HIRAX: The Hydrogen Intensity and Real-time Analysis eXperiment

Jonathan Sievers for HIRAX Collaboration

UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

Astrophysics and Cosmology Research Unit

Astrophysics & Cosmology Research Unit
ACRU

HIRAX

- We would like to me
- Natural design: small
  DE effects. Too low, r
- BAO signal faint, need
- Plan is to piggyback o re
  cylinder BAO experin
- HIRAX supported by nd
  Partnership Developr

Collaborators

UKZN: Sievers, Moodley, Chiang, Hilton, Poole (engineering)

Stellenbosch: Brink

UCT: Woudt, Taylor

Rhodes: Smirnov

UWC: Santos, Maartens, Dave

AIMS: Basset

Carnegie-Mellon: Peterson

ASIAA: Chang

IUCAA: Gupta, Srianand

APC Paris: Ganga, Bucher

NRAO: Ransom

Oxford: Karastergiou

HDU (China): Zhi-Ping Chen

Various & sundry Canadians




Current Design Plan

- Order 10^3 close-packed 5-6m dishes.
- Operate between 400-800 MHz
- Channelizing on FPGA ICE boards (Matt Dobbs)
- Correlation on GPUs.
- Dishes tilt N/S: when "deep enough" on a strip, tilt over to increase f_{sky}.
- Would like to do some beamforming in correlator, kick out small subset of beams to external processing.
- eThekwini municipality very supportive, providing site in Durban, seed funding for prototype. Starting to order parts now!

Parameter Forecasts (Bull et al.)

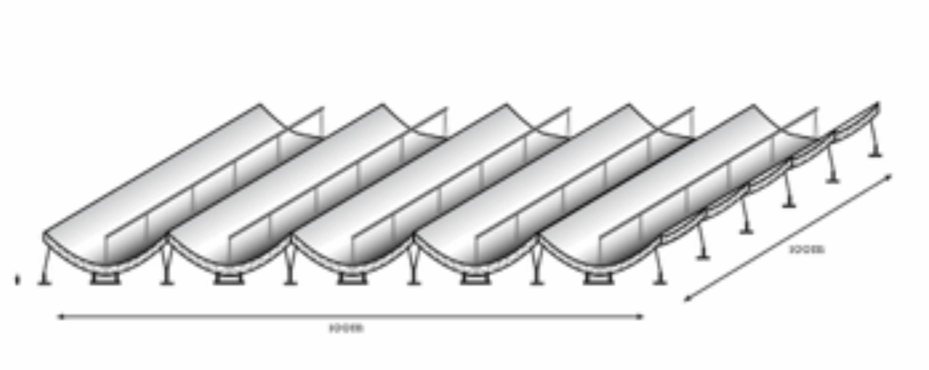
Experiments	A $/10^{-2}$	h $/10^{-3}$	Ω_K $/10^{-4}$	Ω_{DE} $/10^{-3}$	n_s $/10^{-4}$	σ_8 $/10^{-3}$	γ $/10^{-2}$	w_0 $/10^{-2}$	w_a $/10^{-2}$	FOM
Stage I	19.4	34.9	49.6	24.0	38.4	8.1	4.2	34.7	95.2	11.8
Stage II	12.4	21.9	29.9	15.9	37.1	7.8	4.7	14.2	29.6	50.2
Facility	5.4	8.9	12.9	6.9	32.5	6.6	2.1	6.1	15.3	250.9
GBT	80.9	161.3	202.3	115.6	38.6	8.2	25.2	119.1	274.6	0.8
Parkes	63.7	29.4	450.0	47.7	38.3	8.2	2.9	49.3	432.7	2.7
GMRT (ASKAP PAF)	52.3	33.9	135.7	18.2	38.5	8.2	4.1	29.1	155.5	10.0
WSRT	85.7	107.0	189.5	68.0	38.6	8.2	13.5	92.2	250.9	1.7
WSRT + APERTIF	10.8	10.5	38.6	6.5	37.1	7.9	1.8	13.8	61.4	71.9
VLBA	68.9	40.3	630.3	66.8	38.5	8.2	3.5	68.2	603.5	1.4
JVLA	55.3	39.7	156.9	21.5	38.5	8.2	4.5	32.9	178.1	7.7
BINGO	32.3	33.1	95.2	16.9	38.5	8.2	3.5	44.2	174.0	8.4
BAOBAB-128	18.9	42.4	56.9	31.2	38.3	8.1	8.3	29.1	61.7	11.1
CHIME Full	6.6	16.4	23.3	12.2	34.7	7.3	8.0	7.5	22.3	83.9
Dense AA Concept	29.1	31.8	51.6	20.8	38.1	8.1	5.5	24.5	64.5	22.3
KZN Array	7.3	13.5	18.5	10.0	33.2	7.3	4.4	8.1	18.0	117.9
KAT7	77.3	54.7	902.8	95.9	38.6	8.2	4.4	96.3	861.1	0.7
MeerKAT (B1)	13.8	29.1	35.4	21.3	37.9	8.0	4.5	21.8	47.6	25.3
MeerKAT (B2)	10.0	9.2	25.3	6.3	36.5	7.7	1.7	5.6	26.9	219.1
ASKAP	8.0	18.0	22.5	13.2	37.2	7.9	3.5	13.8	30.5	67.8
SKA1-MID Base (B1) SD	7.3	13.6	19.5	10.3	35.6	7.4	2.9	9.9	22.1	108.3
SKA1-MID Base (B1) Int.	29.3	40.7	51.7	27.9	37.8	8.0	12.0	20.6	45.2	20.6
SKA1-MID Base (B1) Comb.	7.3	13.5	18.7	10.2	35.4	7.4	2.9	9.7	21.8	110.6
SKA1-MID Base (B2) SD	8.8	7.7	21.2	5.6	35.1	7.6	1.6	4.0	20.2	368.4
SKA1-MID Base (B2) Int.	496.7	42.3	115.3	21.5	38.2	8.2	14.0	28.8	123.3	11.2
SKA1-MID Base (B2) Comb.	8.8	7.7	21.1	5.5	35.0	7.6	1.6	4.0	20.1	369.1
SKA1-MID Full (B1) SD	7.3	15.1	20.4	11.3	36.3	7.6	3.3	10.9	23.6	93.4
SKA1-MID Full (B1) Int.	40.3	40.6	54.4	28.3	37.8	8.1	9.5	22.6	44.5	20.8
SKA1-MID Full (B1) Comb.	7.1	14.3	18.3	10.8	35.7	7.5	3.2	10.3	22.5	100.7
SKA1-MID Full (B2) SD	8.5	7.5	20.0	5.4	34.7	7.5	1.5	3.7	18.3	423.8
SKA1-MID Full (B2) Int.	447.3	28.8	78.5	14.8	37.5	8.2	9.5	16.3	71.5	30.1
SKA1-MID Full (B2) Comb.	8.5	7.3	19.6	5.4	34.1	7.5	1.5	3.6	18.2	427.8
SKA1-SUR Base (B1)	6.0	13.9	17.9	10.6	34.8	7.3	4.2	7.8	16.6	123.6
SKA1-SUR Base (B2)	4.5	6.5	11.9	5.2	32.5	6.3	1.7	4.0	11.7	471.8
SKA1-SUR Full (B1)	5.7	13.3	17.0	10.2	34.4	7.2	4.1	7.2	15.5	140.7
SKA1-SUR Full (B2)	4.4	6.3	11.7	5.0	32.3	6.2	1.6	3.7	11.1	518.3
DETF Stage IV	2.4	6.9	8.6	5.6	25.0	5.7	3.3	3.7	11.5	451.3

- HIRAX gives excellent (preliminary) parameter constraints.
- Complementary to MeerKAT band 2. HIRAX+MeerKAT B2 gives DE FOM ~370, maybe higher! (observations suggest more optimistic HI fraction)

Other Science

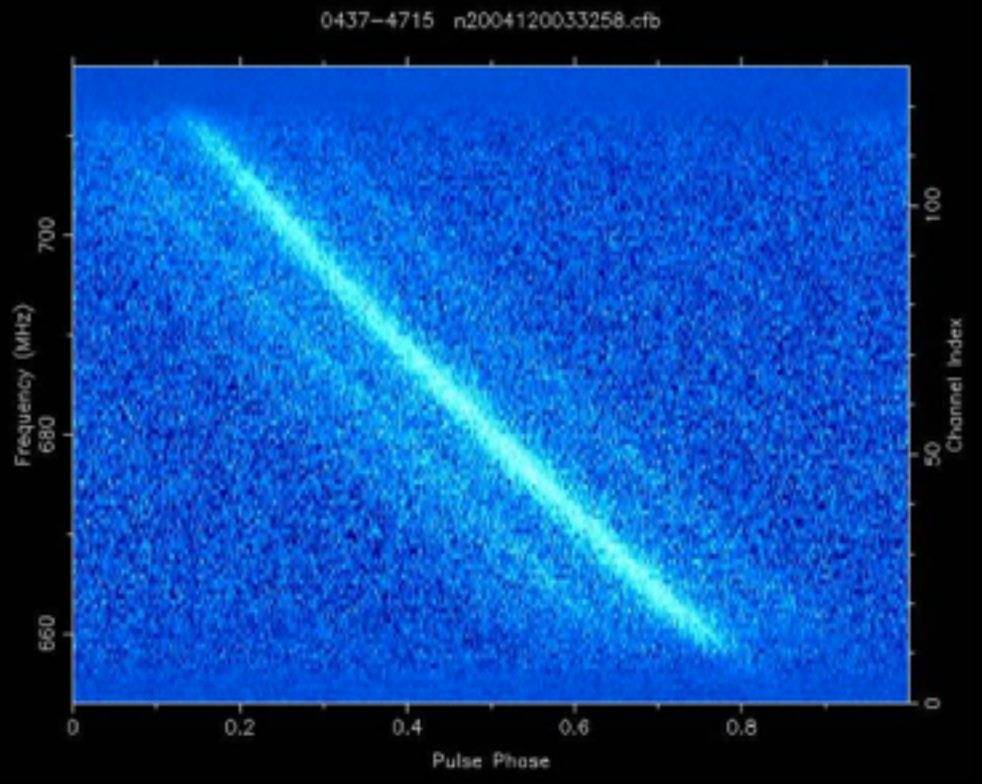
- HIRAX good for many other science projects.
- Excellent for radio transients, fast and slow.
- Pulsar search: 12 μJy/scan - search each beam once? Plus search in galactic centre.
- Neutral hydrogen absorbers: upres frequency in beam-formed data (with a few FFTs on GPUs). Goes to higher redshift than MALS.
- Diffuse polarization of galaxy.
- Technology: have an SKA-sized correlator in the Karoo up & running.
- <insert your science here?> Come talk to us!

CHIME Comparison



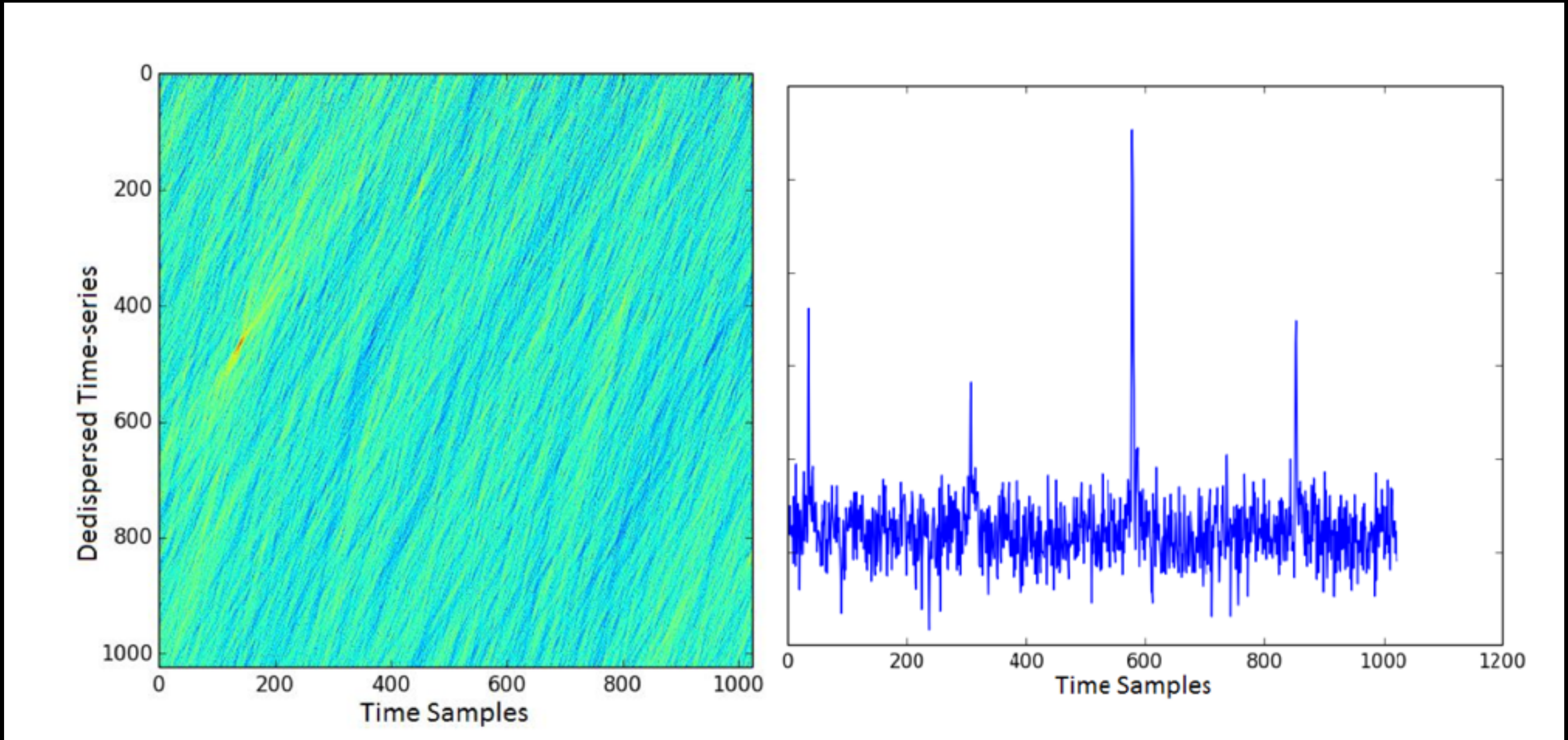
- CHIME is a cylinder array being built at DRAO
- HIRAX fills in other half of sky.
- Karoo significantly better site (lower RFI, no snow)
- Optical surveys better in south, LSST in particular. If foregrounds very hard, cross with optical huge risk mitigation. (plus cross-correlation science)
- Dishes much better at cross-talk, RFI rejection, large-angle science.
- Larger collecting area, longer time in-beam significantly better for sources (particularly pulsars). Far more pulsars in south, too.

What are Fast Radio Bursts?



- Good question! Nobody knows…
- short (~ms), bright (10's of Jy) radio transients
- only handful measured, <10
- thought to come from cosmological distances due to dispersion
- Event rate possibly large - estimate 10^4/sky/day
- Delay = 4015*DM /ν^2. ν in MHz, DM in cm^3/pc, typical DM values for FRB's 10^3. Lag at (800,400,200,100) MHz= (6.5 26 104 415) seconds

De-dispersion Transform



HIRAX pointed up sees same sky as HERA. Have ~minute to send burst trigger to HERA to write baseband. Would be neat!

Calibration

- Need very good calibration to remove galactic foregrounds.
- One technique: redundant calibration - solve overdetermined system for sky values/antenna gains.
- Have you ever met a 100% perfectly redundant array?
- Relax redundant requirement under assumption of Gaussian random field.
- Inspired by HERA kickoff meeting, still writing test-case code. If this has been tried before, let me know!

Likelihood

- Normally, $\chi 2=\sum(g^*_m g_n d_i - m_i)^2/n_i^2$ for antenna gains g, data d, model m, and noise n. n_{ant} gains+~$2n_{ant}$ unique vis.
- If array not perfectly redundant, have large number of model params.
- Instead, write likelihood as: $-2\log(L)=d^T(C+N)^{-1}d\ [+\log(|C+N|)]$ for sky covariance C.
- Why this way? For array with known imperfections, can calculate covariance. Very similar baselines should be nearly, but not exactly, identical.

Reproducing Redundant Calibration

- If starting "close", can linearize problem and neglect determinant: $-2\log(L)=(d+Ag)^T(C+N)^{-1}(d+Ag)$ with solution $A^T(C+N)^{-1}Ag=A^T(C+N)^{-1}d$
- For exactly redundant array, covariance splits into blocks, with diagonal noise plus rank-1 sky covariance.
- Sparse form of C+N means covariance can be applied/inverted/stored in order n_{vis}, not n_{vis}^3 like you might think. Matrix A can also be applied in order n_{vis}.
- In limit $C\to\infty$, can show with sparse form that likelihood reduces to classic redundant χ^2, but without solving for sky parameters. Saves factor of ~20 in brute-force calculation time.
- Can also write curvature factored: solve system via PCG with no n^3 steps.

Inclusion of Extra Info

- Traditional calibration hard for large-angle arrays because no "bright" sources.
- Redundant calibration has no preferred sky model. If I tell you about a source, it doesn't help.
- Correlation calibration can include source information. If I don't let $C \rightarrow \infty$, can let model prefer to put signal in sources even if they aren't dominant. Requires knowledge of source position, but not flux.
- Redundant calibration has phase ramp degeneracy (corresponds to translational invariance). Sources break that - less degenerate is always better!
- With careful bookkeeping ($C_{src}+C_{sky}+N$) invertible in order $n_{vis}n_{src}$.

Non-Ideal Case

- If array is nearly redundant, still get blocks on covariance. Instead of rank-1, will be higher rank, but should be small # of modes. Preserves sparseness.

- Nowhere in math did we assume small deviations: with enough overlap, should be able to calibrate not very redundant arrays.

- At significant computational expense…

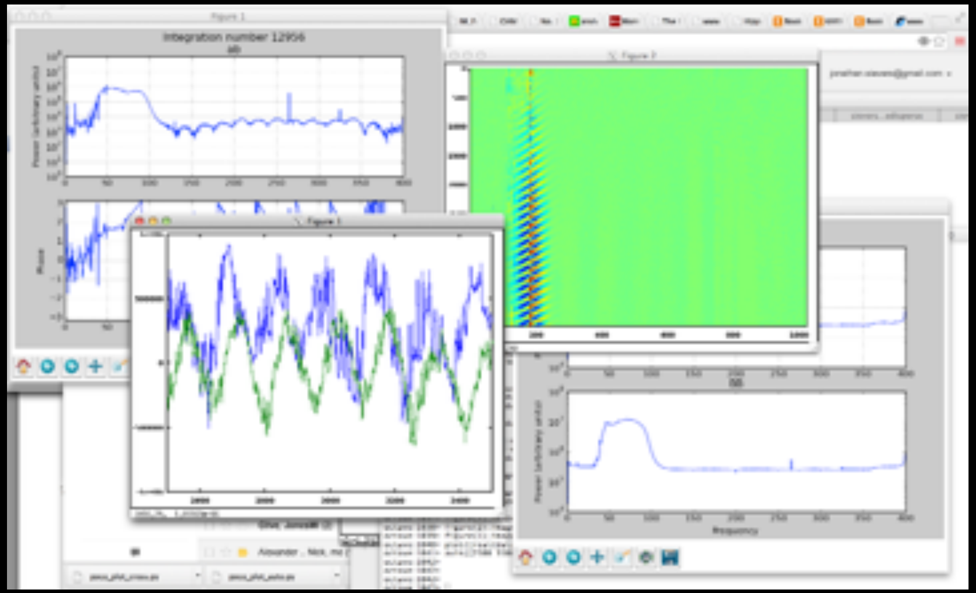
- Key assumption is that sky can be described OK by power spectrum. Critical for estimating how different correlated visibilities should be.

Proto-prototype

Borrowed travelling ROACH board, went to DUT to build 2-element interferometer with Chiang, Peterson, Van Vuuran, Macpherson.

With Installed dishes on roof, cabled everything up through RF chain. Got fringes on sun within 24 hours - first in KZN!

Clockwise, bottom left:
Dish w/ team, including SKA MSc stdents Allotey, Sengate
Inside DUT control rom
First fringes!
Prototype HIRAX feed



Summary

- Proposal submitted to build HIRAX, BAO++ experiment. Expect answer by end of March.
- Vital stats: $\sim 10^3$ 5-6m dishes, 400-800 MHz, 1024 channels. Will need to tilt (by hand) along N-S axis every few months. DE FOM ~100, complements MeerKAT B2.
- HIRAX excellent for other science - pulsars, transients, HI absorbers, galactic polarization…
- Very open to new ideas/collaborators, come talk to us with hardware/analysis/science ideas.
- NB - will be advertising soon for a project manager (thanks to eThekwini) - please point interested candidates to us.