The Hydrogen Intensity and Real-time Analysis eXperiment

21cm Cosmology Workshop 2019 - 22/10/2019

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The Hyc eal-time

Devin Cric @ UKZN

HIRAX Overview

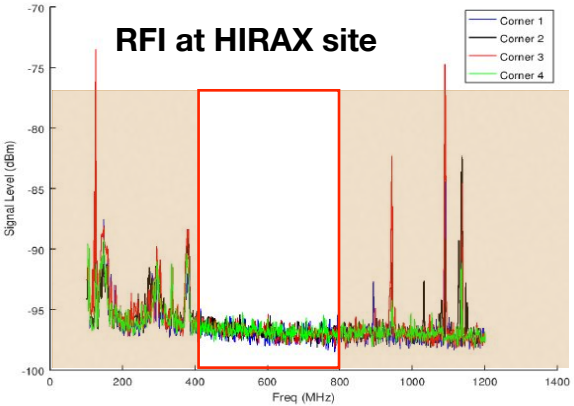
- **H**ydrogen **I**ntensity and **R**eal-time **A**nalysis e**X**periment
- Target: 1024 6m dishes (29,000 m^2) evenly spaced → Redundant baselines
- To be co-located with the SKA in the Karoo (Low RFI, Southern Surveys)
- Dual Polarisation feeds operating at 400–800 MHz (21 cm at z = 0.8–2.5)
- Survey area of 15,000 deg^2 over 4 years (repointed every few months)
- Primary Goals:
  - Measure BAOs across ~4 Gyr, spanning onset of Dark Energy dominated expansion
  - Efficiently map the transient radio sky

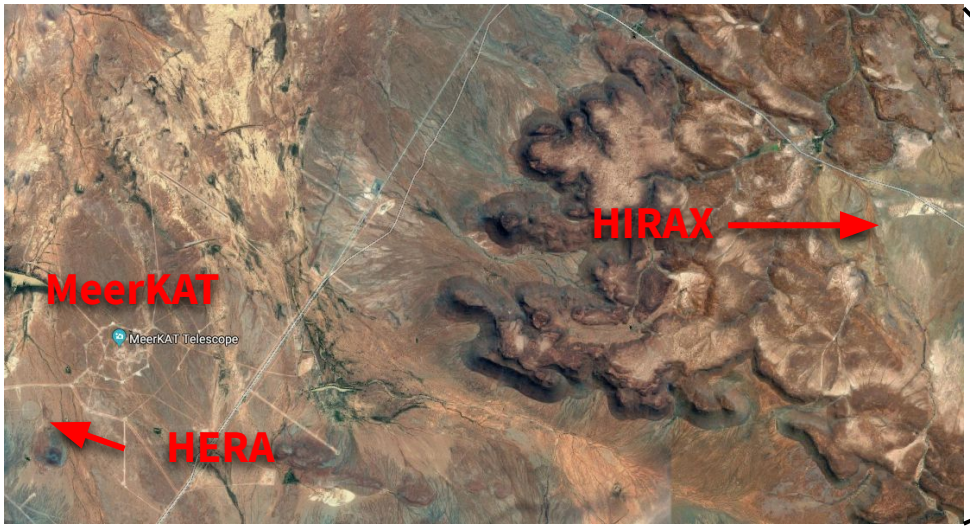
HIRAX Status Updates

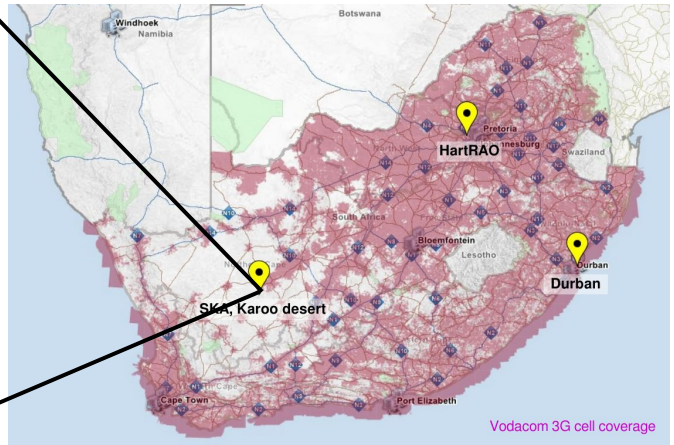
- **2018**
  - Signed site agreement / MoA with SARAO (SKA South Africa)
  - Secured funding for correlator up to 256 dishes through SNSF
- **2019**
  - Secured funding for 256 dishes through South African National Research Foundation (NRF) → Fully funded project budget up to 256 elements
  - Deployed prototype custom f/D=0.25 dishes at HartRAO
  - Aim to start public tender process for dishes
- **2020**
  - Finalise site development plan
  - Start building at Karoo site
  - Actively pursuing funding up to 1024 elements

HIRAX Site

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







Cosmology Forecasts with HIRAX

To determine HIRAX's ability to constrain cosmological parameters we make use of a Fisher matrix formalism

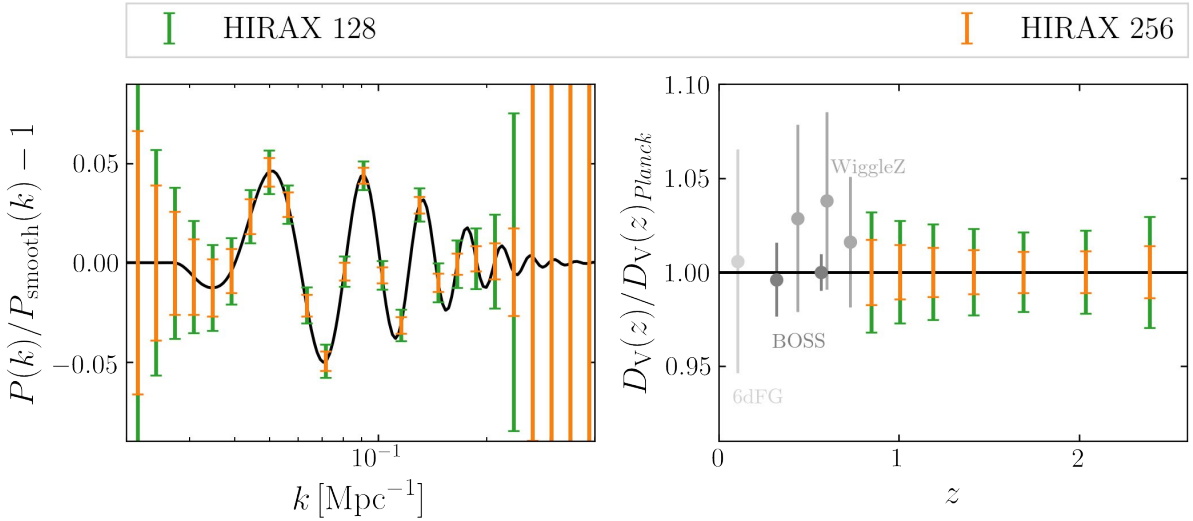
- Based on analysis of Bull et al. 2015
- Currently cosmological constraints assume simplistic treatment of instrument noise and systematics
- Foregrounds are assumed to be subtracted to a residual smooth component of the noise reduced by 10^{-6} in amplitude
- 15,000 $\deg^2$, 4 yr survey, 50% efficiency

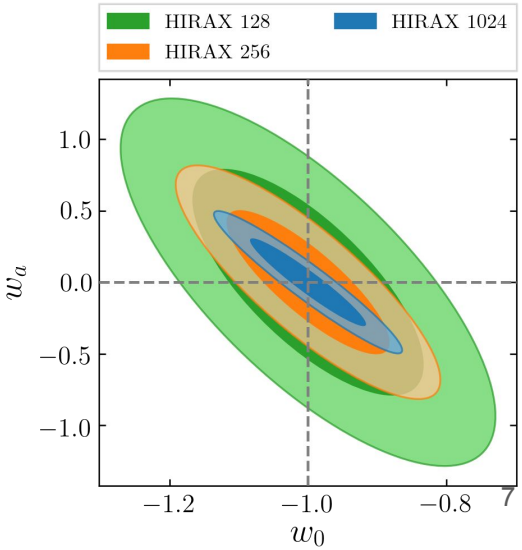
Frequency Range	400–800 MHz
Frequency Resolution	390 kHz, 1024 channels
Dish size	6 m diameter, f/D=0.25
Interferometric layout	32×32 square grid, 7 m spacing
Field of View	15 $\deg^2$–56 $\deg^2$
Resolution	∼5'–10'
Beam Crossing Time	17–32 minutes
System Temperature	50 K

Instrument specification from Newburgh et al 2016

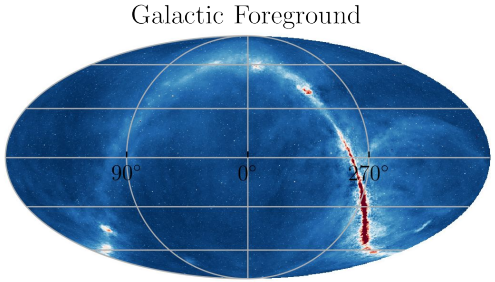
Forecasts: 21cm Cosmology

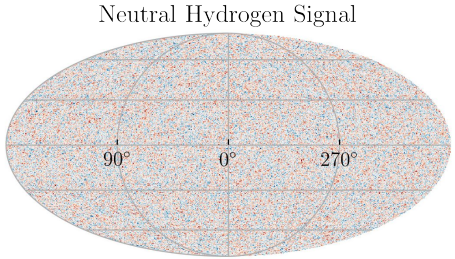
- HIRAX will measure the expansion rate over an as yet under-studied epoch in the universe's history
- **HIRAX 128** aims to provide a detection of the BAO feature in the 21cm power spectrum
  - Additional constraints and boosted detection will come from cross-correlation studies
  - Won't provide significant boost to current dark energy constraints
- **HIRAX 256** has the potential to provide constraints on the dark energy equation of state competitive with other measurements, over a different epoch and with different systematics
- **HIRAX 1024** will provide state-of-the-art constraints and potential for probing non-linear scales

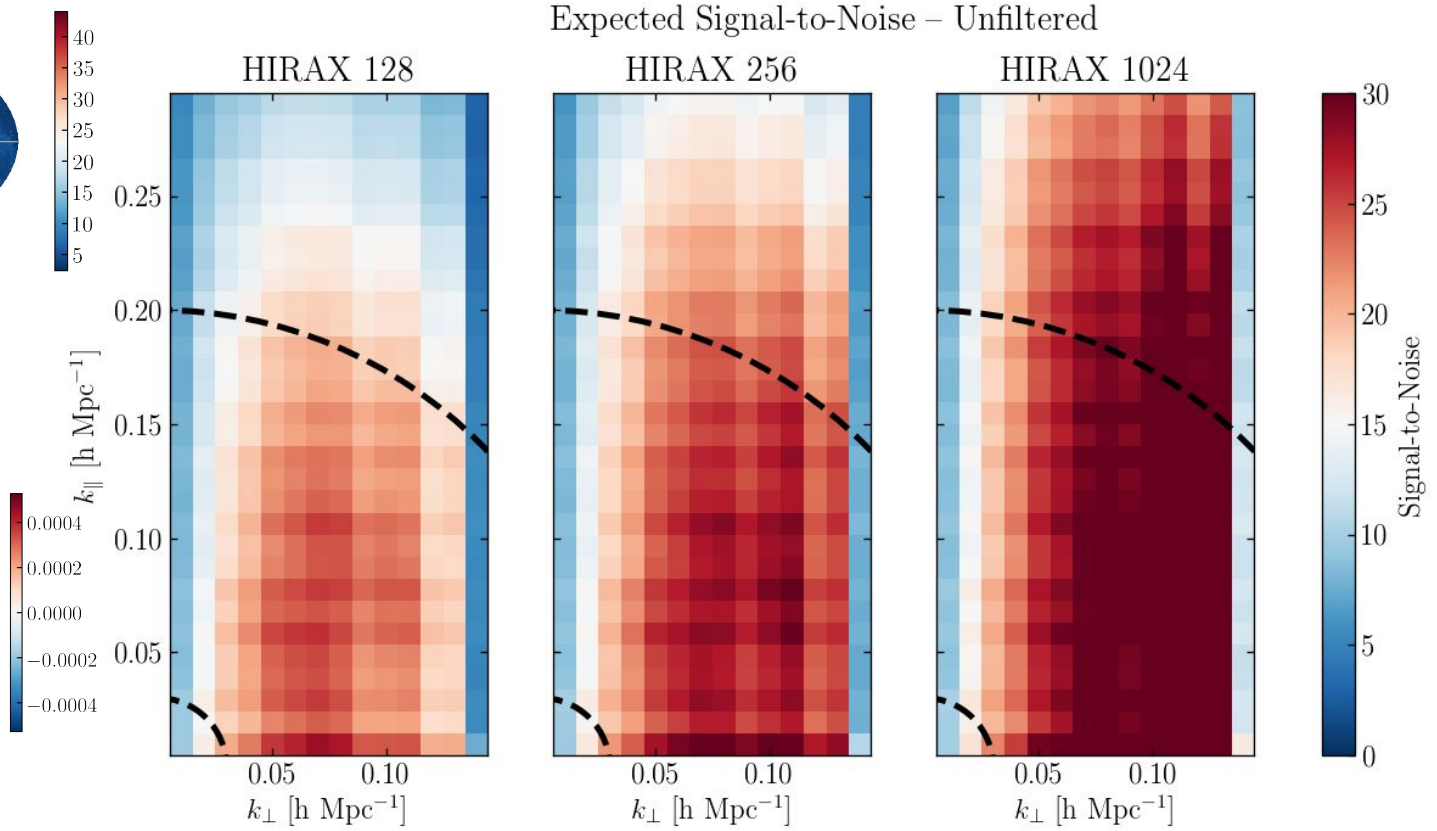




Extending PS Forecasts to Full Sim. - m-mode

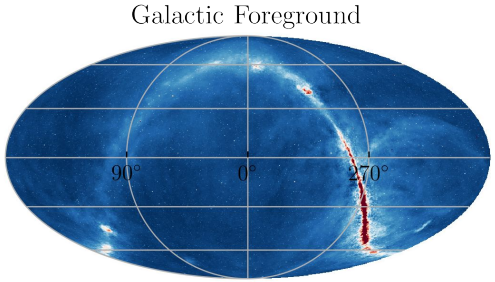


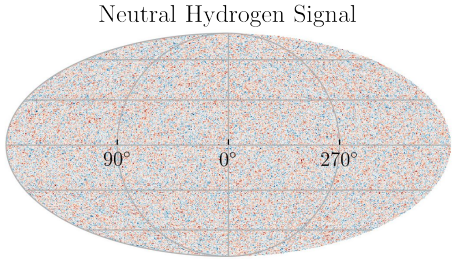


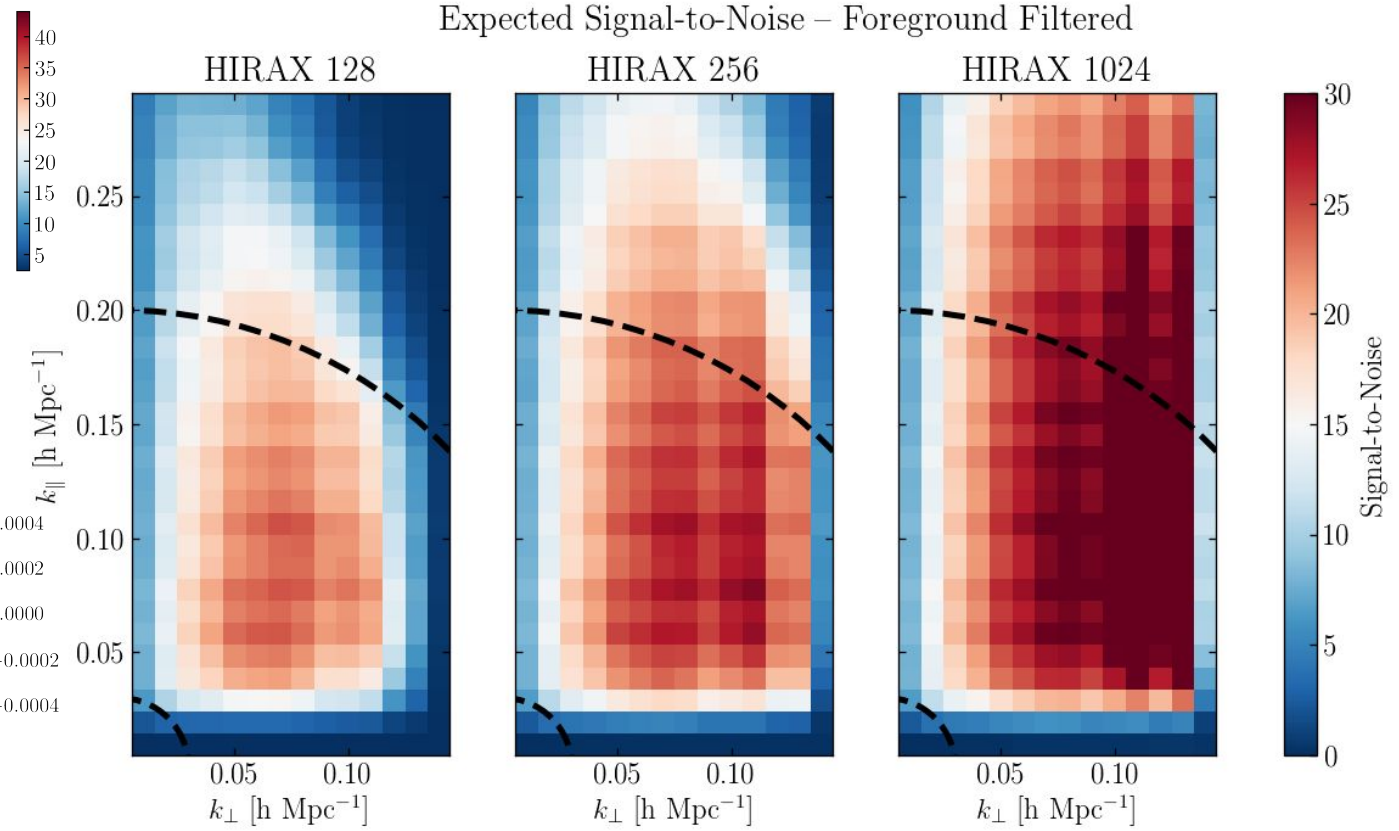


*Core baselines only, 550-650 MHz (¼ full bandwidth), ~6000 deg^2, artificial high resolution cut

Extending PS Forecasts to Full Sim. - m-mode







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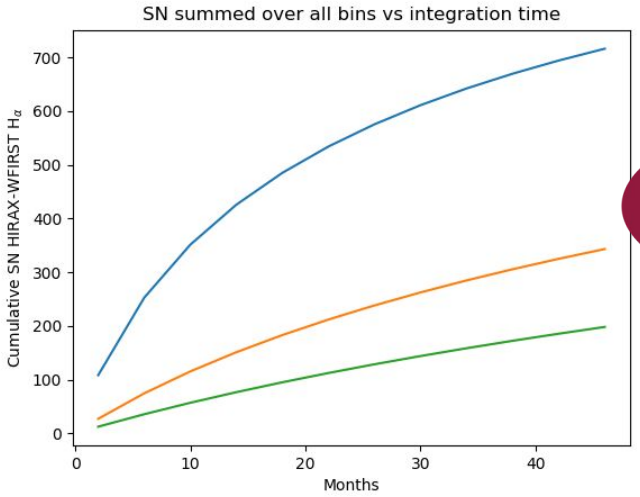
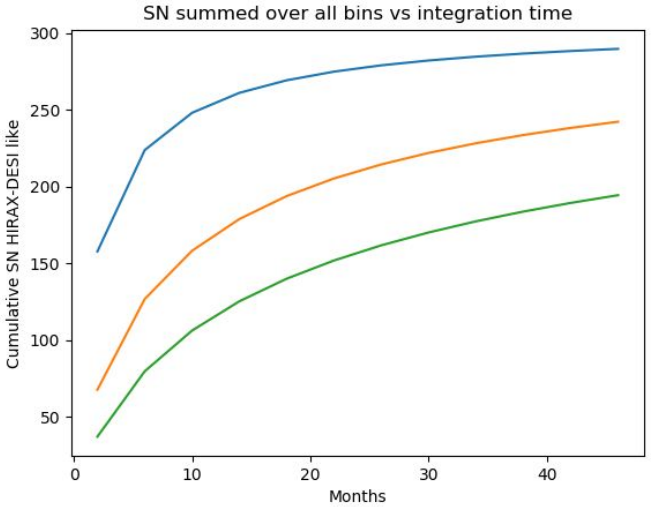
Forecasts: Cross-correlations



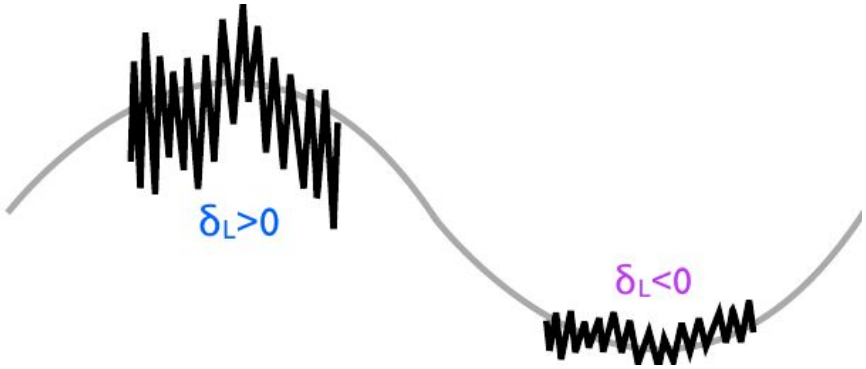


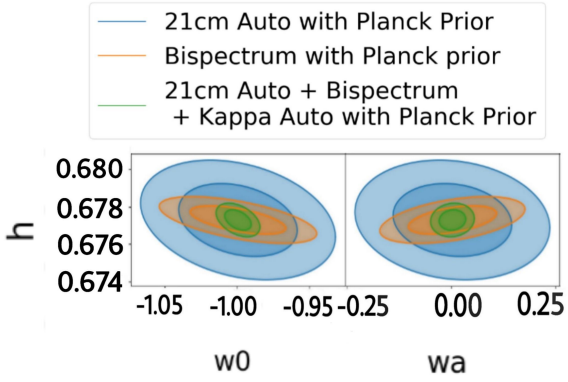
- Anticipated 21cm detection is high assuming naive scaling of noise with integration time
- Cross-correlation studies offer detection opportunities with reduced systematics and different cosmological parameter dependence

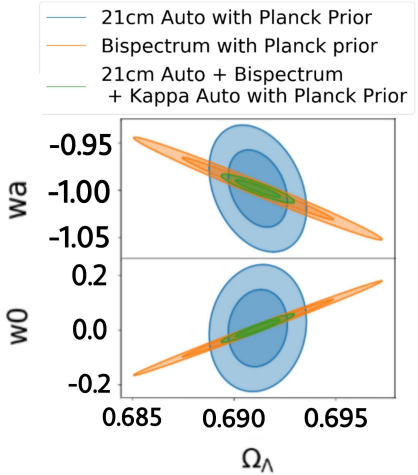
Forecasts: 21cm x CMB Lensing

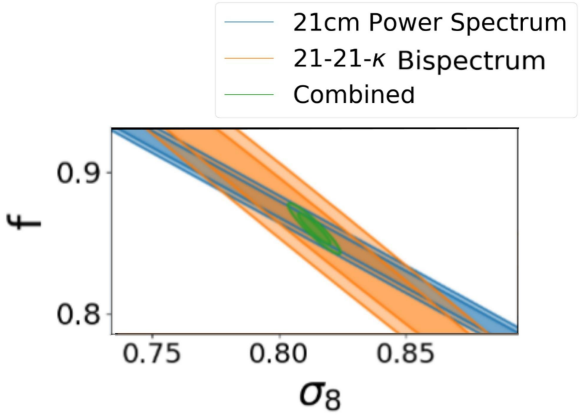
Direct 21 cm x CMB lensing signal vanishes due to 21 cm foreground in long wavelength LoS modes. Need to use higher order correlations

- Use Bispectrum: Low-k lensing modes cross with two high-k 21 cm modes.
- Moodley et al. *in prep*

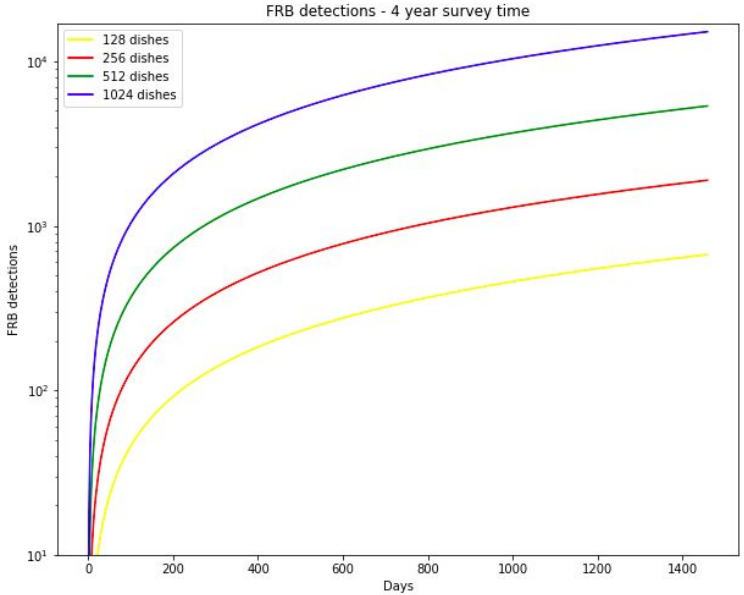


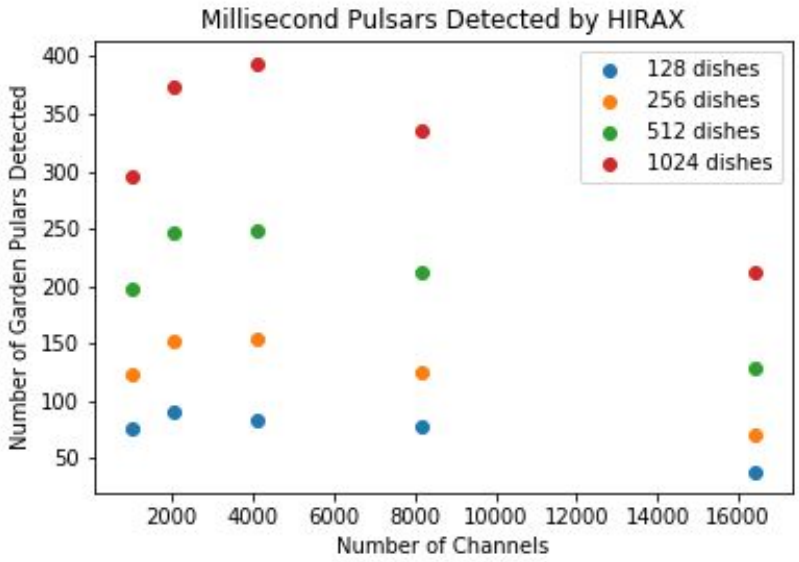






Forecasts: Transient Searches



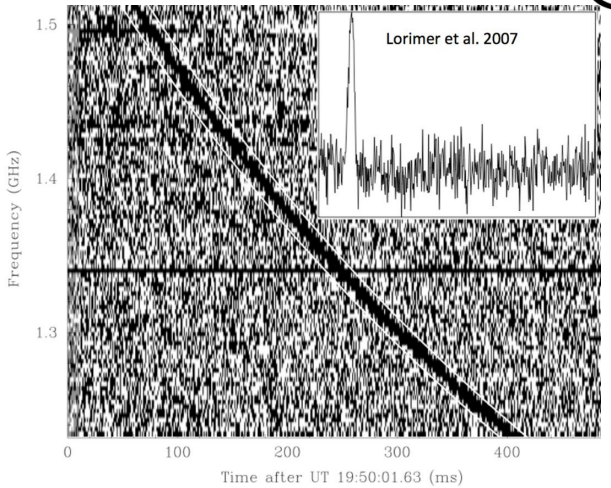


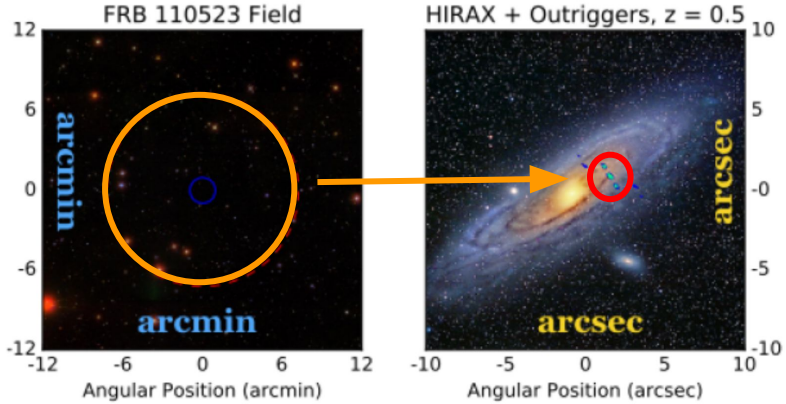
At all scales, HIRAX will provide a sophisticated platform for pulsar and FRB searches, greatly adding to southern sky detection rates.

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

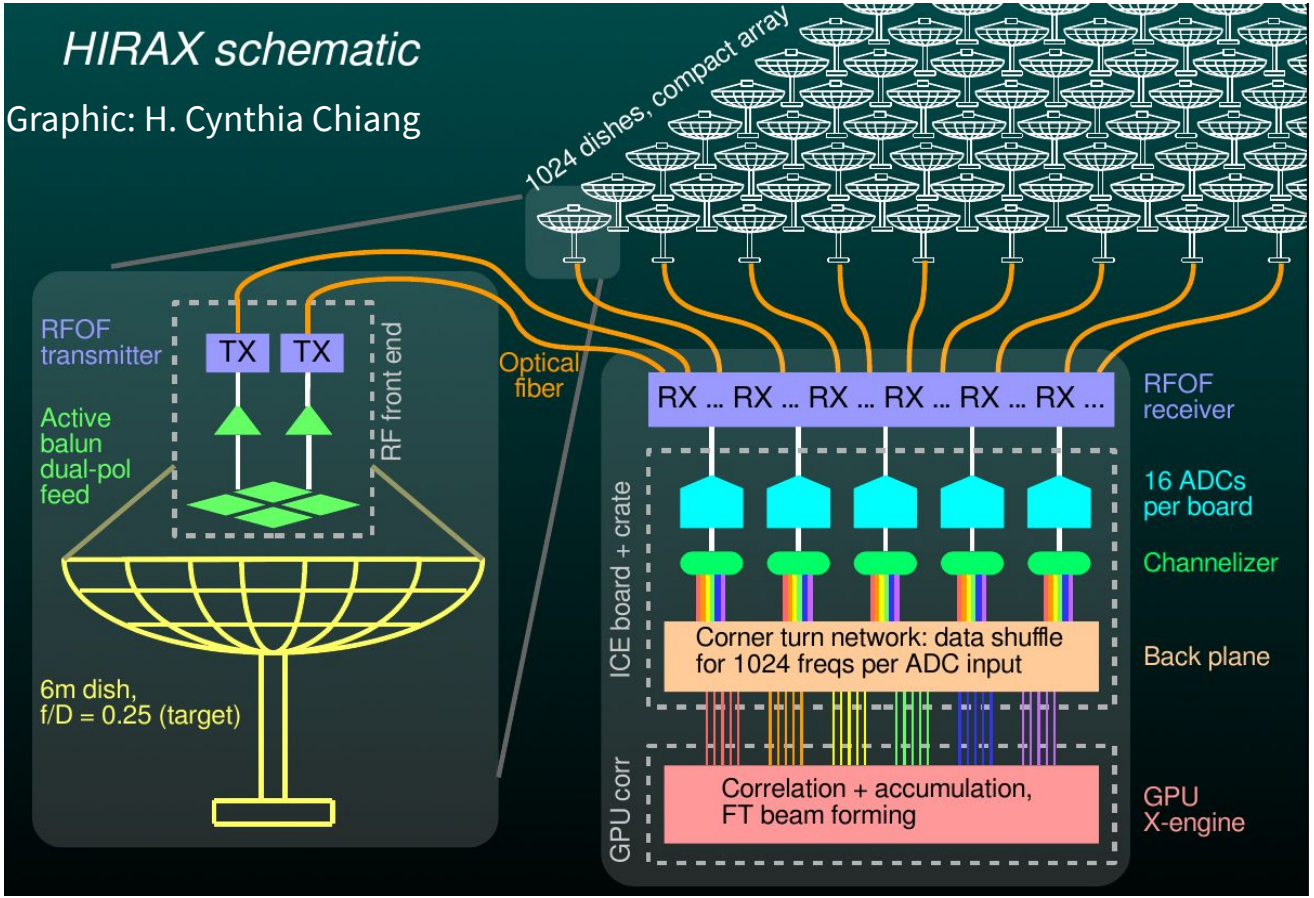
Radio Transients: FRBs

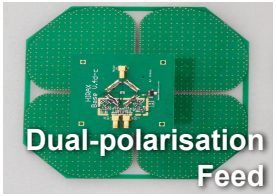
- Flexible beamforming backend for transient searches
- Fast Radio Burst Search and Localization
- Aim to extend HIRAX to potential outrigger stations throughout Southern Africa to aid in localization

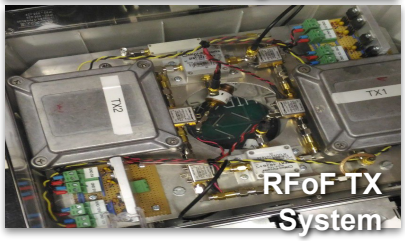




Instrument Overview



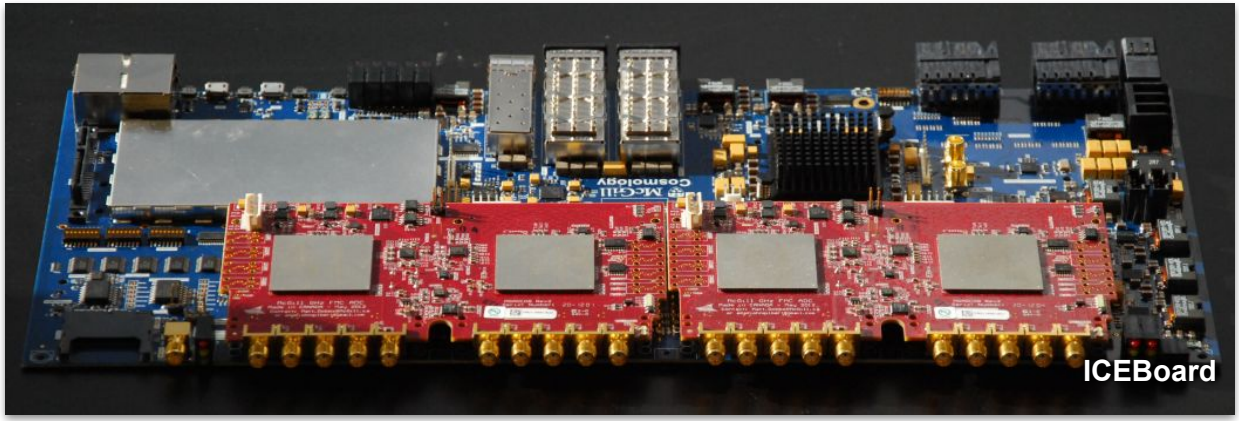




Instrument Overview

Backend:

- ICE based CHIME F-Engine design
- Modernised CHIME-like X-Engine

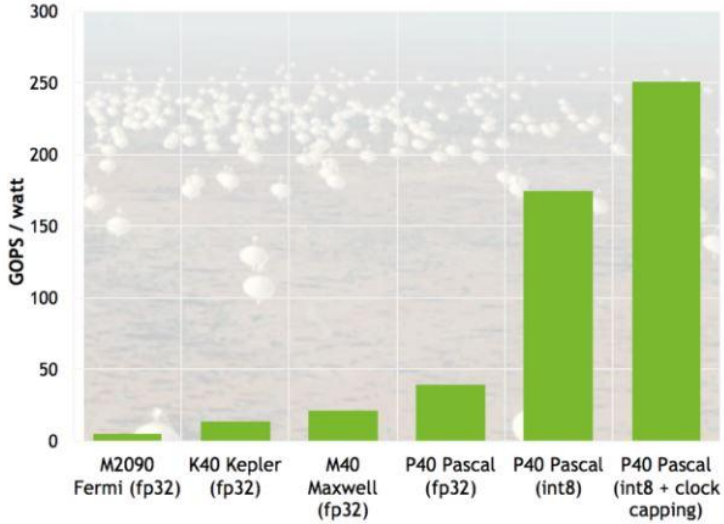


Current work: Correlator

- Using consumer hardware based correlator
  - Developed by ETH-Zurich & U of Toronto
- HIRAX will require ~6.7 Peta OPS for correlation
- ~A few dozen modern GPUs for compute, ends up being I/O limited

PCIe v4.0 will double currently available bandwidth to consumer GPUs.

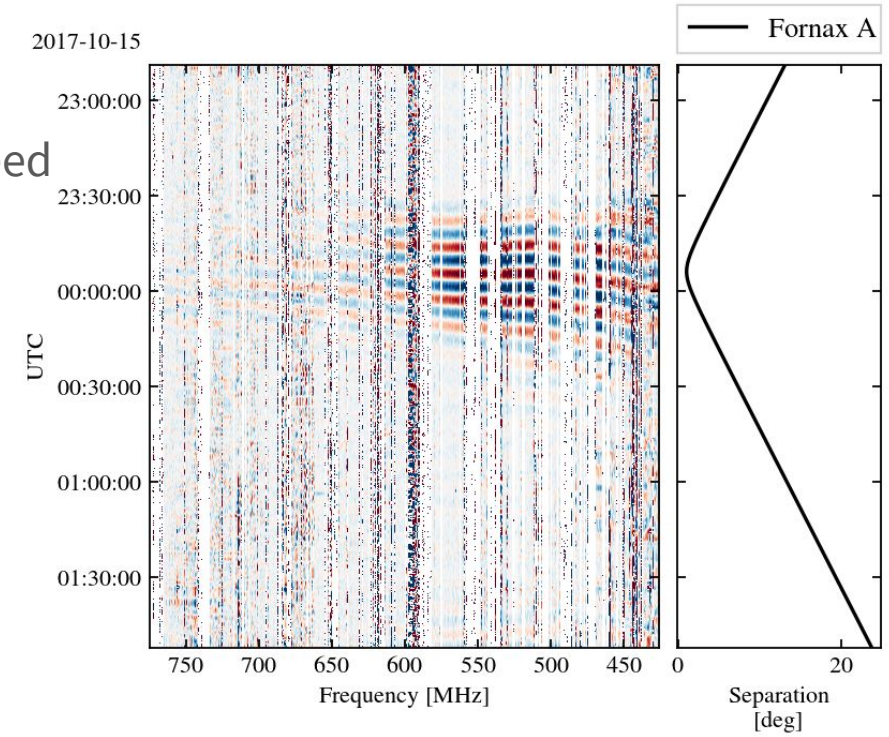
- Nominal solution: 2 ICEBoards (16 dishes) per node
- With PCIe v4.0, could potentially achieve 3-4 ICEBoards (24-32 dishes) per node
  - Potentially: ~ 32 node system for HIRAX-1024 if possible



Modern GPU advances, specifically in mixed-precision operations greatly help with this.

Current Work: Hardware Prototyping at HartRAO

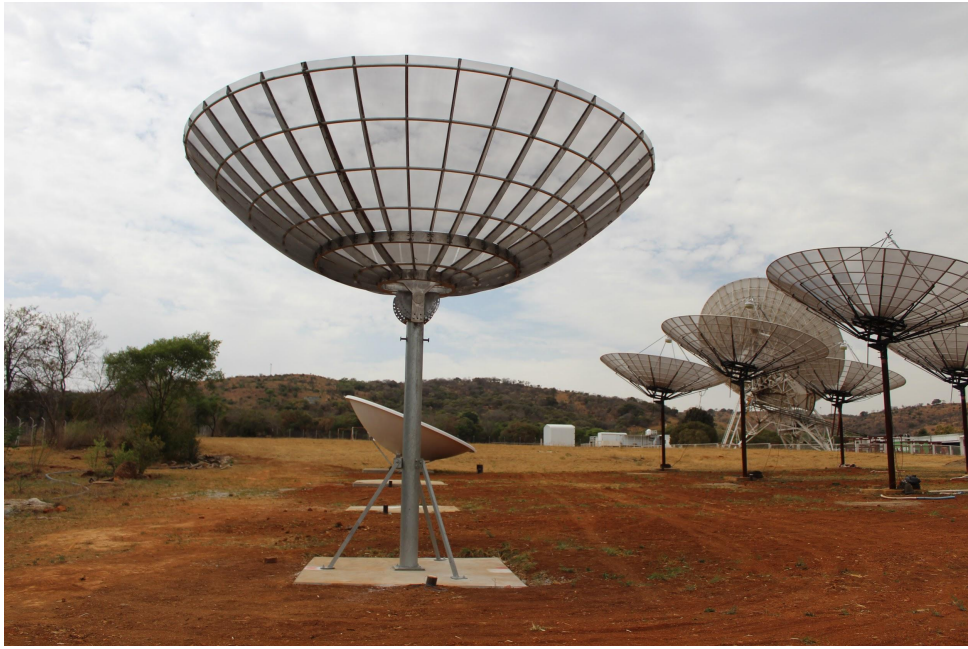
- Fully functional scaled-down digital backend with GPU correlator at prototype site
- Informing hardware design and analysis
- Instrumented with multiple versions of feed and RF hardware



Current Work: Dish Prototyping

Custom, locally produced prototype f/D=0.25 dishes have been developed and deployed at HartRAO

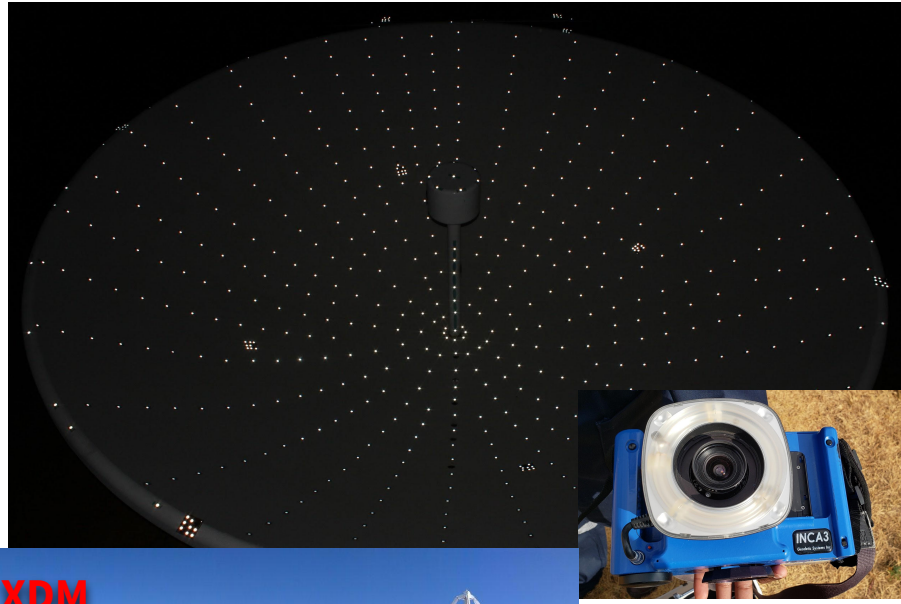
- Fiberglass dish: MMS
- Aluminium dish: Rebcon



Current Work: Dish Prototyping

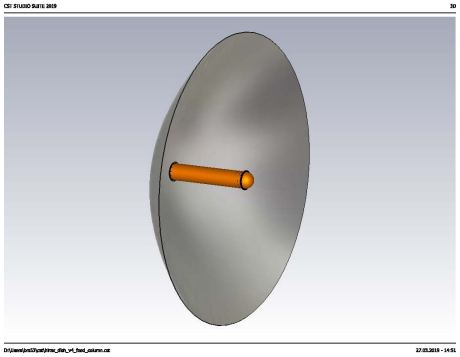
Testing dish verification procedures

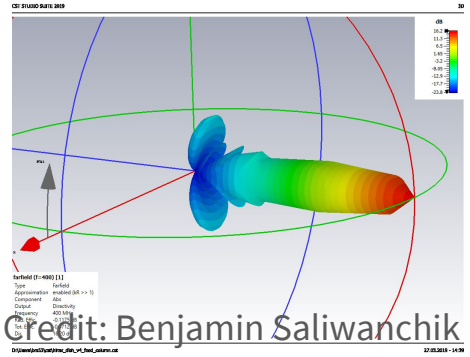
- Photogrammetry
  - Propagating photogrammetric measurements to far-field beams
- Holography
  - Exploring using the nearby 15m XDM telescope for holographic beam measurements



Current Work: Beam Systematics

- Exploring drone beam calibration
  - Testing various kinds of drones
  - Will start testing at HartRAO site soon
  - Need to determine feasibility at Karoo site
- Developing EM simulated beams
  - Comparing with beam measurements
  - Testing effects component level positioning
  - Incorporating periodic boundary conditions to test for array effects

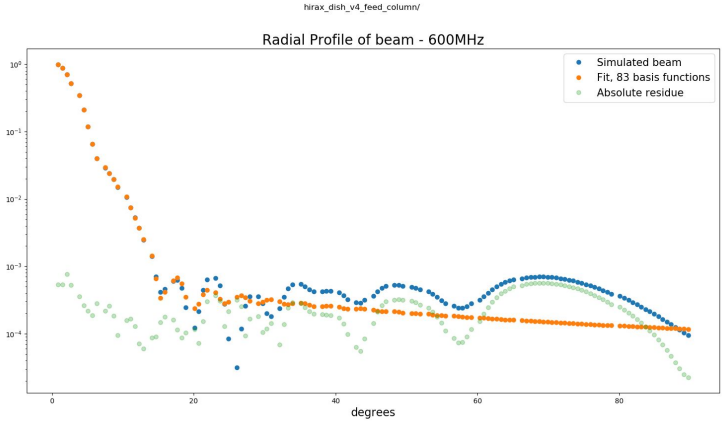


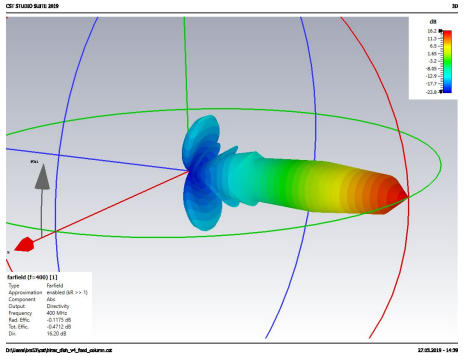


Credit: Benjamin Saliwanchik

Current Work: Systematics Analysis

- Incorporating systematics into analysis pipeline
  - Propagate to power spectrum constraints
  - Refine requirements for dish tender
  - Experimenting with beam decompositions to efficiently capture beam systematics
- Exploring array layout configuration effects on sensitivity, calibration and redundancy
- Testing dish validation procedures and comparing results to simulations and adding to simulations
- Simulating analysis pipeline
  - Including realistic surveys
  - Calibration with CorrCal
  - Flagging etc.





Summary

- HIRAX aims to make competitive Cosmological constraints and act as a sophisticated transient detection platform
- Current focus is in dish prototyping and in understanding systematic effects using prototypes. Feeding this into dish specification
  - Testing dish validation/verification procedures at HartRAO
- HIRAX is funded up to 256 dishes and will begin construction at the Karoo site in 2020

Thank you