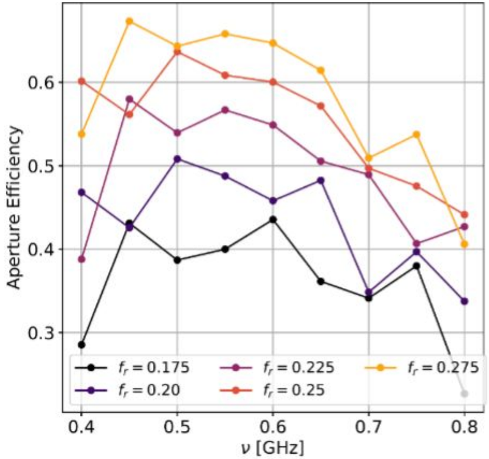
Dish design has been optimised for low cross-talk

- Deep, f/0.21 dishes currently planned
- Reduced systematic coupling effects as cost of aperture efficiency

Exploring full simulations of array-level coupling effects on redundancy

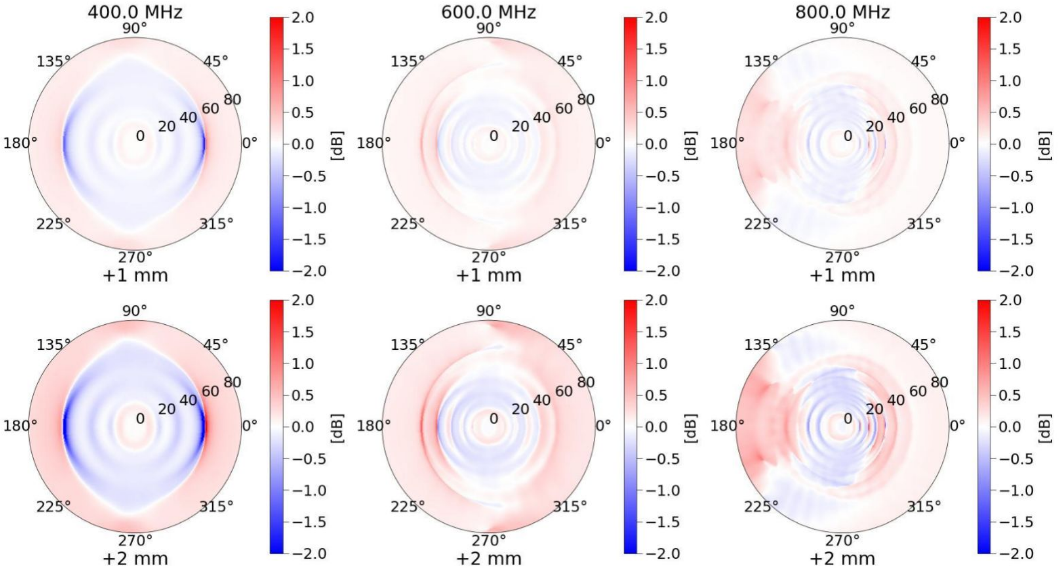
- Fast method-of-moments solver (QG)
- Incorporating array position dependent effects in simulations
- Effect of repointing on coupling to be evaluated

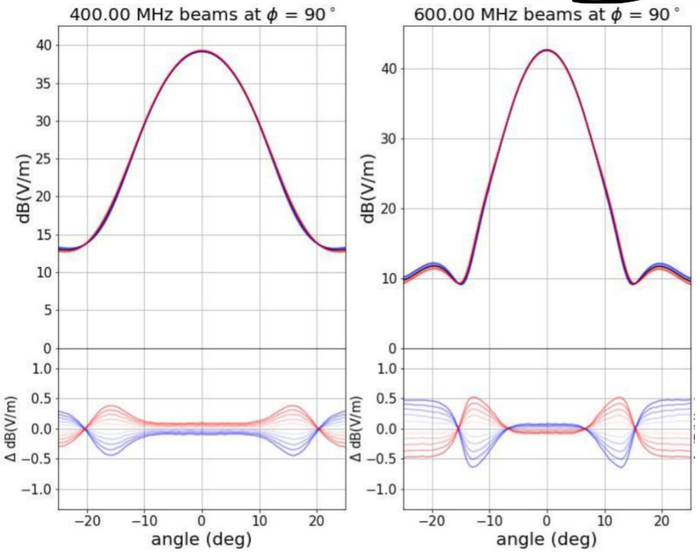




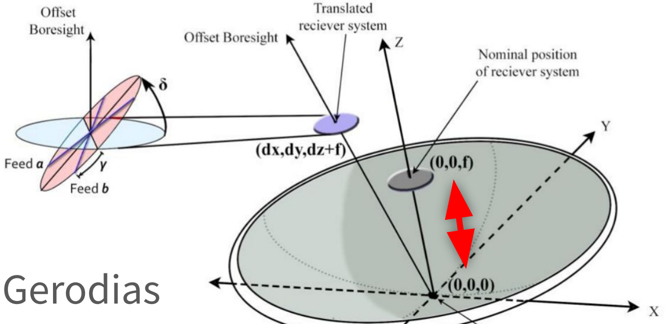
Aaron Ewall-Wice, Quentin Gueuning

Telescope Mechanical Assembly - Focal Axis



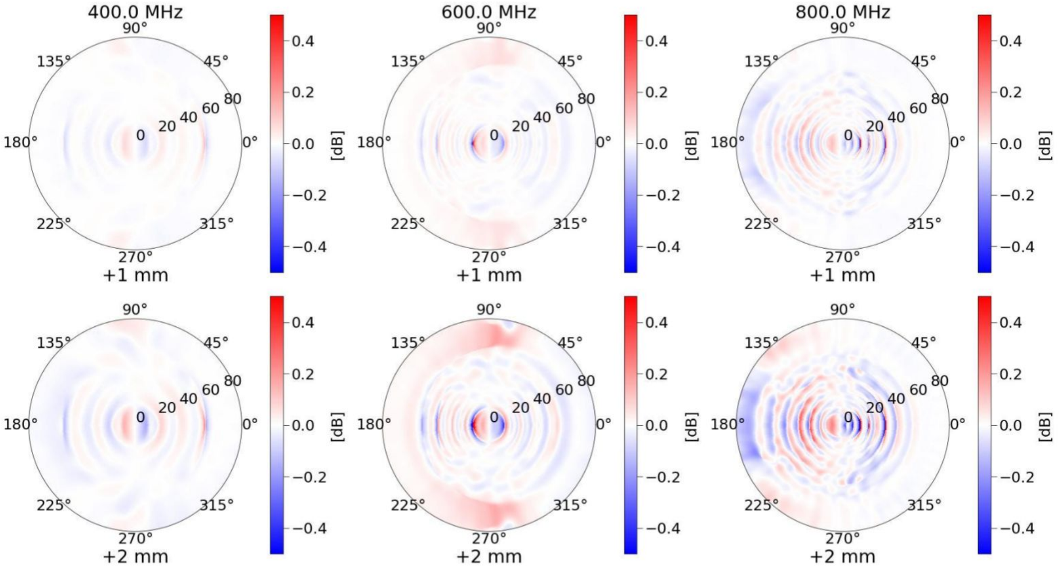


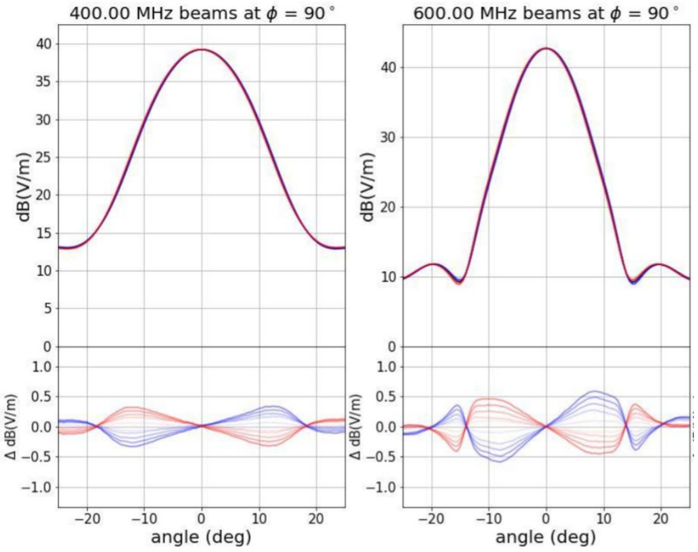
- Primarily effects sidelode structure



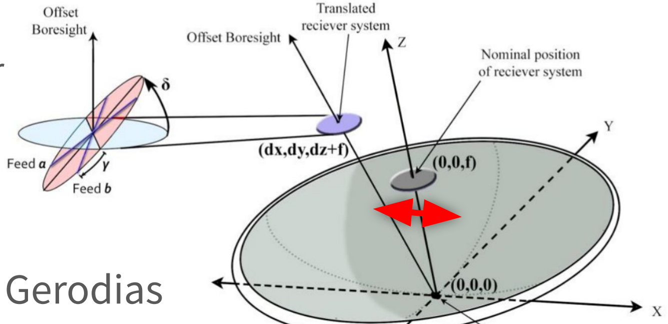
Beam Simulations: Kit Gerodias

Telescope Mechanical Assembly - Focal Plane





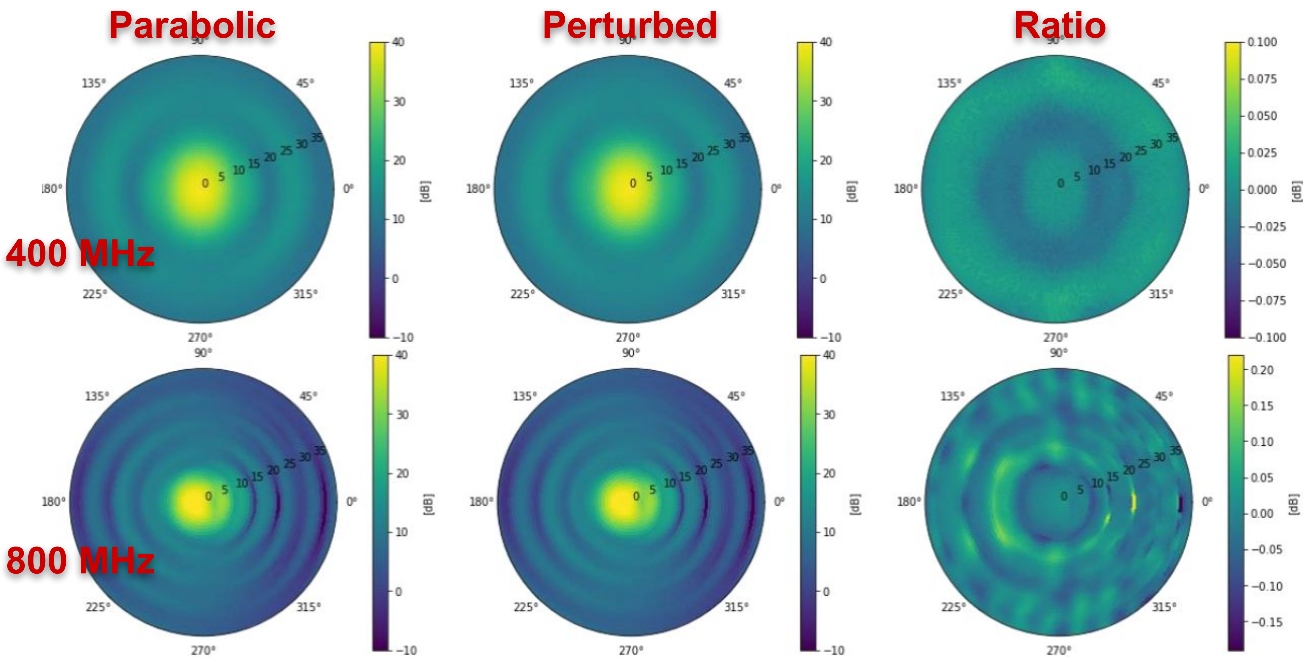
- Shifts beam centroid/effective pointing
  - Large systematic effect for tolerances feasible to design for
- Distribution of mis-pointing across the array is a large systematic concern

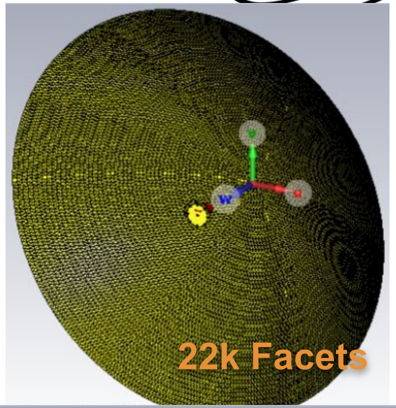


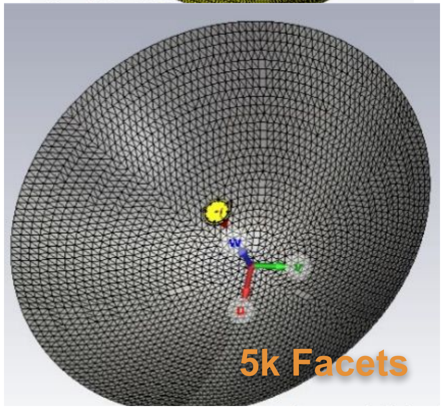
Beam Simulations: Kit Gerodias

Dish Surface

- Perturbing faceted model of dish surface
    - Random and coherent distortions







Benjamin Saliwanchik, Kit Gerodias, Sindhu Gaddam

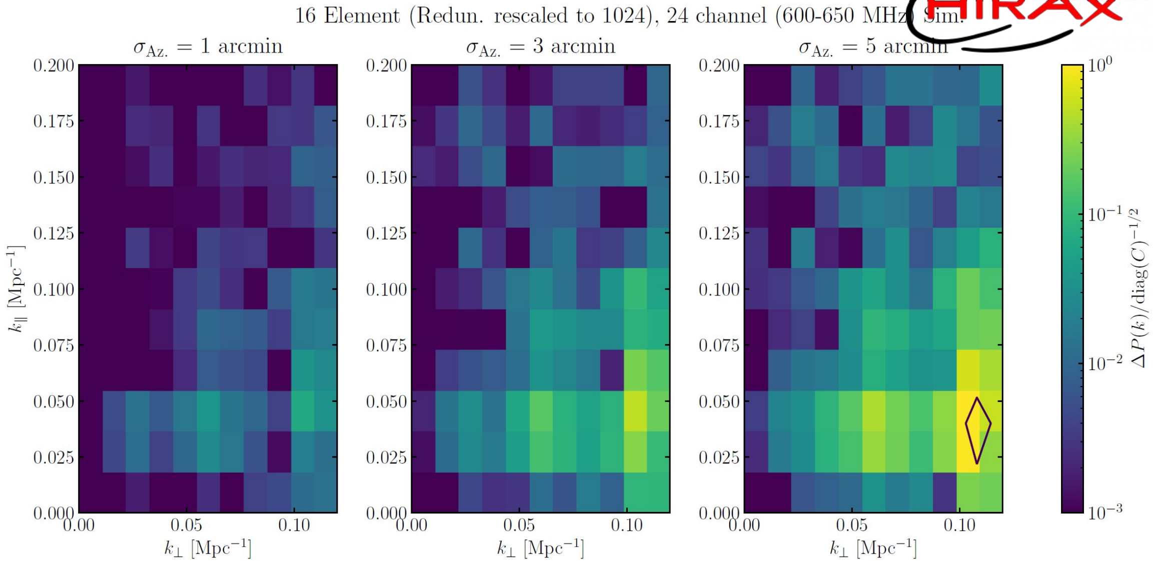
Systematics Propagation to Cosmology

Current dish requirements set by:

- Perturbing per-feed response based on distribution of systematic offsets over array
- Averaging down linearised systematics over redundant baselines
- Propagating residual to foreground filtered power spectrum

Extending to with:

- No explicit linearisation
- Full rel. and abs. Calibration steps
- Accounting for systematics in modelling and filtering



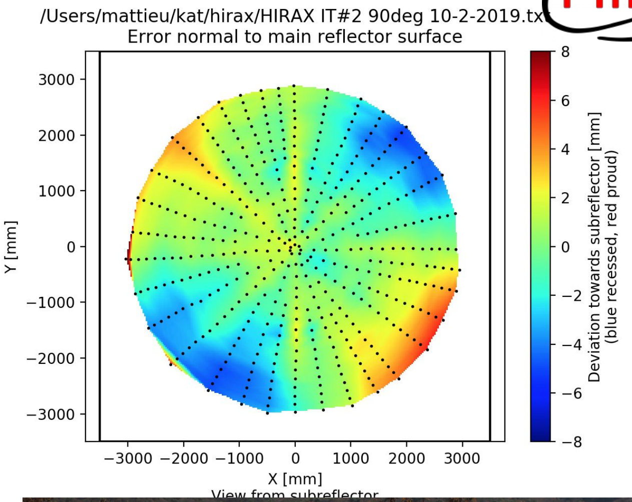
Telescope mechanical parameter	Target precision (RMS)
Receiver position relative to focus	0.5 mm
Receiver orientation relative to boresight vector	2.5′ polar and azimuthal
Dish surface deviations	1 mm
Dish vertex position relative to elevation axis	1 mm
Orthogonality of boresight vector and elevation 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′

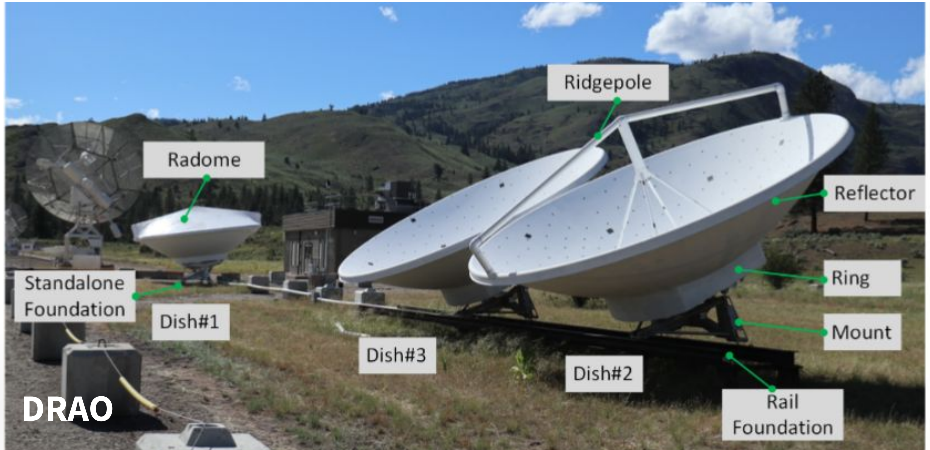
~ λ/100 - λ/50

Beam Simulations: Ben Saliwanchik, Elizabeth Peters, Kit Gerodias

Dish Prototyping

- Developing dish characterisation methods at prototyping sites
- Prototype composite dishes at HartRAO and DRAO
- Deploying finalised dish design prototypes in Klerefontein Karoo site early 2023
- Photogrammetry/metrology for dish surface reconstruction and positioning within array
- Holographic beam mapping where possible

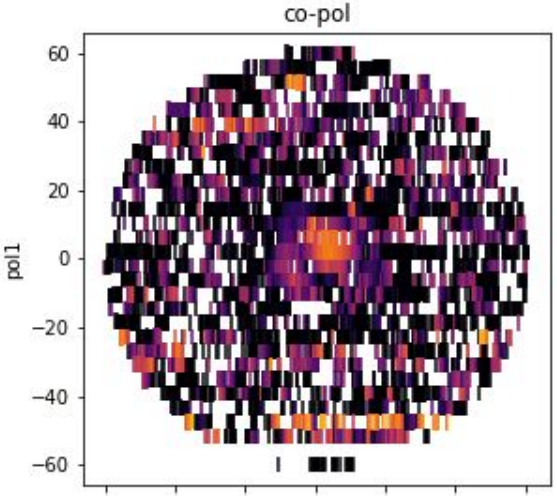


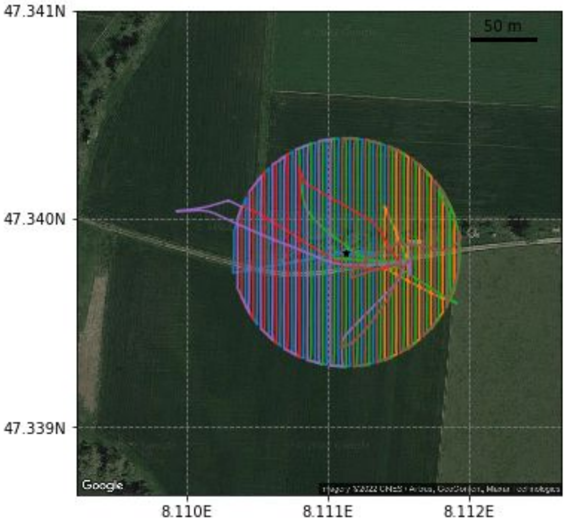


Drone Beam Mapping at Bleien

- Drone mounted transmitter for direct beam mapping of
- Test flights at Bleien Observatory in Switzerland
  - Also with Yale group 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





Conclusions

- HIRAX has the statistical power for a compelling cosmological intensity mapping survey
- Overcoming foreground challenge is difficult and requires a controlled and well-characterised instrument model
- Stringent requirements set based on design ↔ simulations loop
  - Major systematic is effective pointing uncertainty across the array
- Static dishes cannot be easily calibrated directly, requires reconstruction with metrology/drone measurements.
- Instrument characterisation analyses being compared and developed with prototype sites
- Intend to incorporate informed instrument model into forward modelly based analysis.
  - See Pascal Hitz talk for fast sky simulations
- Dishes with final design to be deployed 2023 and early science data expected. Will learn a lot!

Thanks!