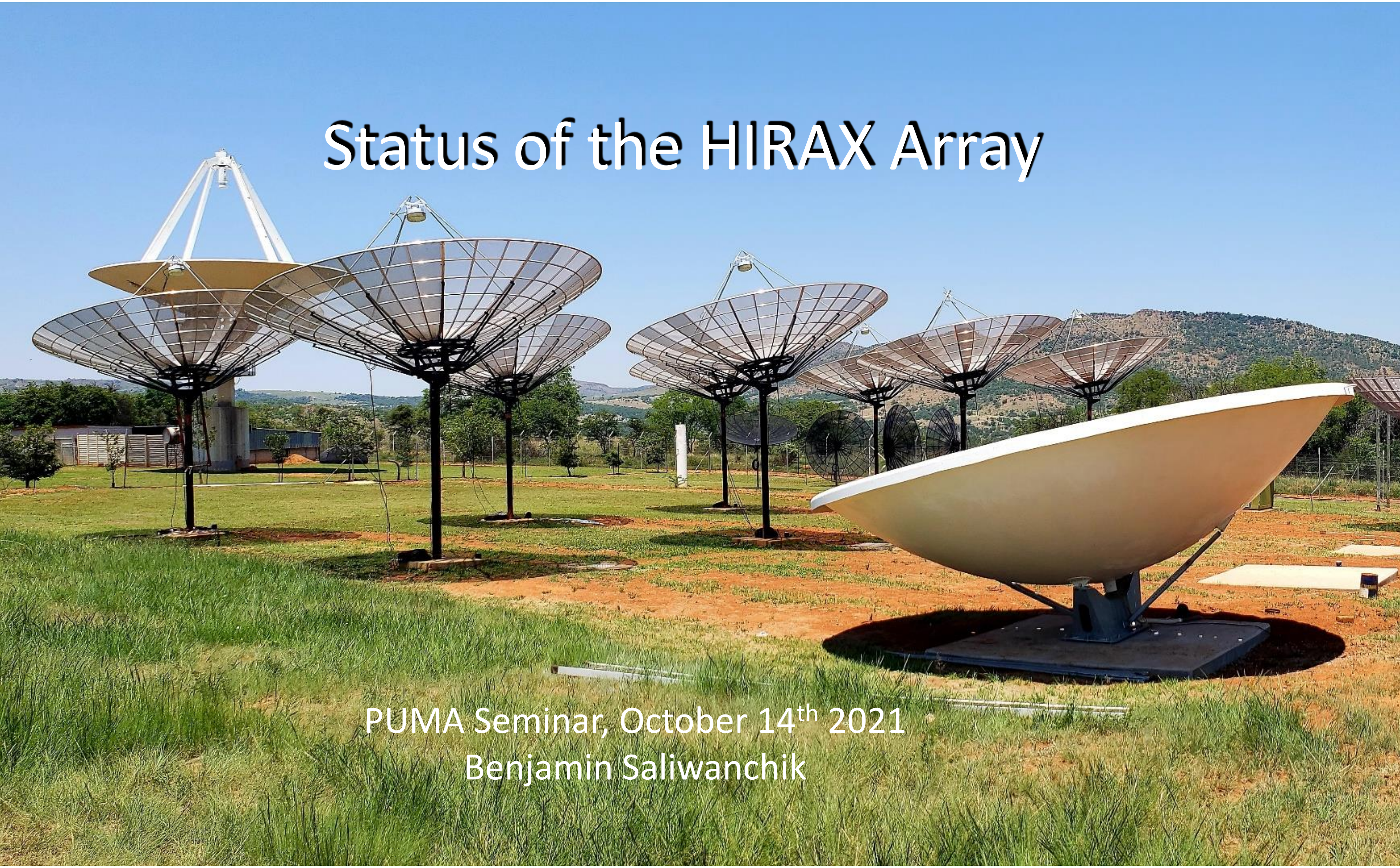
Status of the HIRAX Array



PUMA Seminar, October 14th 2021

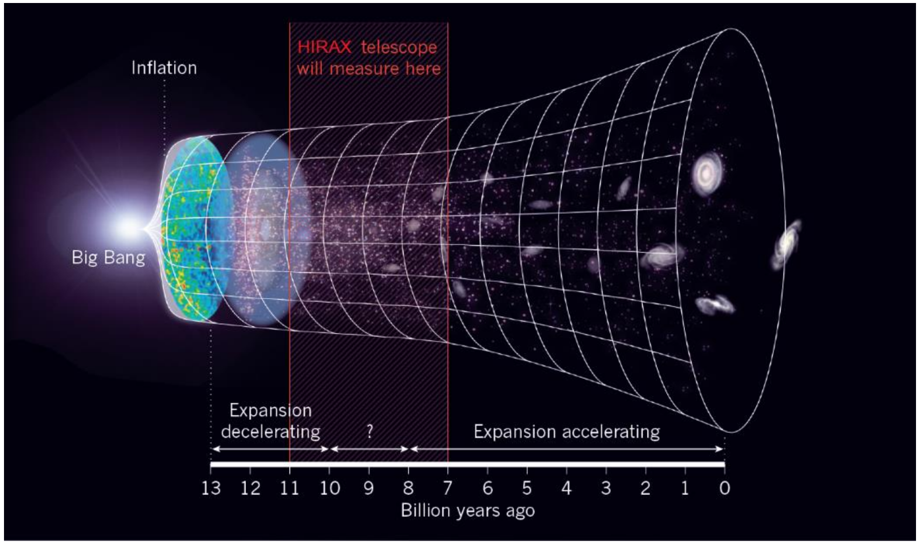
Benjamin Saliwanchik

Outline

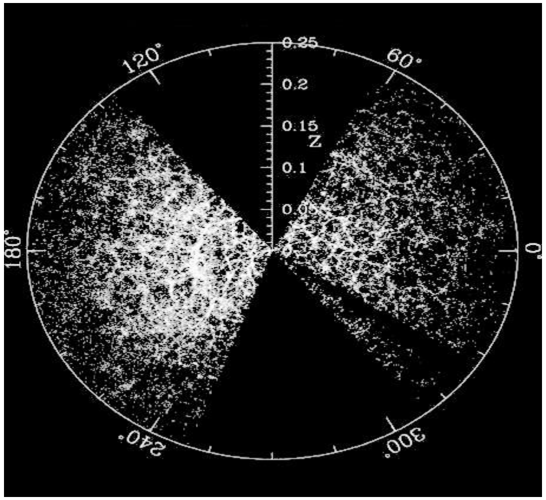
- HIRAX design
- Current status, ongoing work
- Science forecasts / secondary science

21 cm Line as Cosmological Probe

- Can use 21 cm hyperfine transition in HI to study LSS and growth of structure in universe
- Dark energy drives expansion of universe in late times: can measure with standard ruler (BAO)
- Signal known to exist, but faint: O(0.1 mK), while galactic foreground is O(10^5 K)
- Achieving sensitivity of 1-2μJy necessary, requires large interferometric array.



0.8 < z < 2.5



HIRAX: Who are we? Where are we?

HIRAX

University of KwaZulu-Natal
Inyuvesi Yakwazulu-Natali

BIUST
Botswana International University of Science & Technology

APC, CNRS, France

The University of British Columbia

Rhodes University
Where leaders learn

EPFL

ETH zürich

CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut canadien d'astrophysique théorique

Université de Genève

University of Oxford

NRF National Research Foundation
SARAO South African Radio Astronomy Observatory

University of Toronto

IUCAA

West Virginia University

Wisconsin
University of Wisconsin–Madison

University of the Western Cape

University of Cape Town
Iyunivesithi yaseKapa • Universiteit van Kaapstad

PI Perimeter Institute for Theoretical Physics

DUT Durban University of Technology

AIMS

McGill University

Carnegie Mellon University
Pittsburgh Pennsylvania 1900

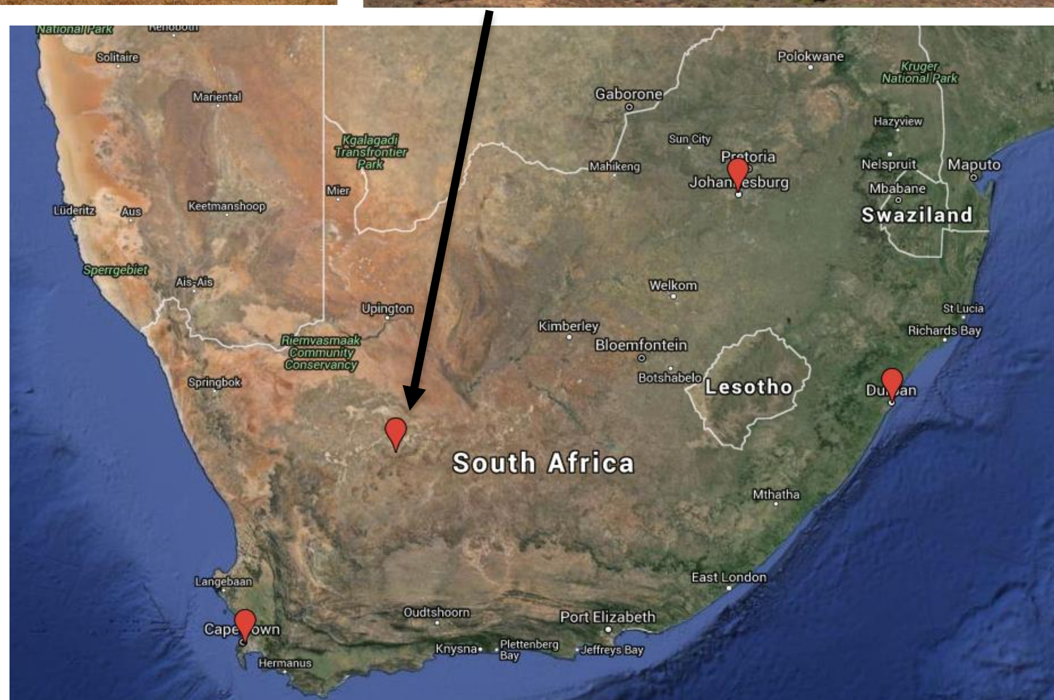
Universiteit Stellenbosch University

JPL
Jet Propulsion Laboratory
California Institute of Technology

Yale

Brookhaven National Laboratory

HIRAX: Who are we? Where are we?



HIRAX Design and Goals

Instrument:

- Initial array is 256 close-packed 6-m dishes, build out to 1024 over ~3 yrs
- Operating frequency: 400 – 800 MHz, equivalent redshift = 0.8 – 2.5
- Survey area of 15,000 deg^2. Daily sensitivity of ~12μJy
- Manually repoint every 180 days, 4 years for full survey (~1μJy)

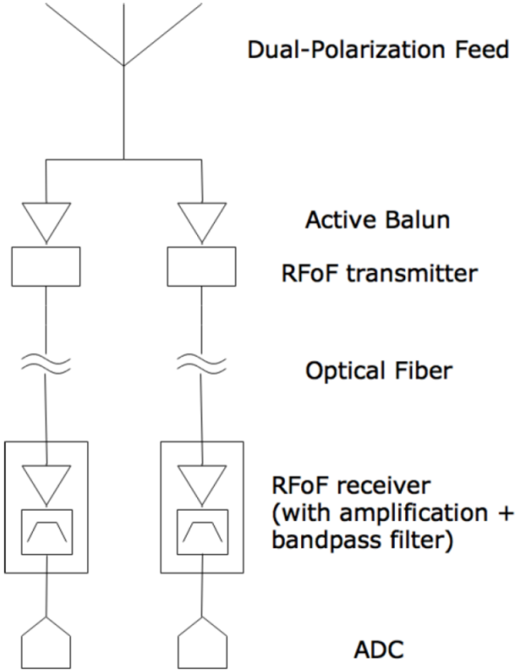
Science goals:

- Measure baryon acoustic oscillations with HI intensity mapping to characterize dark energy
- Radio transient searches
- Pulsar searches
- Neutral hydrogen absorbers
- Diffuse polarization of the Galaxy

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

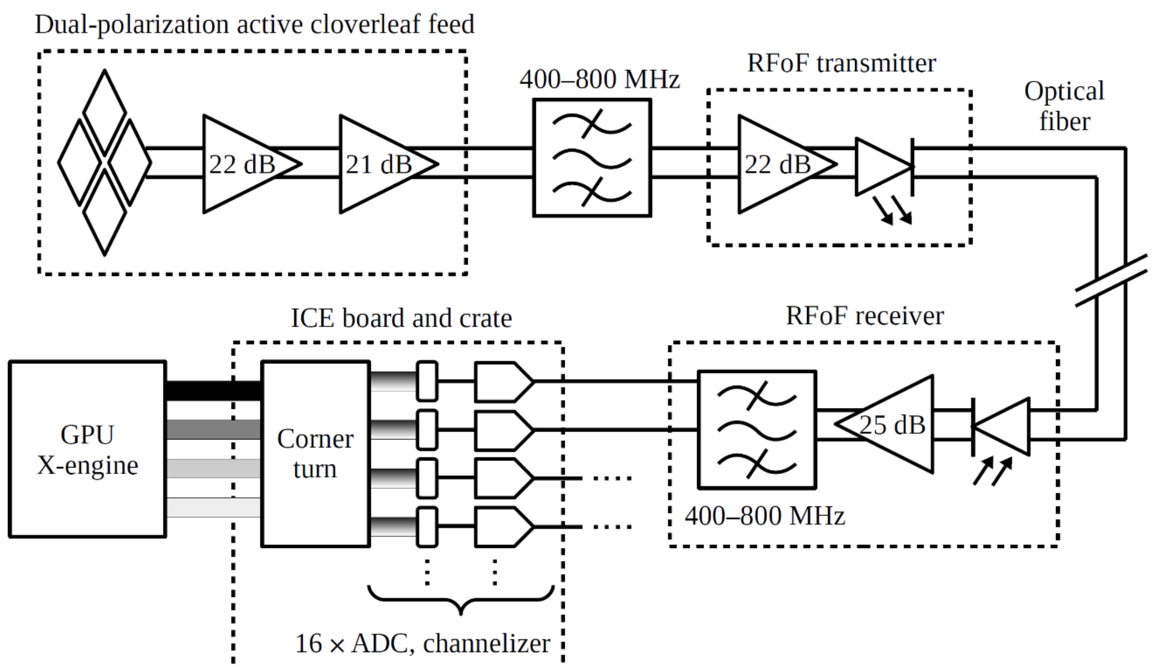
Feed and Signal Chain

- Feeds are dual polarization cloverleaf antenna based on CHIME feed
- Low loss (< 0.15dB) and small reflectivity (< -0.15dB) across wide band
- Consists of FR-4 dialectric (PCB) with metalized layer, PCB balun
- Ring choke circularizes beam, decreases crosstalk and ground spillover
- Fiber used to carry signal from dishes to correlator (~250m)
- ~90dB total gain, 65dB before RFoF Tx
- RFoF Tx relatively noisy, requiring high amplification before so that system noise is dominated by initial LNA
- RFoF Rx also contains band defining 400-800 MHz filter



Backend Electronics

- FX system: FPGA ICE board channelizer, GPU correlator.
- F-engine digitizes at 8-bit precision, channelizes to 1024 frequency channels. 16 sky channels per board, 128 boards for full array
- Custom backplate for corner-turn operation (Transform from input of all freq. channels on single dish to bundles of single freq. from all dishes)
- X-engine correlates all sky inputs for 1024 frequency channels at 4+4-bit precision



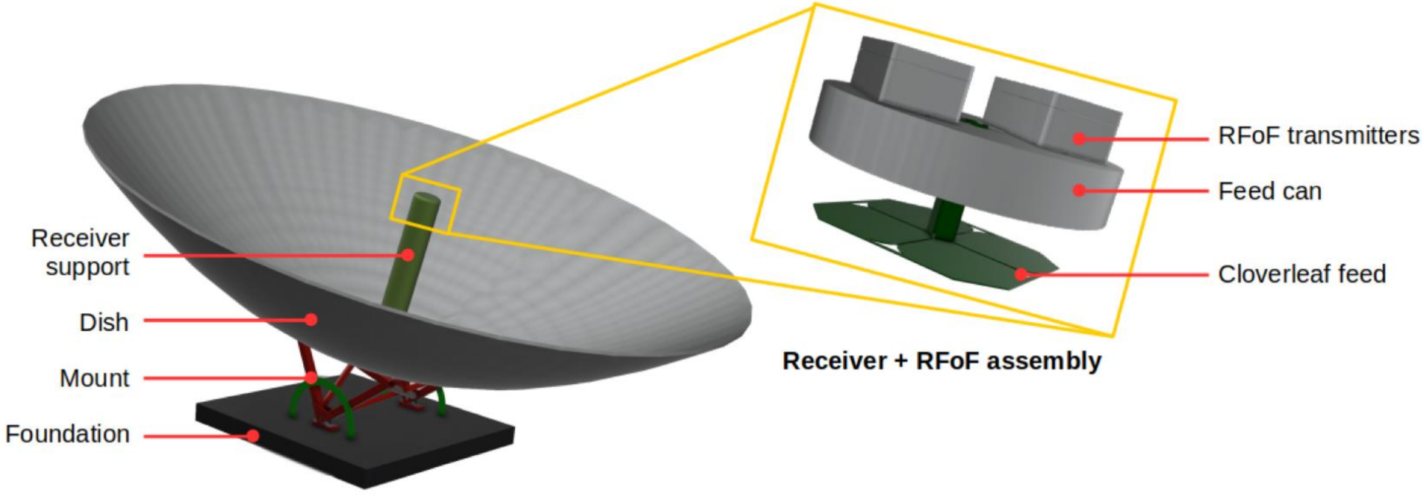
Backend Electronics

- Correlator for HIRAX-256 consists of 8 nodes, each correlating 128 channels (50 MHz bandwidth)
- Produces raw visibilities with ~10s integration time
- Additional outputs: formed beams for FRB, HI absorber, and pulsar searches
- Processes 1.6 Tbps in a single rack—8x bandwidth of CHIME X-engine due to increased I/O performance of PCIe 4.0 for GPU and network card interconnects
- Baseline stacking, HI absorber data products, and real-time transient search all performed on site, reduced data transmitted off site

Parameters	**Value**
Motherboard	GIGABYTE G482-Z52
Processor	2 $\times$ AMD EPYC™ 7452, 32 cores each
RAM	1TB
GPU	2 $\times$ NVIDIA A40, PCIe 4.0
F-Engine Network	4 $\times$ SILICOM PE31640G2QI71-QX4 - 2 $\times$ 40 Gbps
Outgoing Data Network	2$\times$25 Gbps

Telescope Mechanical Assembly

- Low telescope mount improves stability, improves ease of access to feed, reduces cost, still allows necessary +/-30 deg elevation range from zenith
- Simulations say fiberglass receiver column extremely robust: safety factor of 100 and feed displacement <1mm relative to dish under SA record wind speeds
- Easier to position feed, adjust focal point, reduces polarized scattering and beam asymmetry vs feed leg configuration



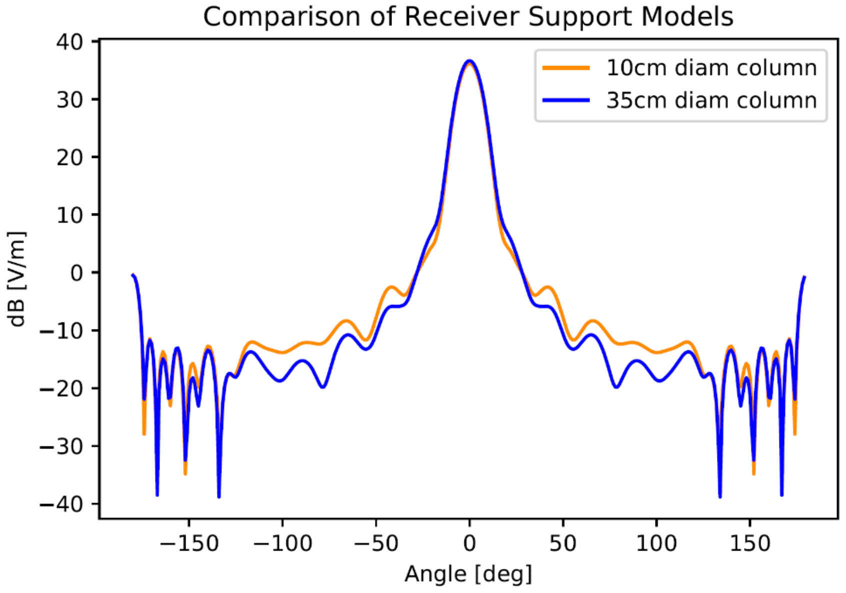
Telescope mechanical assembly

Receiver + RFoF assembly

CST EM Simulations

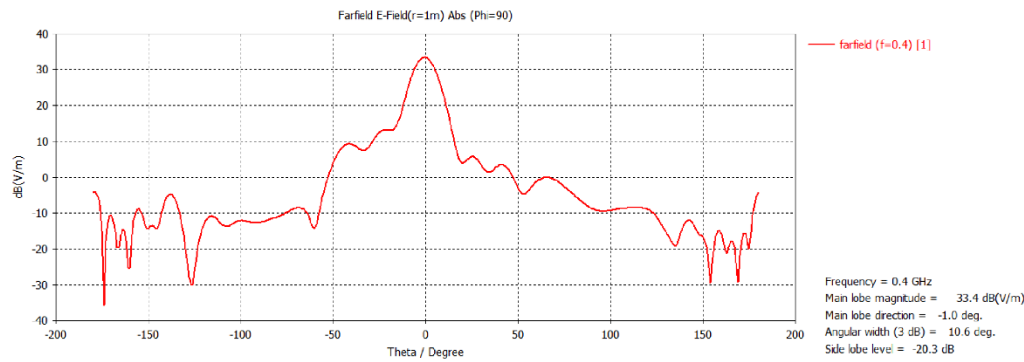
- Different configurations of the receiver support mechanism were simulated, including multiple feed legs, and a central feed column with varying diameter.
- A fiberglass feed column was found to be optimal for RF as well as mechanical criteria.
- Larger diameter feed columns generally have lower loss (less material in forward beam path if diam > feed), sidelobe amp varies with freq but generally lower.

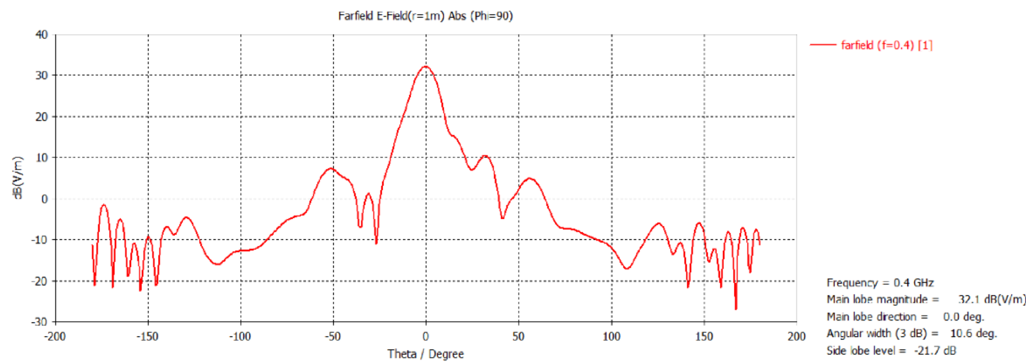
400 MHz

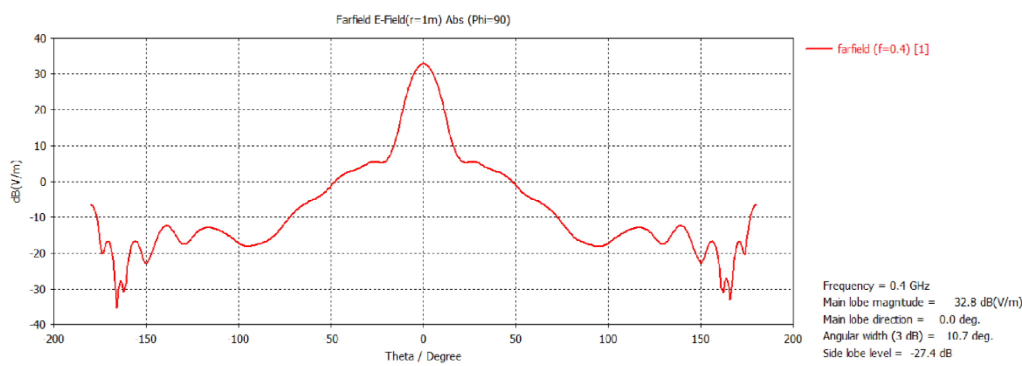


CST EM Simulations

- Feed power cabling was found to be a significant source of potential asymmetry in the beam, even for small diam wire.
- Data is on RFoF, not relevant
- Plots show beams at 400MHz with 15 AWG wire (1.5mm diam) running [top] from feed to dish edge, [middle] from feed to dish vertex 18cm offset from boresight (at column diam), and [bottom] along feed boresight to dish vertex
- Feed column provides natural enclosure for feed and cabling.

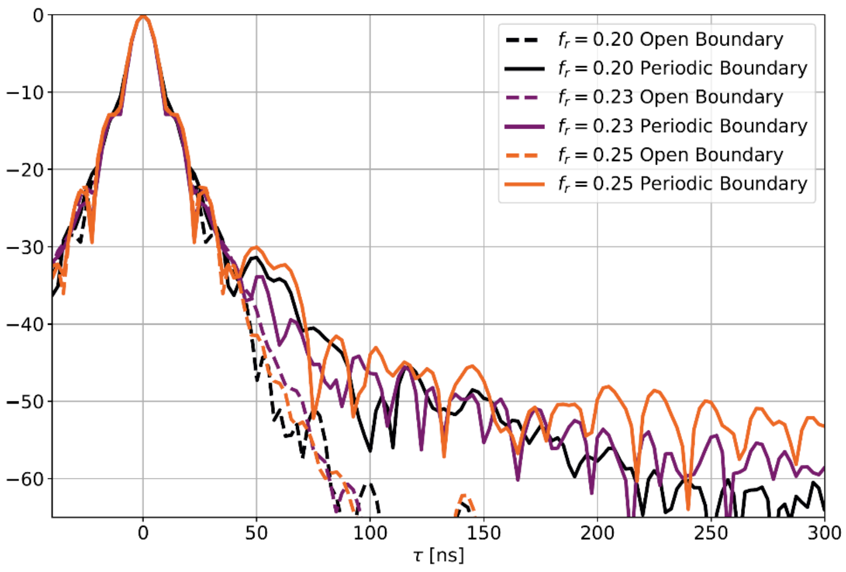






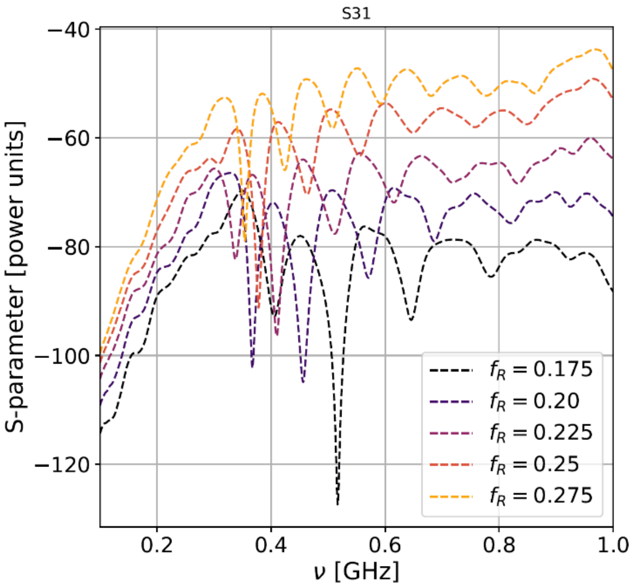
CST EM Simulations

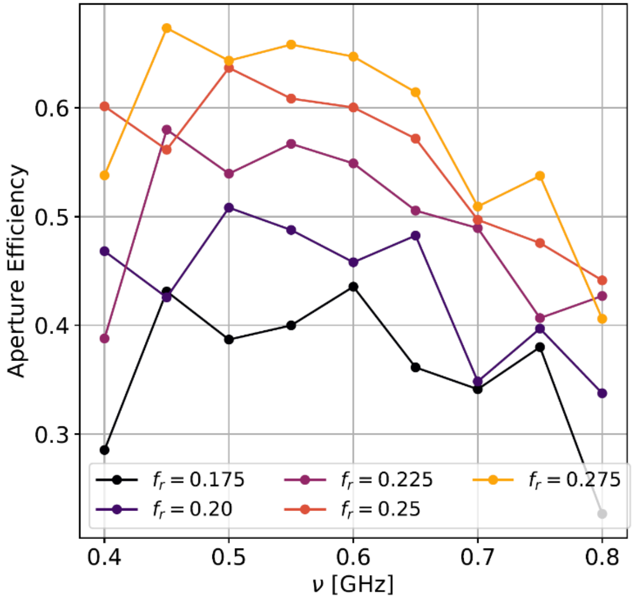
- Also examined dish f-number.
- The instrument delay kernel shows how foregrounds leak from small Fourier modes into large, cosmologically interesting, modes. Want to minimize width.
- Dashed lines show shallower dishes better for single dish, because reduces internal scattering.
- However, in array configuration deeper is better, because it reduces intra-dish scatter.



CST EM Simulations

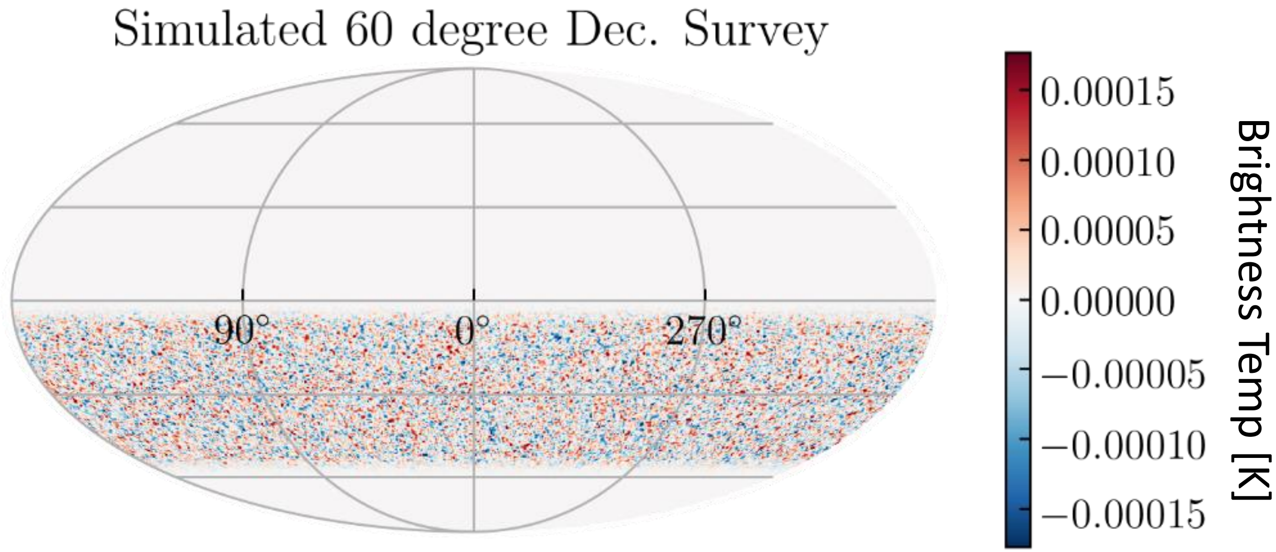
- Crosstalk amplitude (S31) reduced in array with deeper dishes, but aperture efficiency also reduced.
- Geometries below f/D = 0.225 are also increasingly difficult to mechanically support
- We selected f/D = 0.23 as the optimal focal ratio, which reduces S31 by ~10dB relative to the prior 0.25 design, while only reducing efficiency by ~5%.





Cosmology Simulations

- Devin Crichton (UKZN) developing cosmo sim pipeline for HIRAX
- Produces synthetic visibilities by mock observing simulated skies, uses m-mode analysis of Shaw et al. (https://arxiv.org/abs/1401.2095)
- Exploring the influence of survey design and systematics on our power spectrum sensitivity, and working towards an understanding how this will affect our ability to remove foregrounds.
- Using importing CST beams from simulated dishes for end-to-end, instrument to cosmology modeling



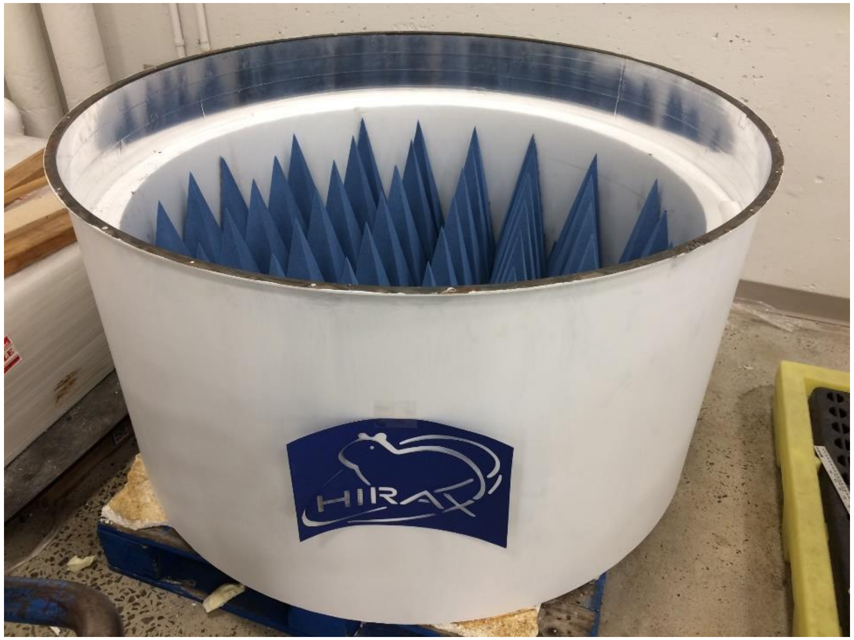
Derived Specifications

- Using cosmology simulations observed with varying CST beams, we set specifications for the necessary accuracy of instrument parameters to achieve desired foreground removal and cosmo param accuracy.
- We find symmetry of telescope mechanical assembly very important, and repeatability across array.
- Specifications highly significant for setting necessary manufacturing accuracy, and assessing cost of construction and assembly
- E.g., will need to use small number of dish molds, to reduce variations in dishes.

Element	Specification	Notes
Axial symmetry of receiver support	± 1 mm	
Receiver support RF attenuation	< 0.5 dB	
Deviation of power cabling from boresight	± 2 mm	
Rigidity of receiver support	± 0.5 mm	In x,y, and z dimensions
Positioning of receiver relative to focal point	± 0.5 mm	In x,y, and z dimensions
Orientation of receiver relative to boresight	± 2.5 arcmin ± 1.5 arcmin	polar angle azimuthal angle
Dish diameter	± 3 mm ± 1 mm	Accuracy Precision
Dish shape accuracy	± 3 mm	Deviation from ideal paraboloid
Dish electrical connectivity	< 5 mm	Maximum dimension of gaps
Dish surface conductivity	$> 1 \times 10^6$ S/m	

Feed Noise Temperature Measurements

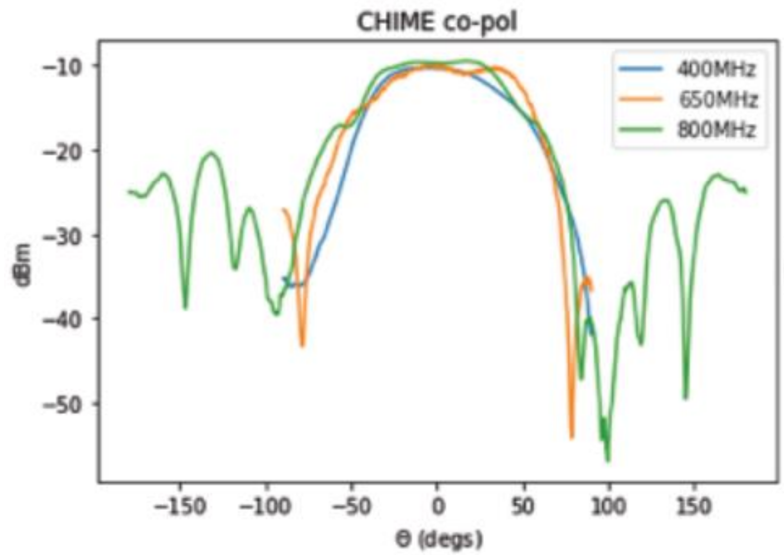
- Assessing accuracy of feed parameters also crucial
- Emily Kuhn (Yale) designed cryogenic RF-chamber for making y-factor noise temp measurements of feed: differential measurement between hot (300K) and cold (77K) loads
- Optimized cryostat and absorber dimensions, taking into account warm and cryogenic operation.
- Developed fabrication methods for 1.6 m diameter, 500+ L liquid cryostat
- Preliminary measurements indicate feeds within spec

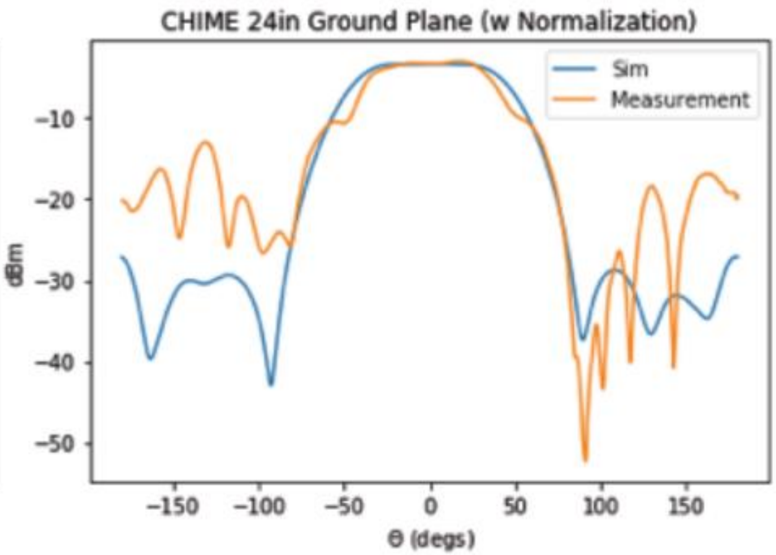


Feed Simulations and Measurements

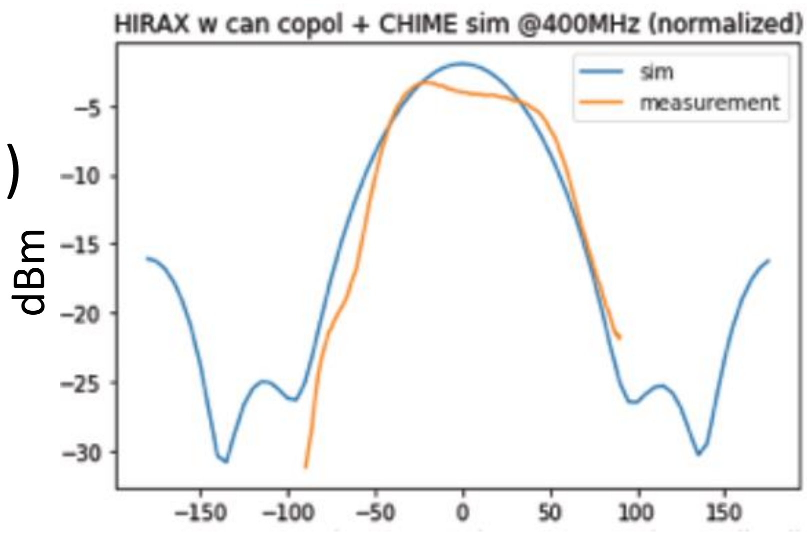
- Performed beam measurements at JPL MESA facility, and North Carolina State University
- Measured CHIME (passive), HIRAX (amplified), and biconical (calibration) antennas
- Verified HIRAX/CHIME beam width and gain. Learned about interesting coupling of biconical antanna to calibration drone! (And how to fix.)

CHIME Feed Measurements at JPL



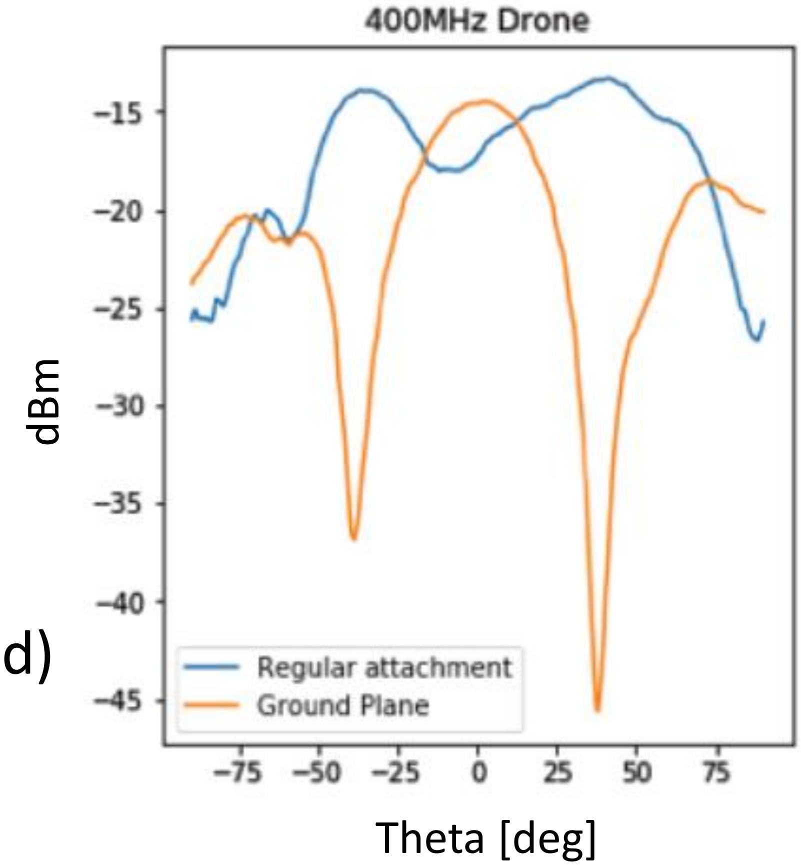


(Un-normalized)



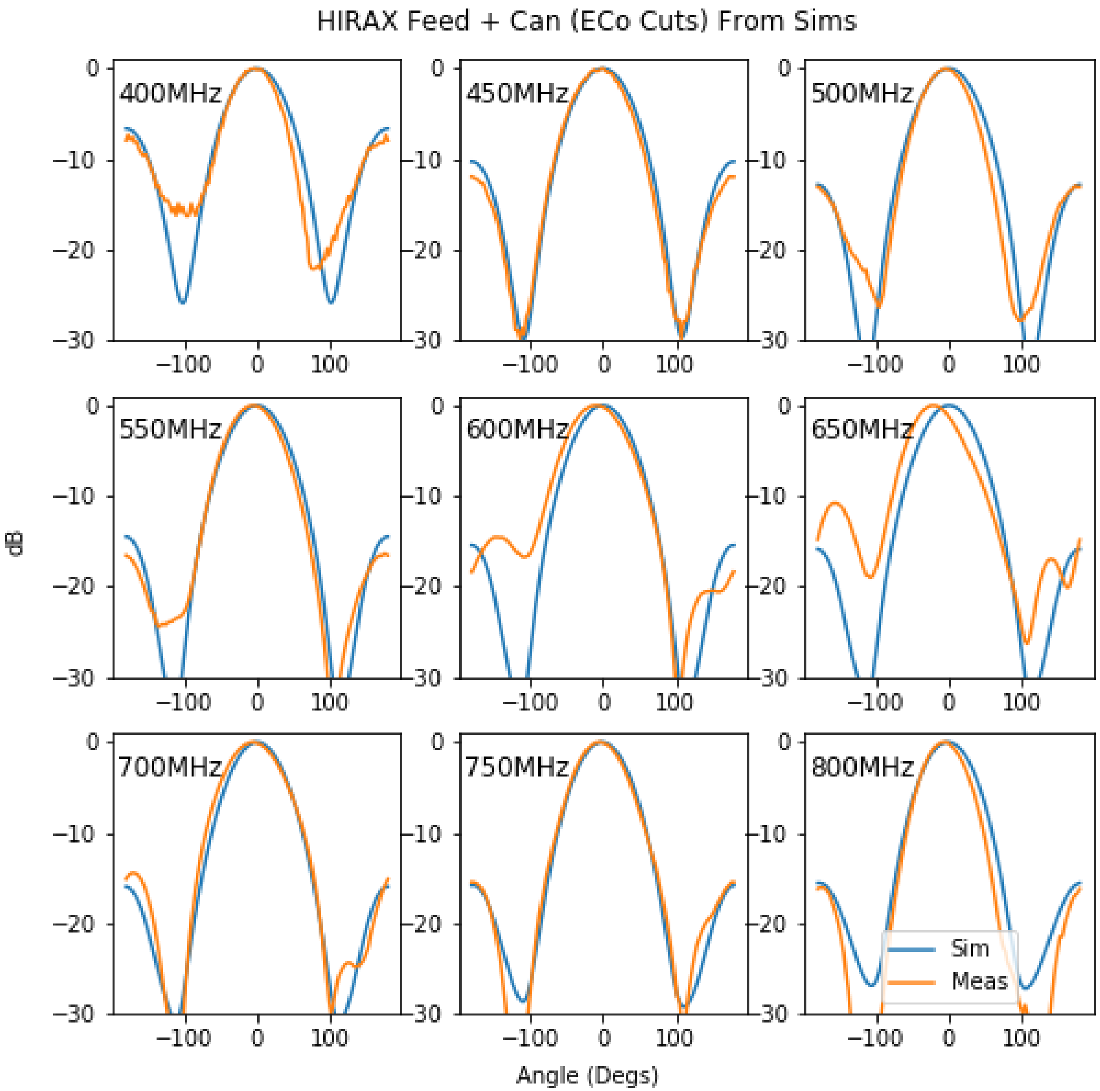
Theta [deg]

CHIME Feed Measurements at JPL



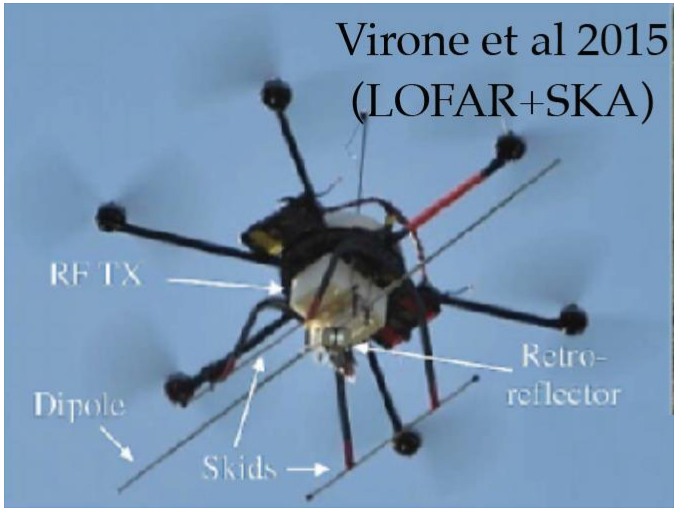
(Un-normalized)

HIRAX Feed Measurements at NCSU



Difficulty of Calibration

- Calibration also essential for instrument! Need better than 1% calibration in gain, polarization, beam shape.
- Can’t steer telescope, can’t look through array at source on ground
- Astrophysical sources, and artificial satellites have limited declinations
- Calibration with incomplete sky data difficult
- Solution: drones!



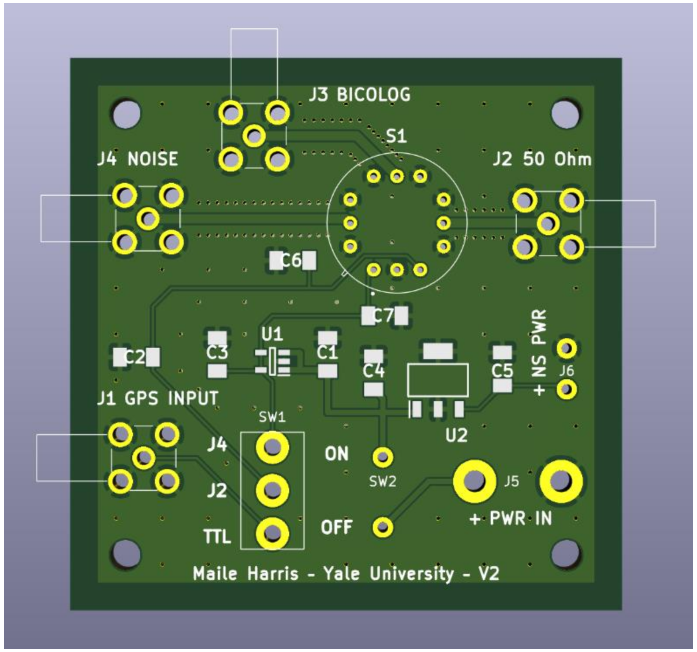
HIRAX Drone System

HIRAX Drone System

- Currently using DJI Matrice drone. Can easily reach HIRAX far field. (For 6m dish, $2*D^2/\lambda$ is 200m at 800 MHz)
- Uses custom switchable broadband noise source and biconical antenna
- Performed dish calibration measurements of DSA-10 at OVRO (top photo), at BMX at BNL (bottom), and at the HIRAX prototype array at GBO

Noise Source

- Commercial 400-800 MHz source for HIRAX/CHIME, 1-1.5 GHz source for BMX/DSA, with 90 dB ENR
- Source switchable with TTL from GPS PPS, switch board developed by myself and Maile Harris (Yale).
- Antenna is biconical antenna from Aaronia. Very uniform gain, broad beam.



Drone Accuracy Specifications

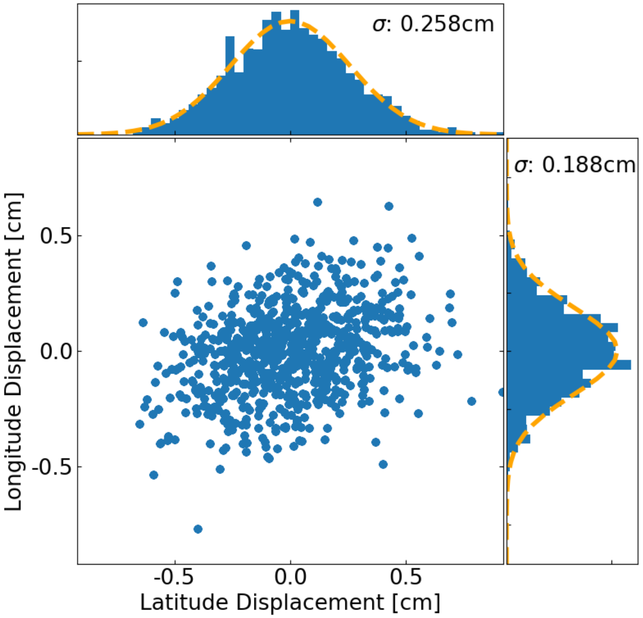
- Need very high positional and angular accuracy for beam calibration.
- Figures below for CHIME, slightly less stringent for HIRAX
- This problem has three parts:
  - 1) recovering data from drone
  - 2) verifying positional/angular accuracy
  - 3) matching to data from telescope

Measurement	Accuracy requirement
Position	16 mm
Tilt	0.57 degrees
Polarization angle	0.8 degrees

Table 1: Requirements for drone location, tilt, and polarization angle. This assumes a biconical antenna pattern from the drone.

Drone Accuracy Specifications

- Chief difficulty is measuring position and rotation of drone
- Real Time Kinematic (RTK) differential GPS provides RMS < 1cm



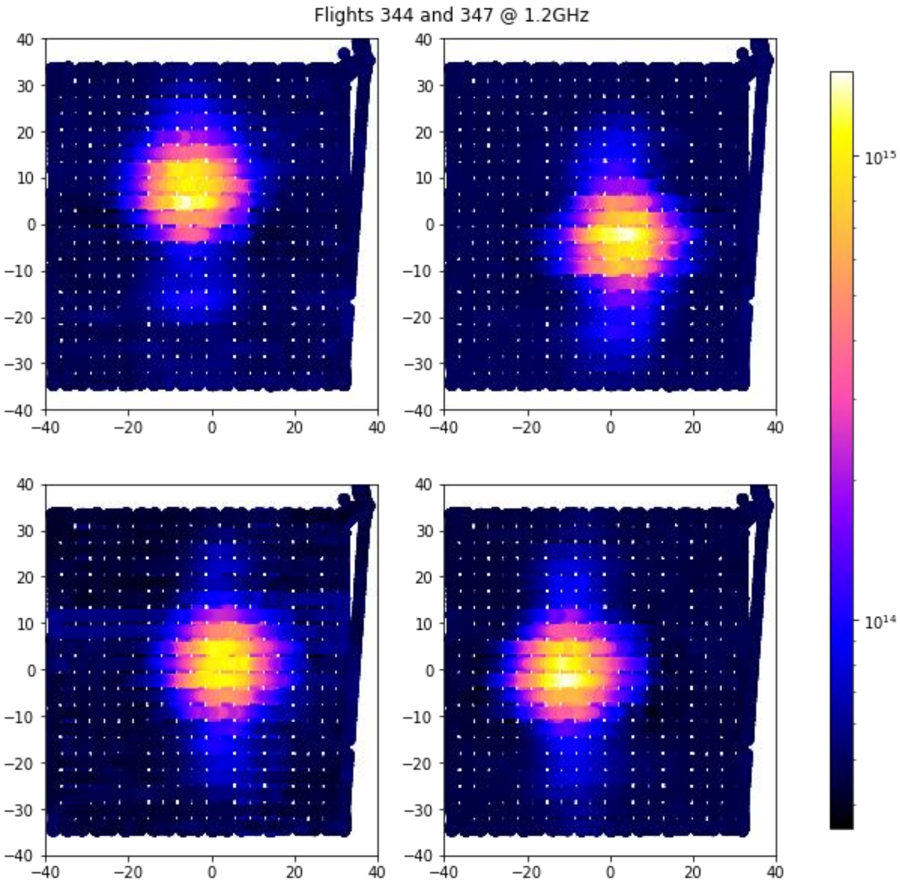
Drone position measurements by Maile Harris and Annie Polish (Yale)

Drone Produced RFI

- RFI from drone potential concern.
- Using drone with radio control frequencies outside instrument band is essential, but onboard electronics and motors always RFI source.
- DJI Matrice uses brushless motors, significantly lower RFI.
- Measurements at DSA and GBO indicate RFI significantly lower amplitude than RF noise source.

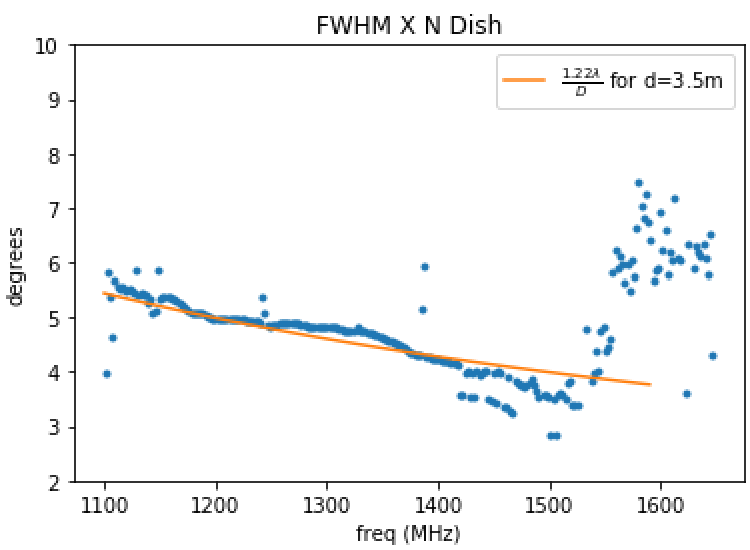
Drone Beam Mapping - BNL

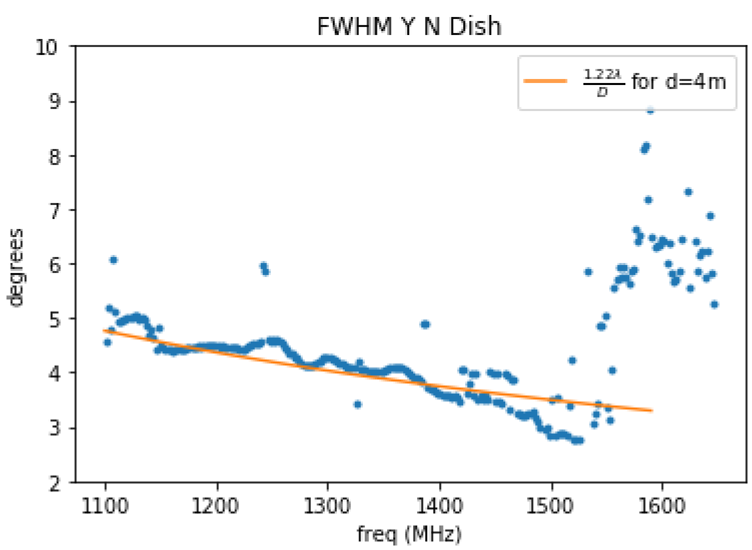
- BMX telescope is 21-cm prototype at BNL, consists of four zenith pointing off-axis parabolic dishes, frequency range 1.1-1.5 GHz
- Conducted beam mapping of BMX in March 2020.
- Fit 1D, 2D Gaussians across frequencies
- Beam widths and sidelobes locations consistent with BMX simulations.



Drone Beam Mapping - BNL

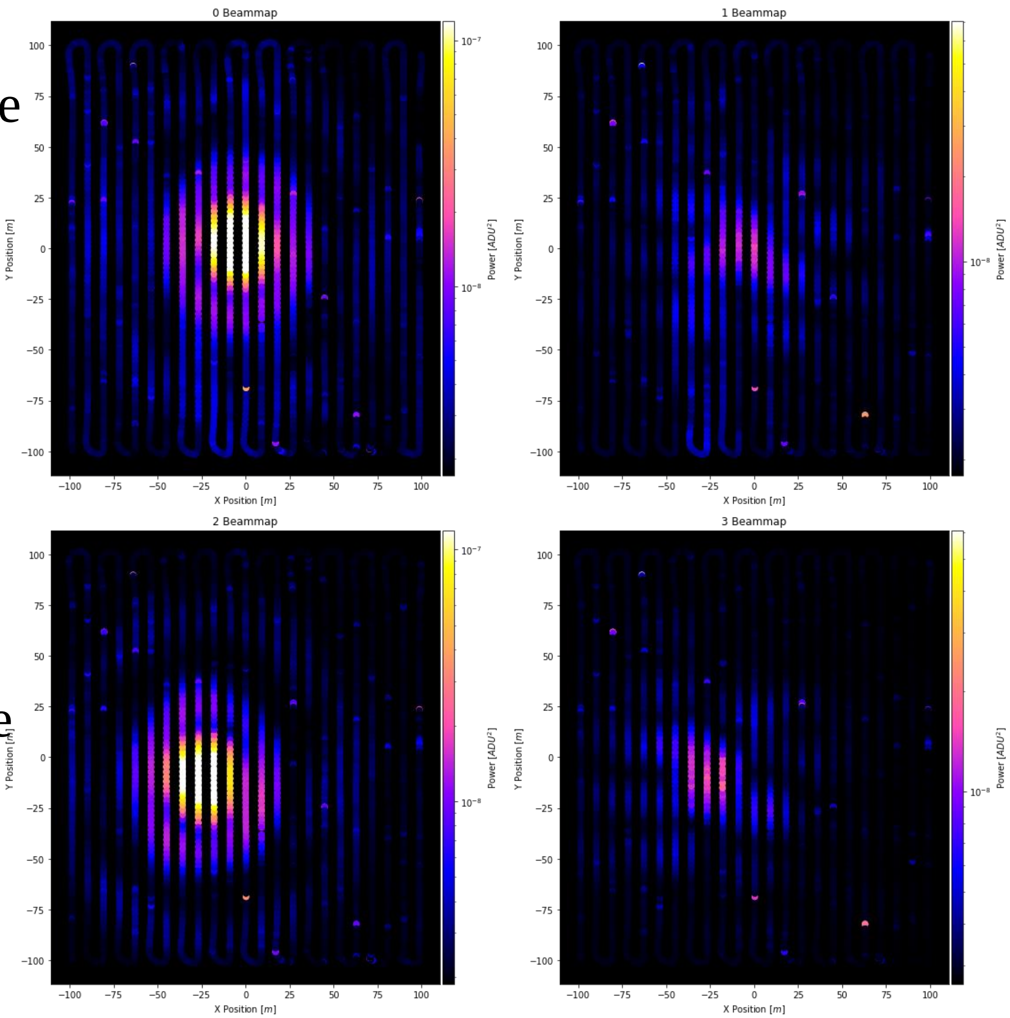
- Dish FWHM fit across band consistent with Rayleigh criterion:
  $\theta = 1.22\ \lambda/D$
- Recovers asymmetric dish diameter
- Filter at 1.5 GHz





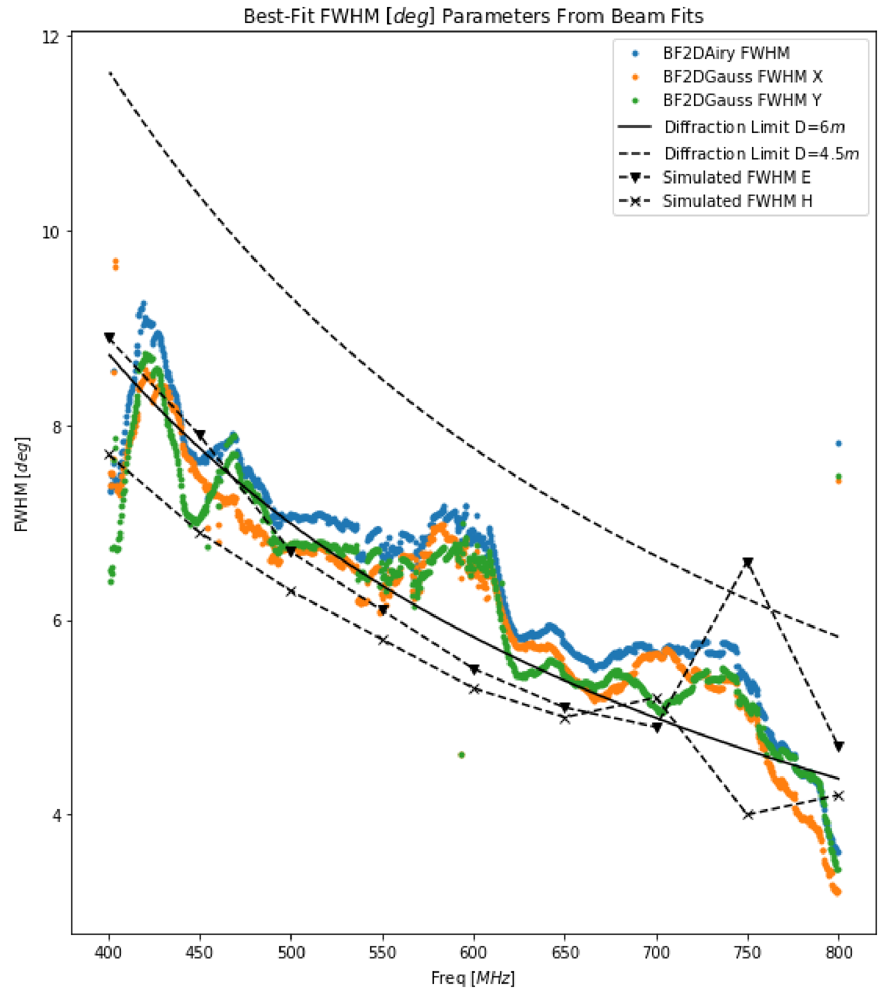
Drone Beam Mapping – GBO

- Flew similar beam mapping campaign over HIRAX prototype dishes at GBO in August 2021
- Used newer flashing noise source, perform background subtraction
- Left plots show co-pol for two dishes. See two sidelobe rings! Significant improvement in mapping precision.
- Right is cross-pol, but may be dominated by co-pol leakage due to feed response or mis-alignment with pol axis
- Preliminary, analysis ongoing



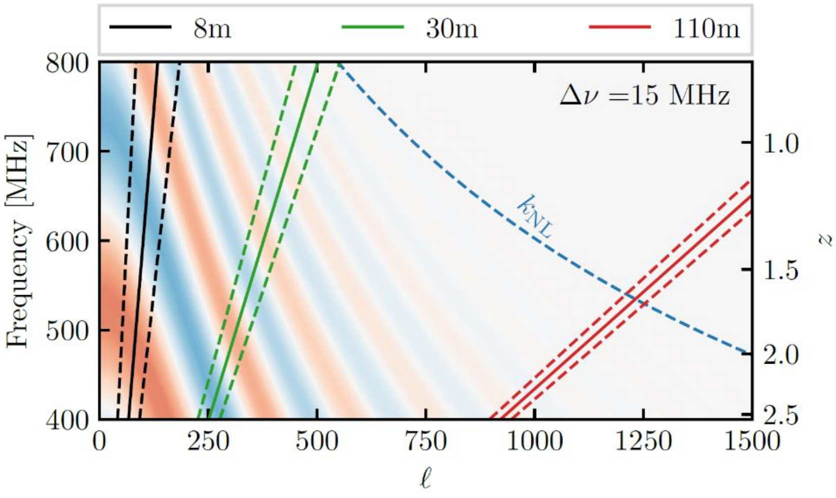
Drone Beam Mapping – GBO

- Fitted beam width well matched to Rayleigh criterion, simulations
- Can distinguish dish diameter, but not accurate enough yet to distinguish between simulated E and H plane widths



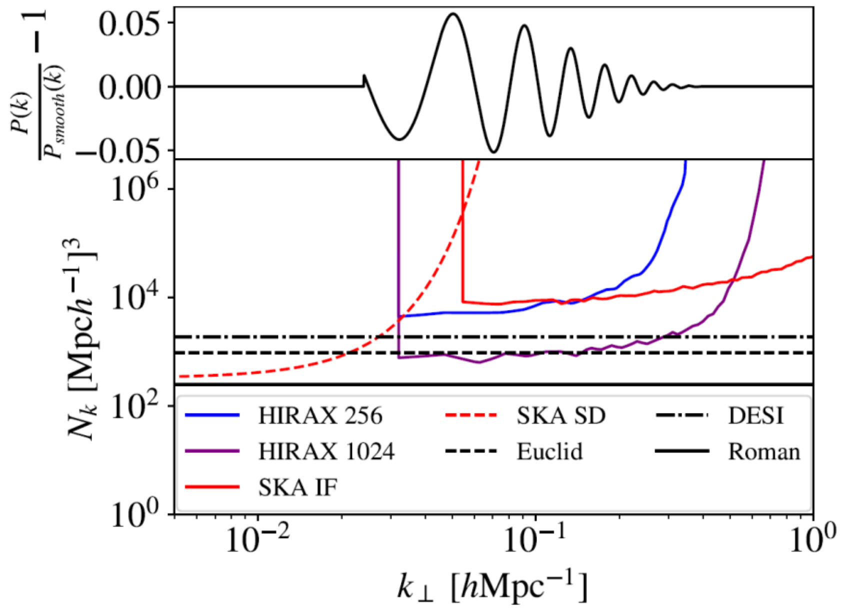
HIRAX Cosmology Forecasts

- Taking the instrument design into account, we can now make some forecast for expected cosmological constraints.
- Figure shows the angular scales accessible to HIRAX as a function of frequency.
- Background color is BAO structure in line of sight modes. k_{NL} is the non-linear scale.
- Demonstrates importance of short baselines and compact array layout for cosmology.



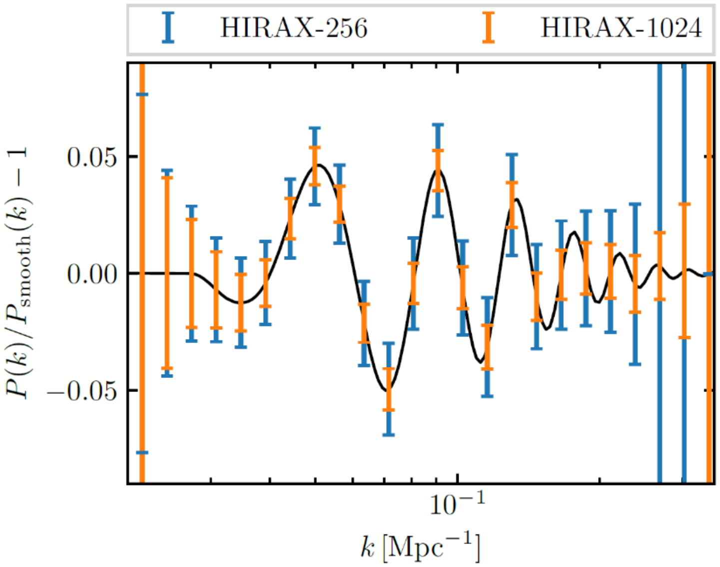
HIRAX Cosmology Forecasts

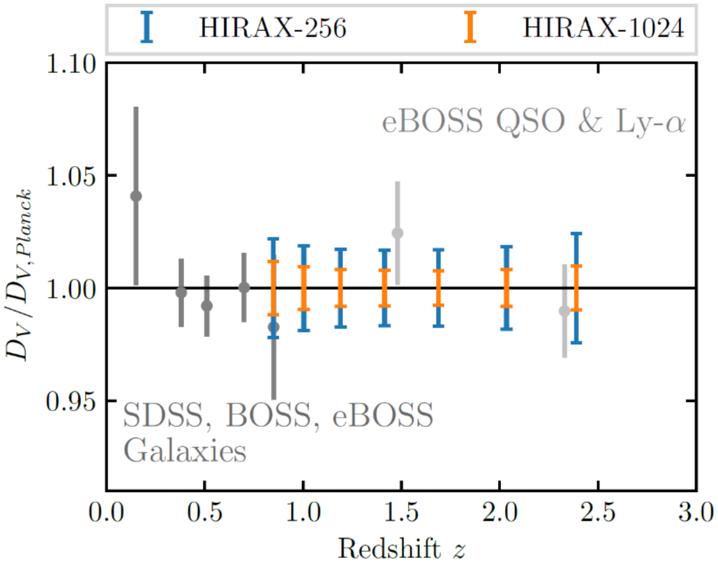
- Comparison of HIRAX's power spec sensitivity from Fisher forecasts to SKA-MID, and shot noise estimates for upcoming spectroscopic surveys.
- Top is BAO spectrum at z = 1.2 for reference of relevant scales.
- Over BAO scales, HIRAX-256 is comparable to SKA-MID, and HIRAX-1024 to current and next-gen spectroscopic surveys (but with different biases).



HIRAX Cosmology Forecasts

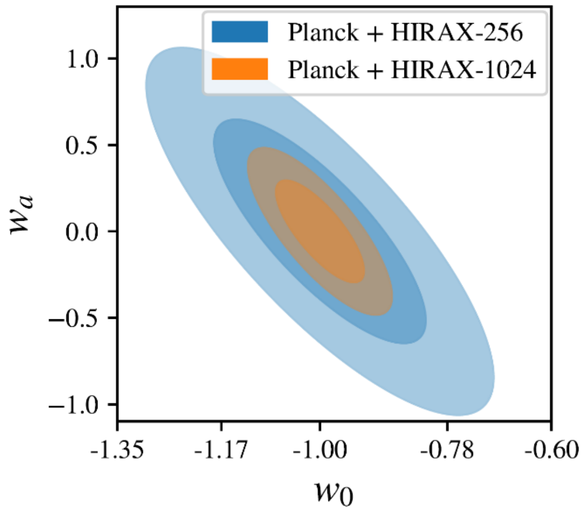
- Constraints on the BAO spectrum and distance scale based on 15,000 sq deg survey with 256 and 1024 element arrays, 50K noise temperature, 4 years of observing with 50% efficiency (17500 hrs).
- HIRAX should resolve the first 3-4 peaks of the BAO spectrum, leading to percent level constraints on D_V.

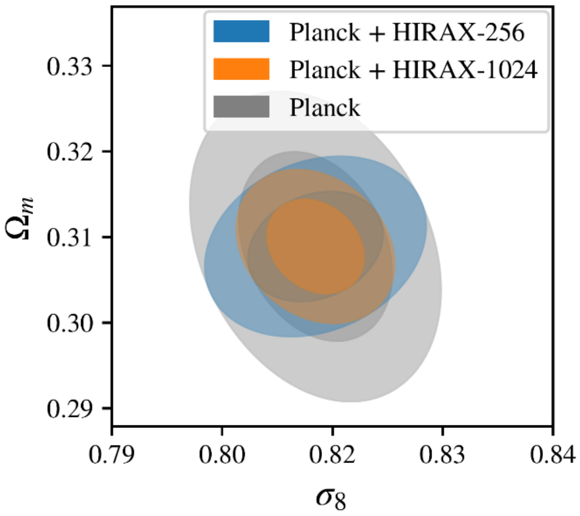




HIRAX Cosmology Forecasts

- Constraints on the dark energy equation of state parameters w_0 and w_a, using the parameterization $w(a) = w_0 + (1\text{-}a)w_a$, and on large scale structure parameters σ_8 and Ω_m. Shaded regions are 68% and 95% confidence intervals.
- Change in degeneracy direction in σ_8 and Ω_m is due to relative contribution of *Planck* priors.





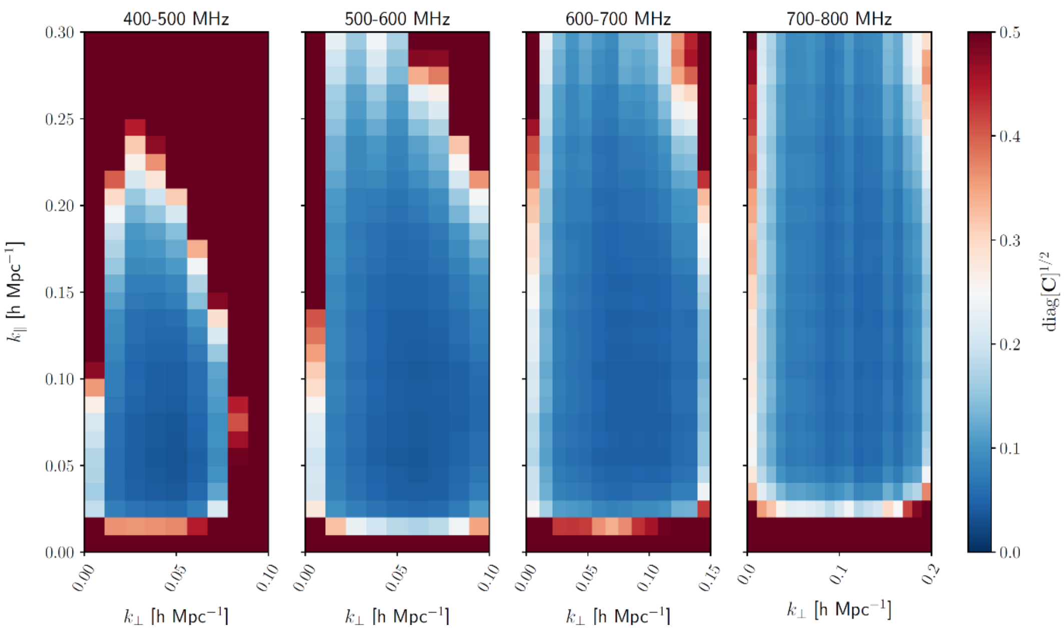
HIRAX Cosmology Forecasts

- Marginalized 68% cosmological parameter forecast constraints for HIRAX compared to the current state-of-the-art constraints from the eBOSS cosmological analysis for various dark energy cosmologies.
- HIRAX-256 should measure Ω_Λ and w_a to better precision than eBOSS, and HIRAX-1024 will exceed current constraints on w_0.

HIRAX-256 + *Planck*	σ_8	Ω_Λ	w_0	w_a
ΛCDM	0.00441	0.0039	-	-
wCDM	0.0047	0.0042	0.0739	-
w_0w_aCDM	0.0053	0.0043	0.1223	0.4332
HIRAX-1024 + *Planck*				
ΛCDM	0.0027	0.0034	-	-
wCDM	0.0028	0.0036	0.0316	-
w_0w_aCDM	0.0038	0.0037	0.0506	0.1965
eBOSS + *Planck* + SNe Ia + Lens.				
ΛCDM	0.0056	0.0047	-	-
wCDM	0.0092	0.0066	0.027	-
w_0w_aCDM	0.0093	0.0069	0.073	0.5200

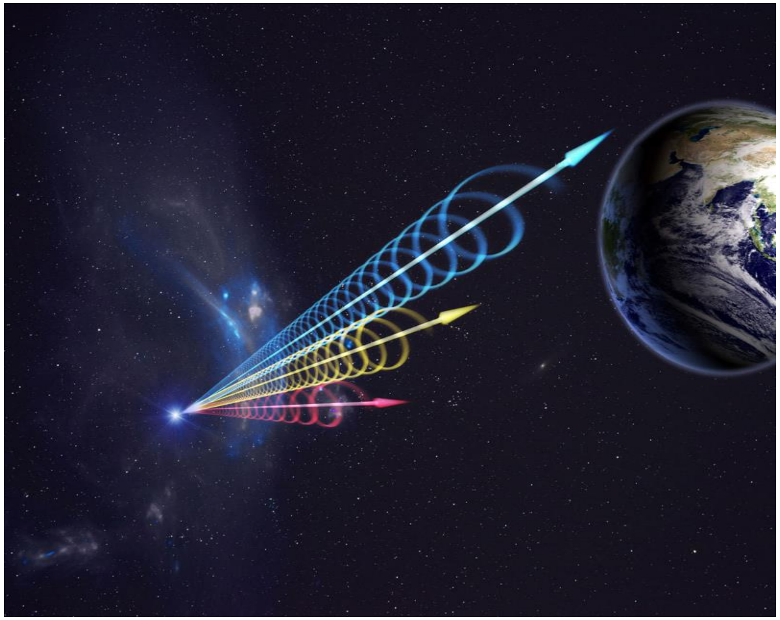
HIRAX Cosmology Forecasts

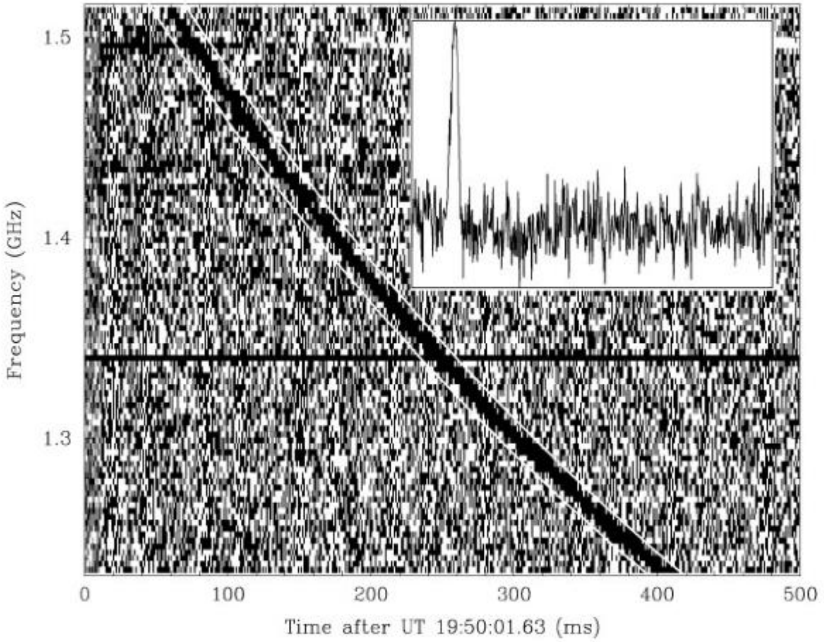
- Above estimates assume negligible calibration residuals. A more realistic method accounts for process of RFI filtering, mode filtering, and foreground deprojection.
- Estimated relative errors shown below in recovered band-powers over 100 MHz sub-bands, using the *m*-mode pipeline. Foreground filtering applied assuming ideal knowledge of instrument.
- This method results in 5-8% error in binned power spec. Minimum variance method should reduce by further factor of 2. Future work will compare cosmo constraints with Fisher matrix results.



Fast Radio Bursts

- Fast radio bursts: short (~ms), bright (~Jy) radio transients at cosmological distances (from dispersion measure and optical counterparts to repeaters)
- Total event rate is estimated to be 10^4 per day over full sky
- CHIME is demonstrating high event rate can be achieved down to 400 MHz
- HIRAX will use outrigger arrays with ~1000 km baselines to achieve 0.1” localization of detections

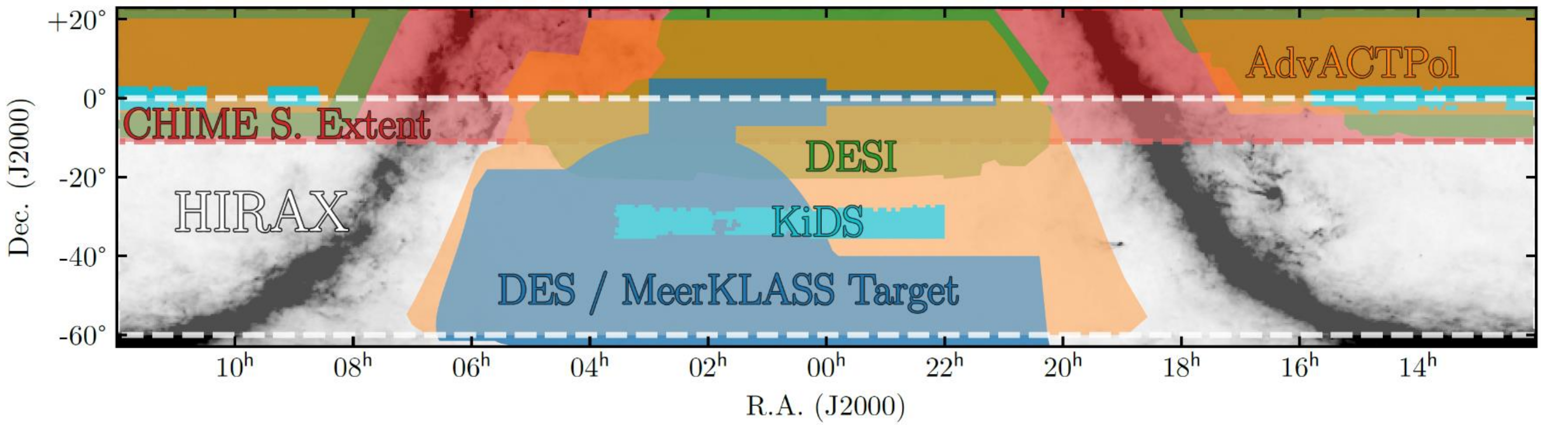




HIRAX Science Forecasts

HIRAX-256 will:

- Achieve 7% constraints on the dark energy equation of state, w_0, with Planck priors
- Detect and simultaneously localize FRBs to 0.1”
- Conduct pulsar search at full baseband and monitor known pulsars for pulsar timing studies
- Conduct a blind HI absorber search with ~3kHz spectral resolution, out to z=2.5, covering the peak of the global star-formation rate at z ~ 2.
- Conduct cross-correlation studies with numerous optical/infrared and microwave LSS surveys.



Future Array Plans

- Improved antenna y-factor measurements at Yale in coming months.
- Analyzing beam mapping results from GBO f/D=0.38 dishes.
- First drone beam maps from HIRAX f/D=0.23 prototypes at DRAO in Canada and HartRAO in SA when international travel is possible.
- Next development stage: Construction of HIRAX-256 in Karoo in 2022.

- See Crichton et al. for array details: arxiv 2109.13755

  Saliwanchik et al. for instrument design and simulations: 2101.06338

  Kuhn et al. for noise temperature measurements: 2101.06337

  Or our collaboration website: https://hirax.ukzn.ac.za