BMX Interferometer: Calibration Studies for a 21cm Intensity Mapping Experiment

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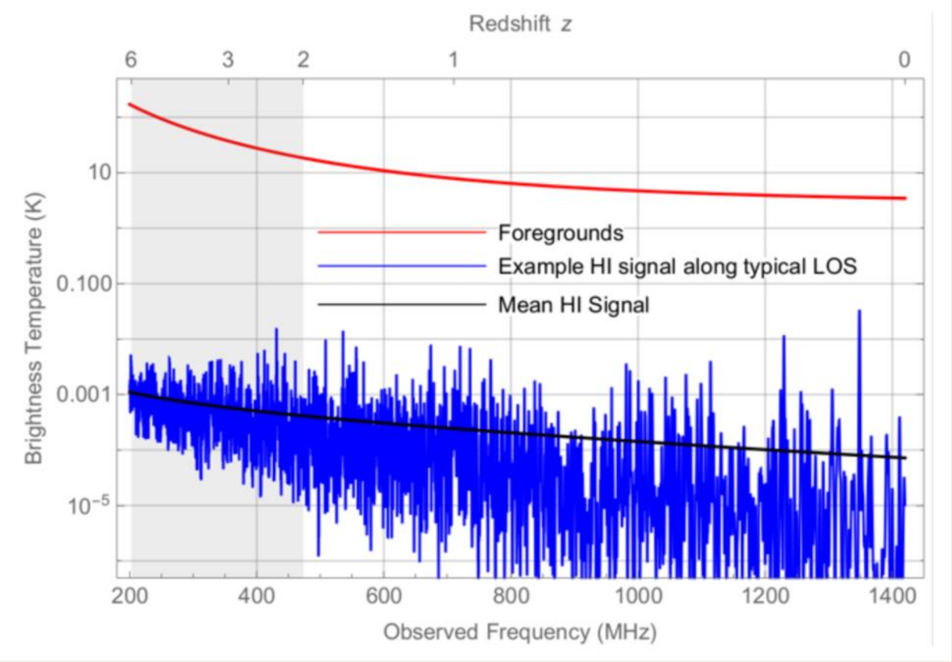
Gregory Troiani ((UMKC)

Clarence's plenary talk
PUMA whitepapers:
1., 2., 3.
2020 SPIE
Paul's 2019 CPAD talk

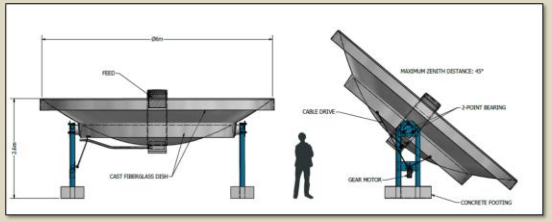
Key technological challenges for 21cm line intensity mapping

- Since the cosmological 21cm signal is ~10^4 weaker than astrophysical foregrounds, the major challenge for this method is ***foreground mitigation***.
- The key to achieving clean foreground separation is ***calibration***:
  - Antenna element primary beam angular response vs. frequency
  - Gain and phase response of the signal chain vs. frequency
  - Accurate sky maps of (polarized) galactic and extraglactic sources
- Precision timing distribution to ensure coherent recording of GHz signals arriving at thousands of stations separated by km
- Power-efficient, real-time processing of network data streams approaching 1Pb/sec
- Robust and mass-producible methods of dish and receiver manufacture



BMX dish

Notional PUMA dish

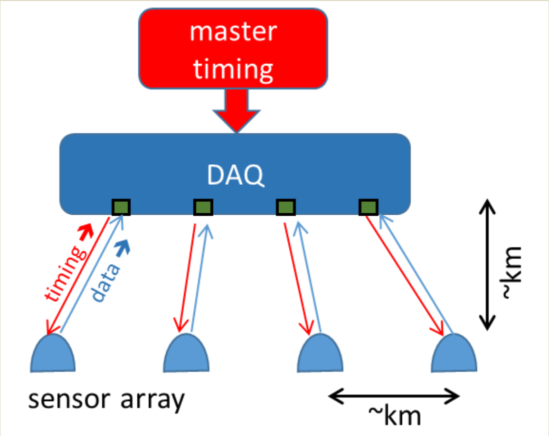


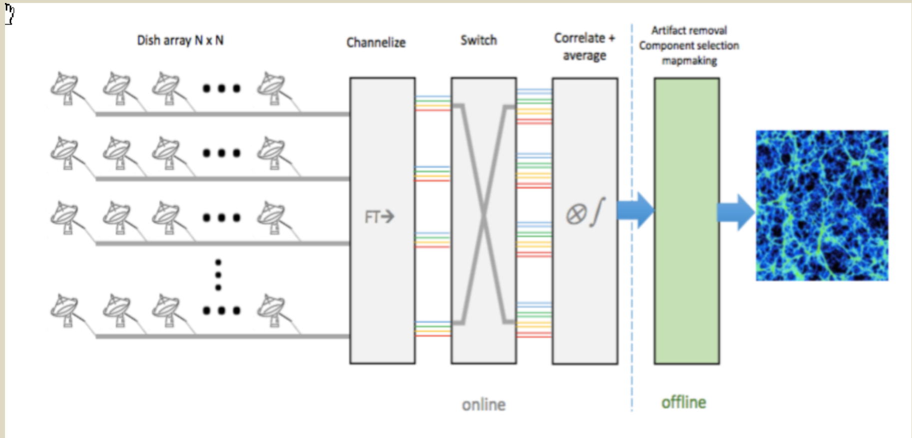
Composite dish construction

CHORD

HIRAX

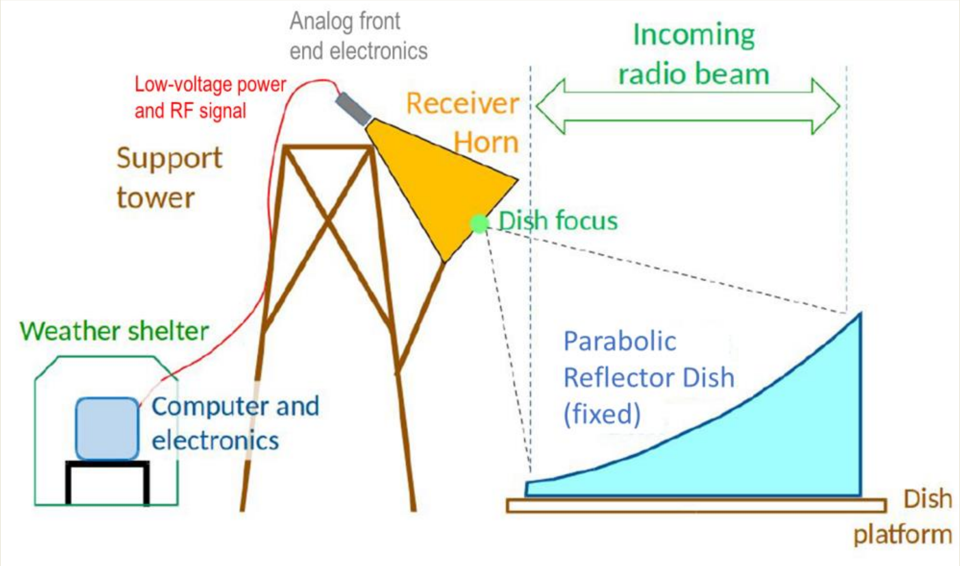
SKA



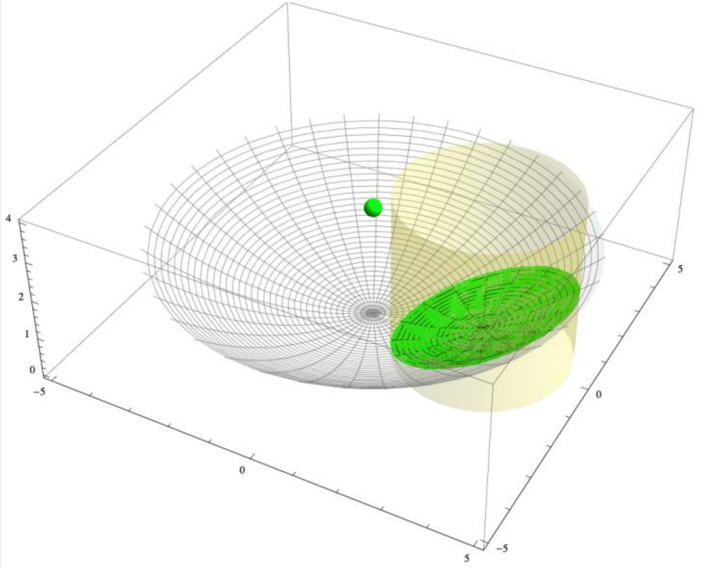


BMX instrument

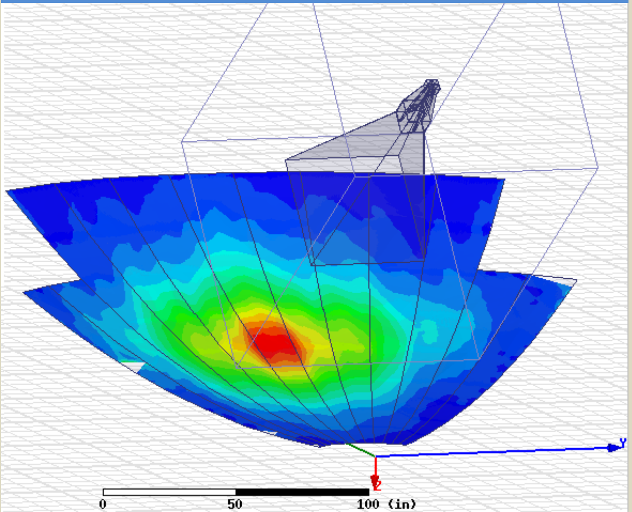
Off-axis configuration of single dish + receiver



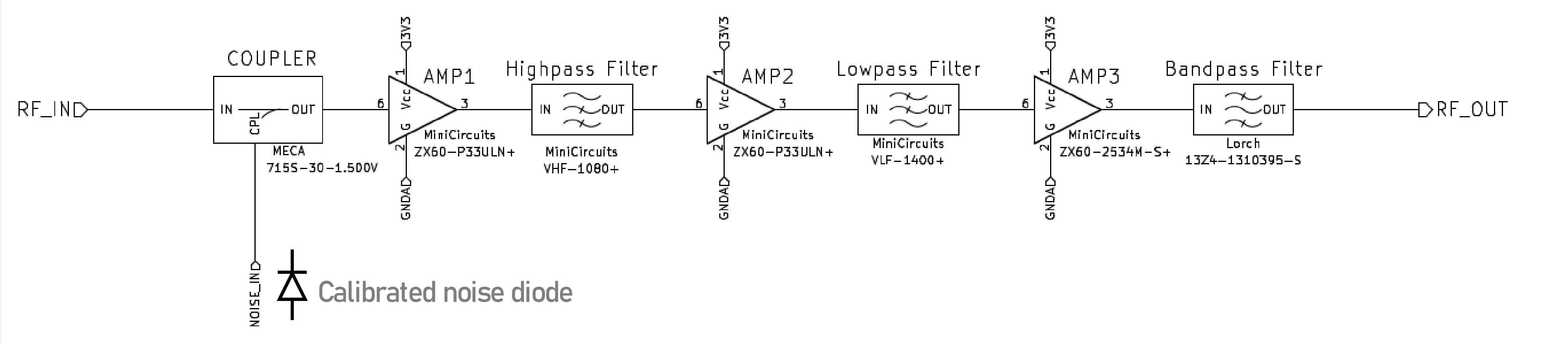
Parent paraboloid



EM Sim of illumination pattern on dish

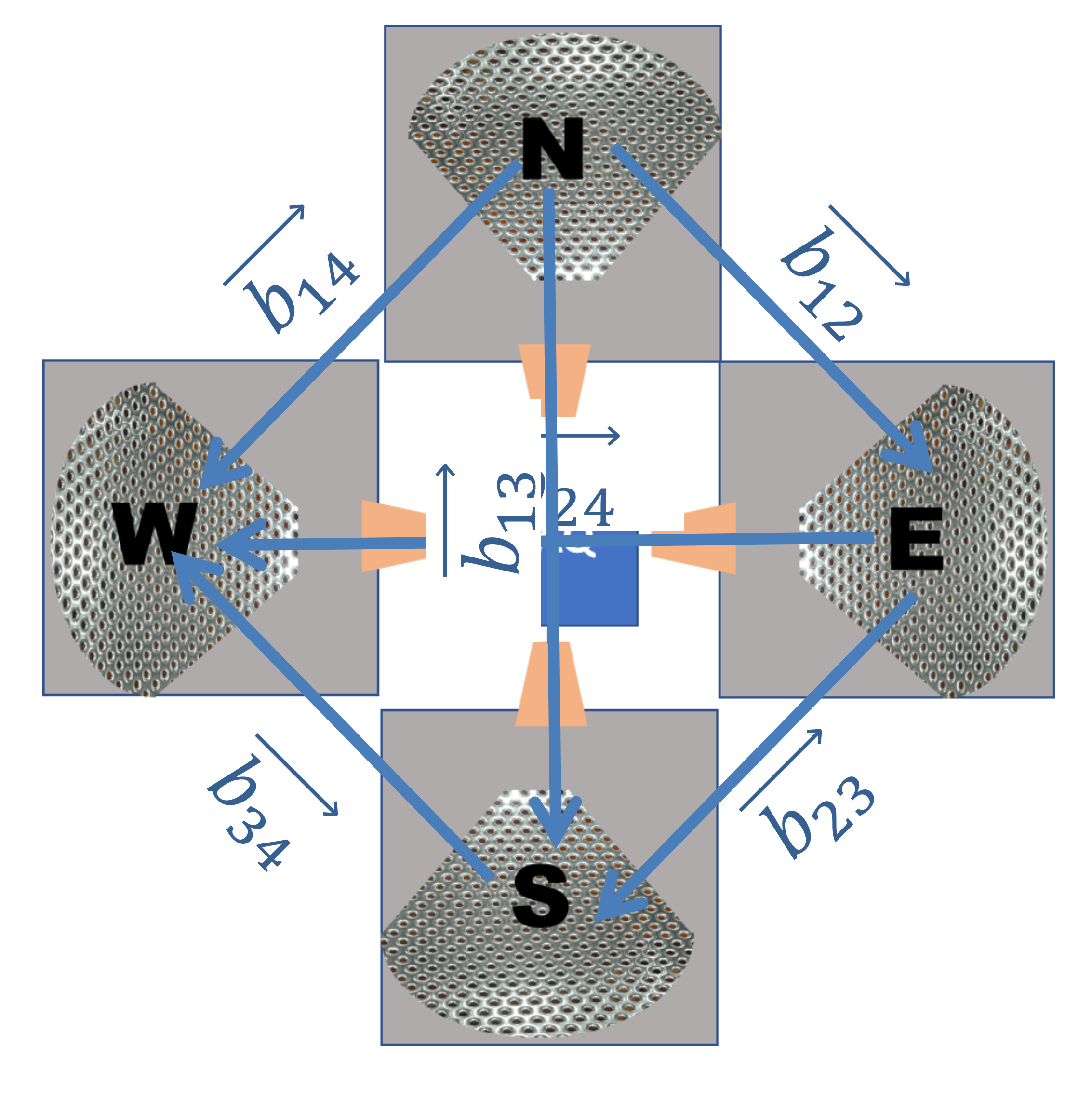


Front end electronics



Telescope layout

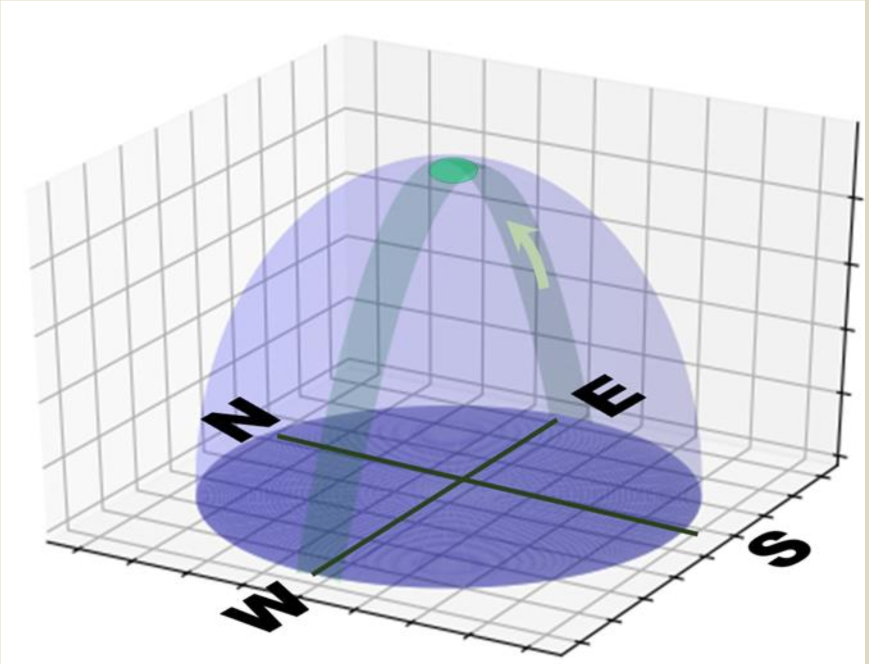
Reflector array and baselines



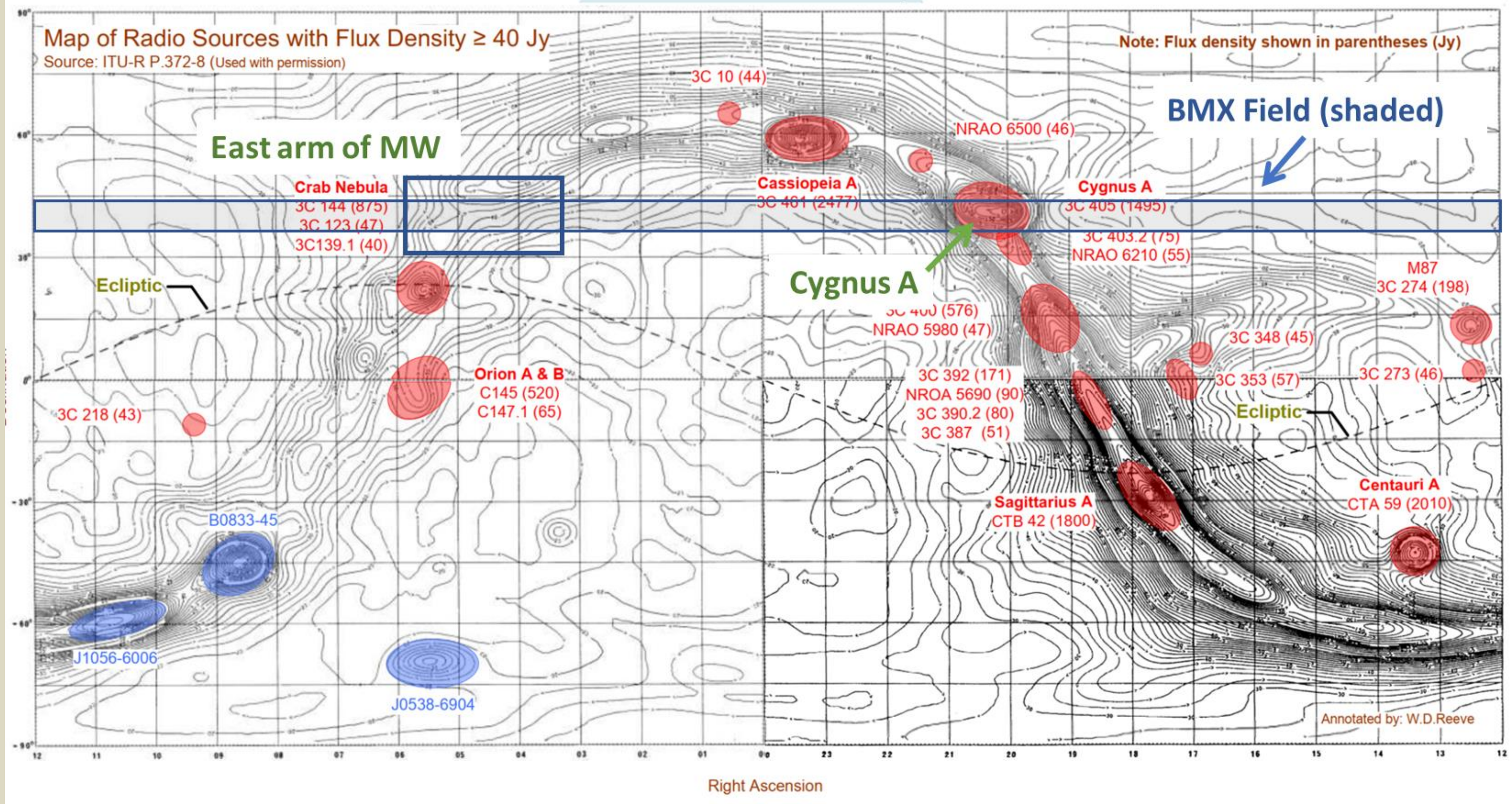
Location on BNL campus

BMX field of view on sky

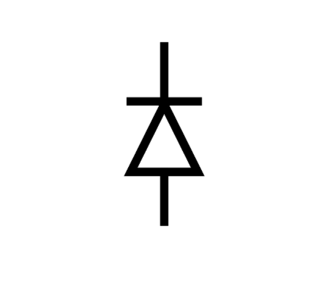
Horizon coordinates

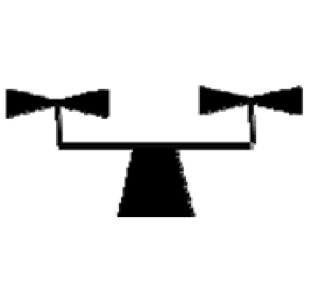


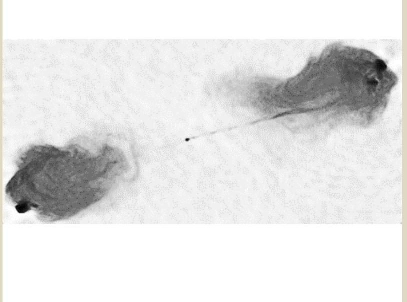
FOV unwrapped superimposed with radio source map



Calibrators





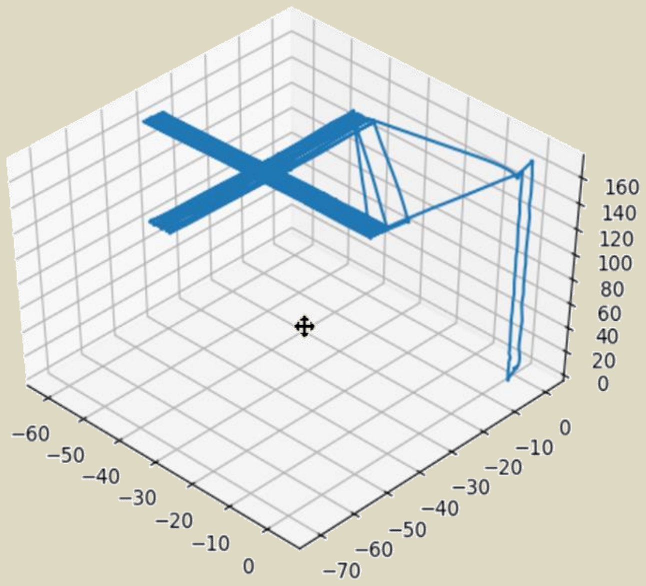


	DIODE	UAV	GNSS	MW	CygA
For:	gain(ν)	beam(ν)	beam	beam, frequency	beam, array layout
Range	0	170 m	2e7 m	5e20 m	6e24 m
Heading angle	-	Any	~NE, ~SW	W	W
Angular rate	-	1 – 1.1 °/s	0.006 - 0.01 °/s	0.0032 °/s (sidereal)	0.0032 °/s (sidereal)
Passes/day	-	up to 10	20 – 30	1	1
Power	3K	200,000K adj.	20,000K max.	1 -- 40K	5 K @ 1.42GHz
Polarization	No	Yes	No	No	No

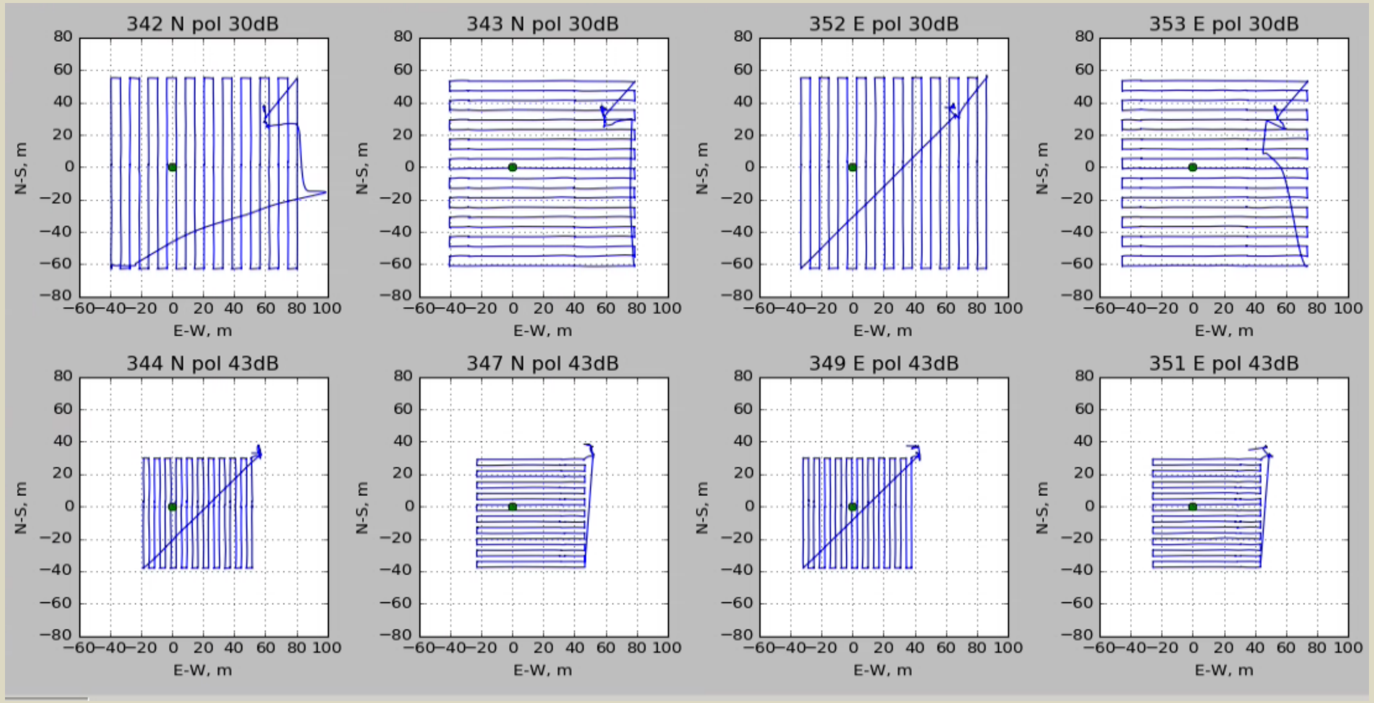
UAV calibrations

- Vehicle: commercial DJI hexacopter. Flight time ~25 minutes per battery change.
- Transmitter: switched, broadband noise source + biconic antenna (polarized). Variable attenuator to set power level.
- Position determination: differential GPS, ~1cm accuracy.
- Timebase: GPS
- Flight plan: ascend to far field (~170m), fly raster pattern over telescope. Drone “yaw” orientation sets polarization direction either aligned with or perpendicular to direction of travel. While flying legs of the raster, typical speed 2 - 4m/s.
- Thanks to Yale team of L. Newburgh for use of DJI

Flight patterns

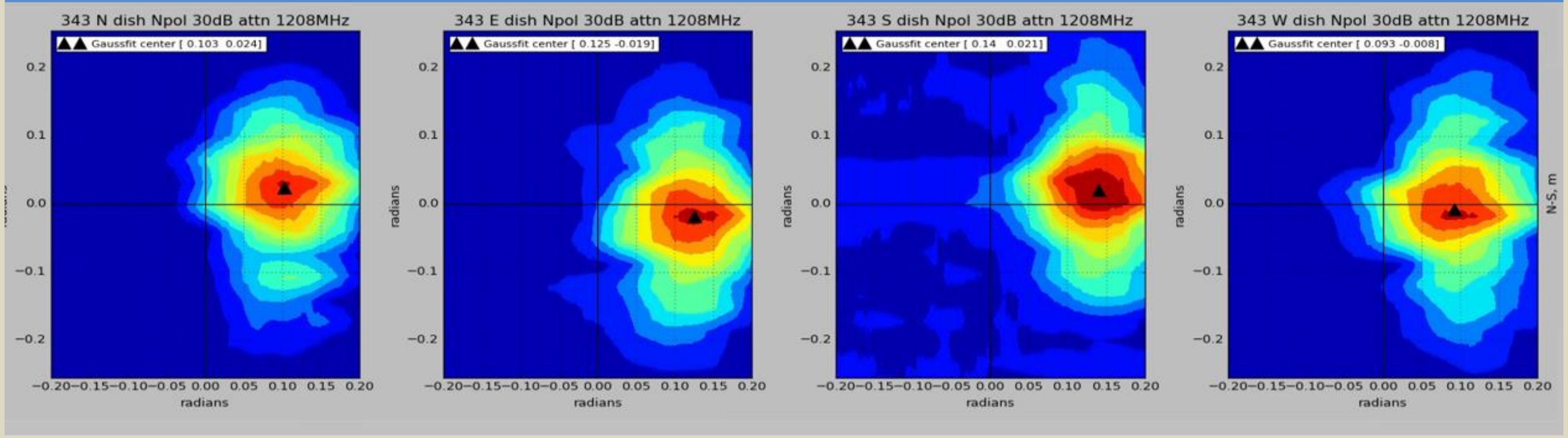


Repeat rasters in N-S, E-W heading, each polarization, each power level
Higher transmit power and larger extent used to probe sidebands

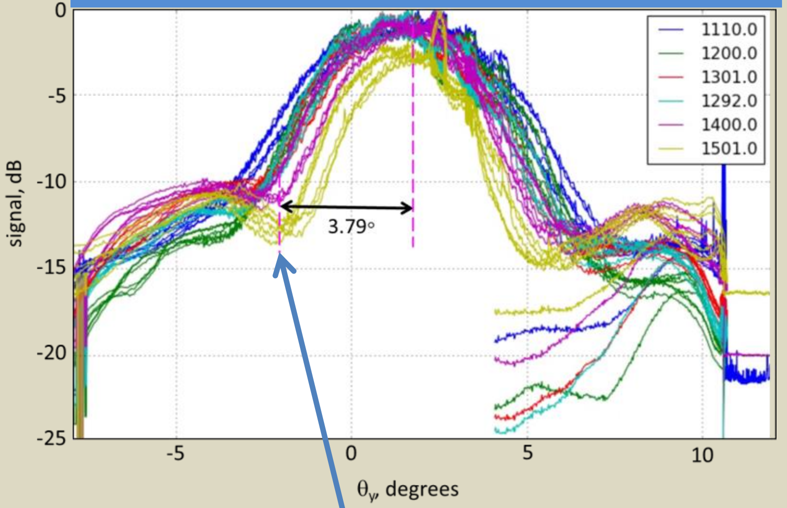


UAV calibrations

We measure the angular response of the 4 dishes…

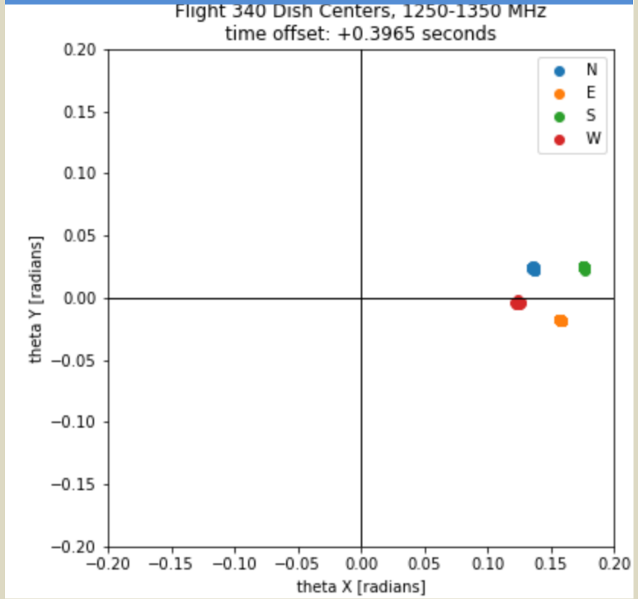


…vs frequency

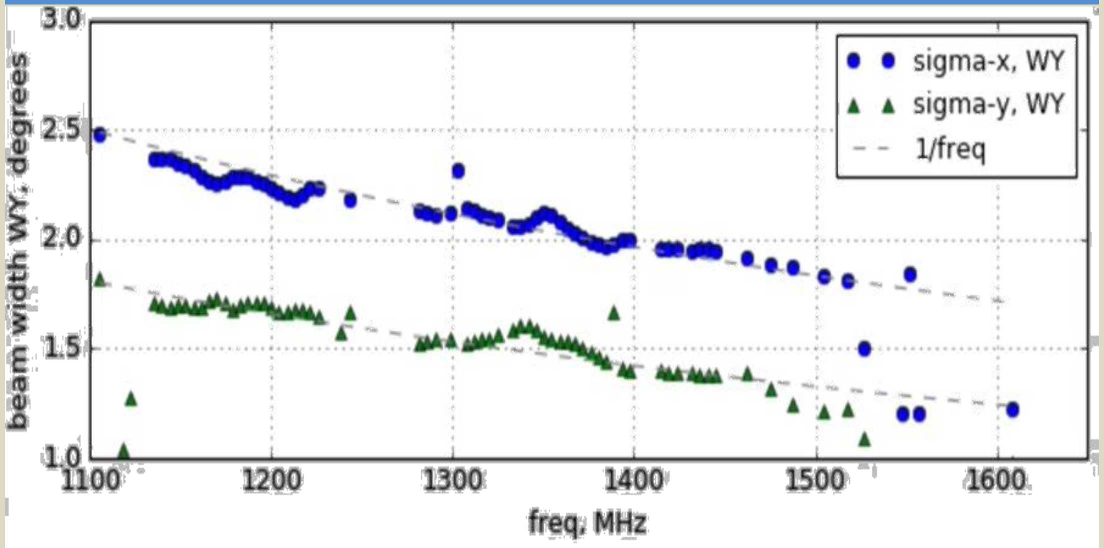


First Airy disc null for 3.95m aperture at 1500MHz

Location of the beam centers



Beam widths

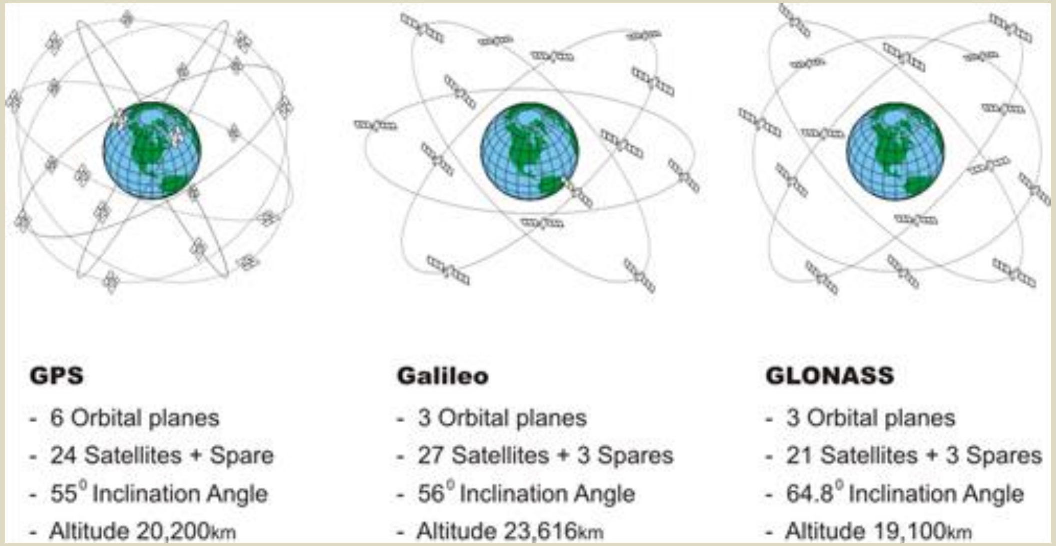


Measured data includes full frequency range and both polarizations per dish.

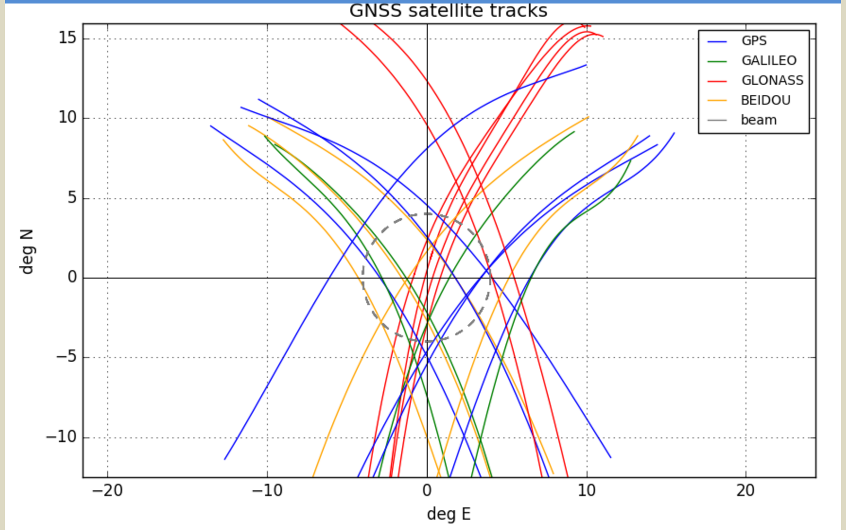
Analysis by G. Troiani

GNSS satellites: constellations, passes over BMX

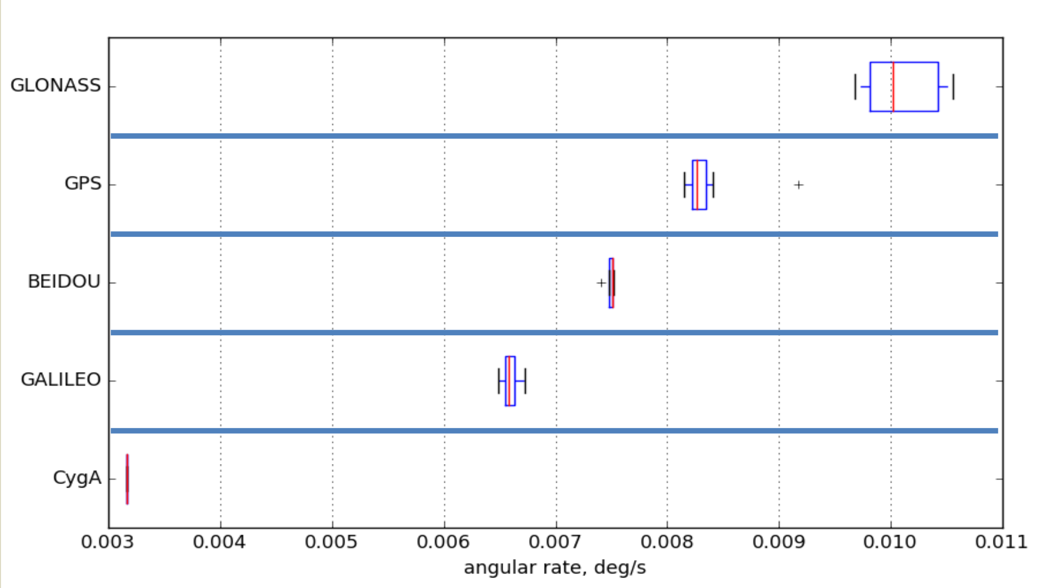
orbits



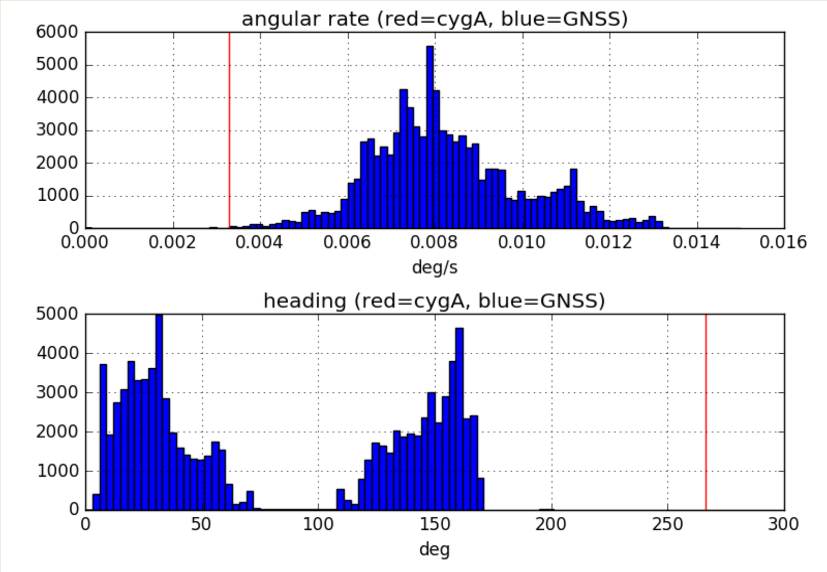
Predicted tracks over BMX



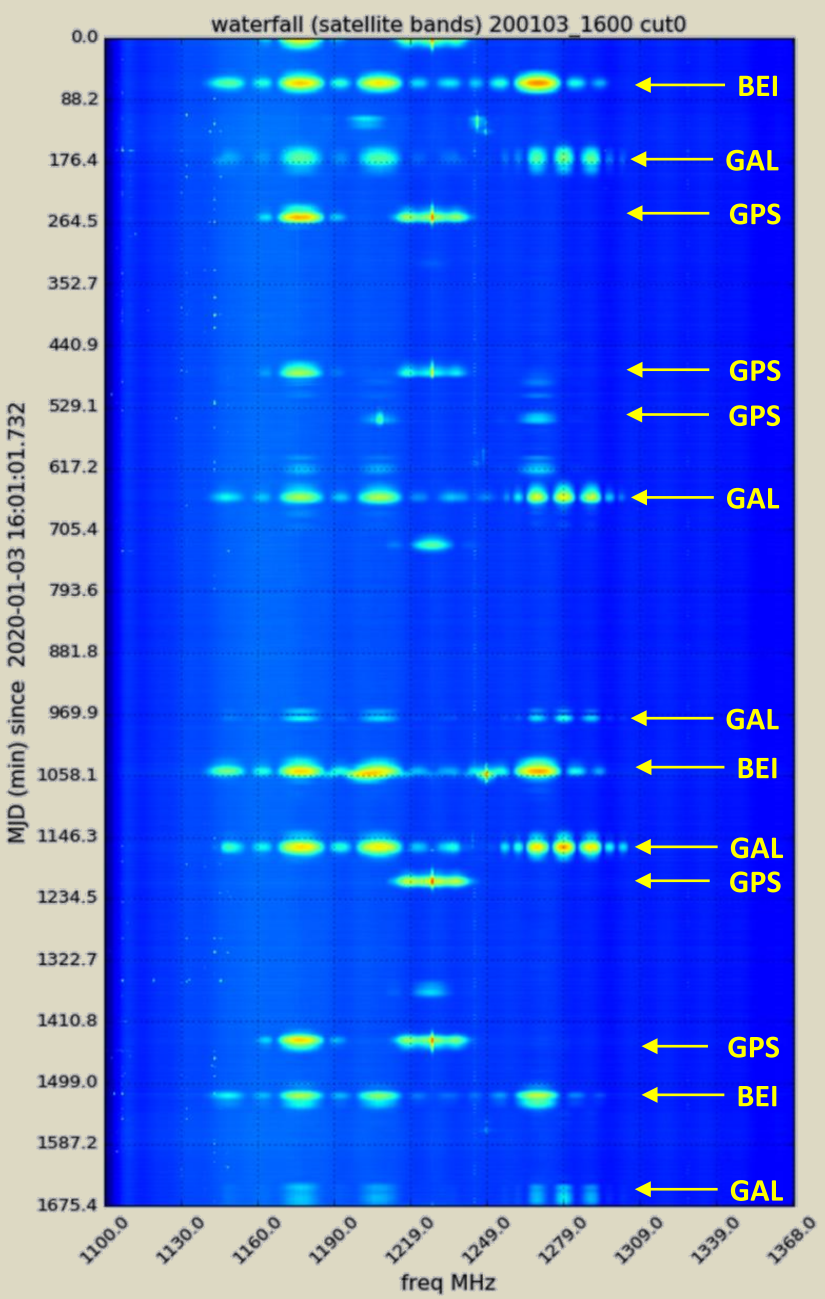
Angular rates by constellation



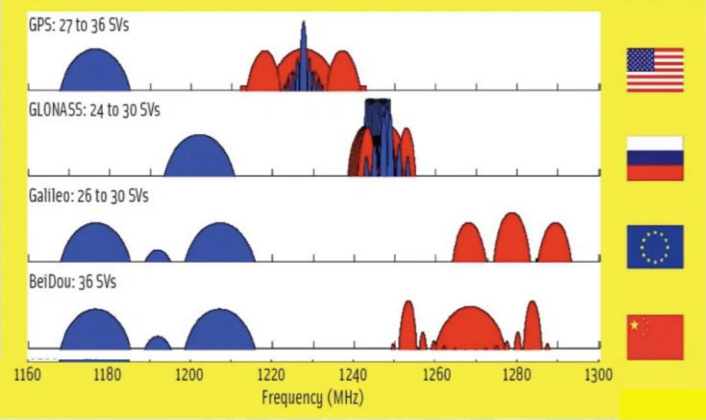
Angular rates and headings



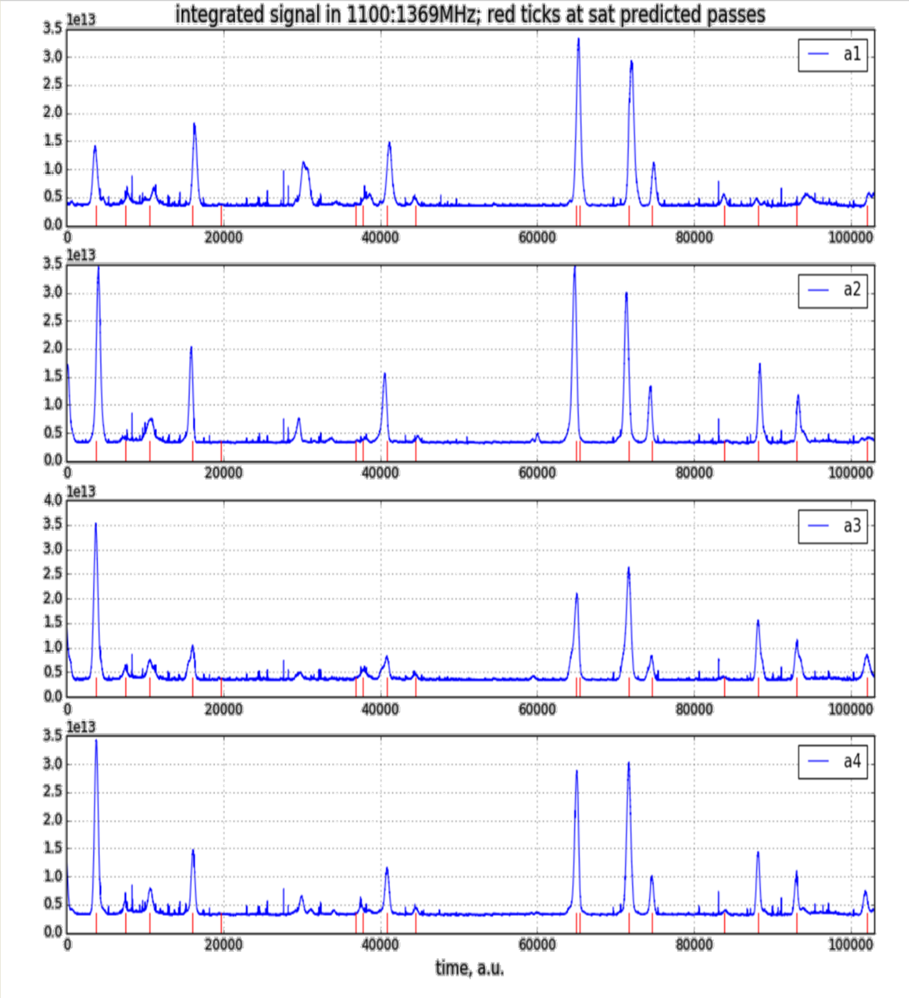
GNSS passes over BMX on 1/3/2020 (13 satellites observed in 4 constellations)



Assigned transmit bands



Observed (blue); predicted times (red)

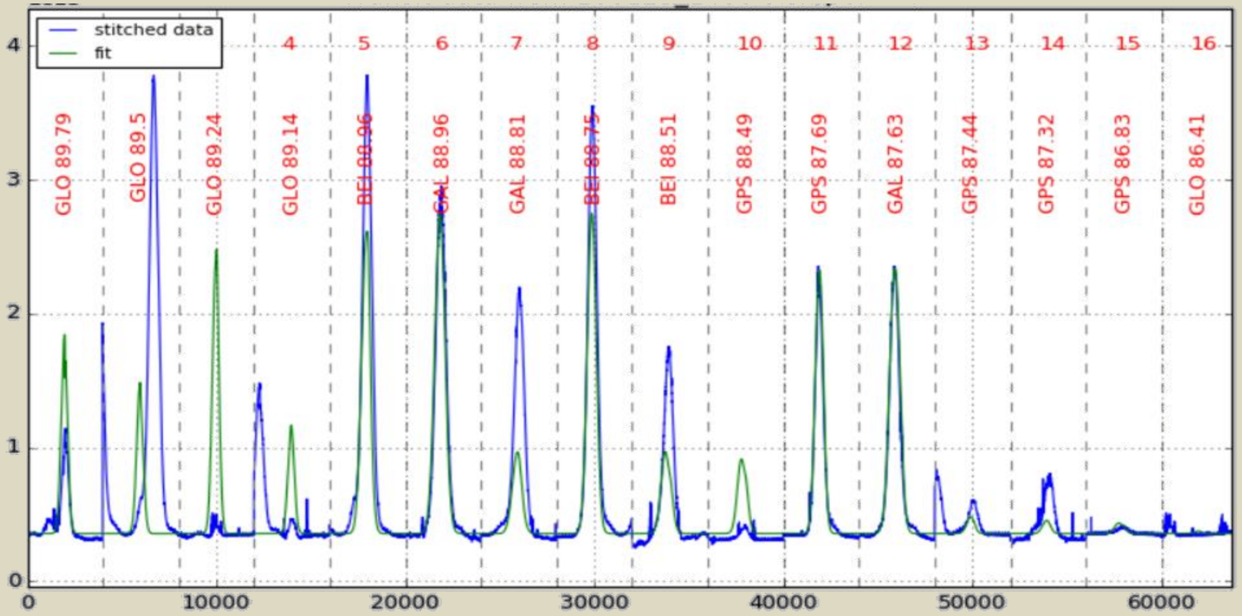


Fitting beam parameters to multiple GNSS signals

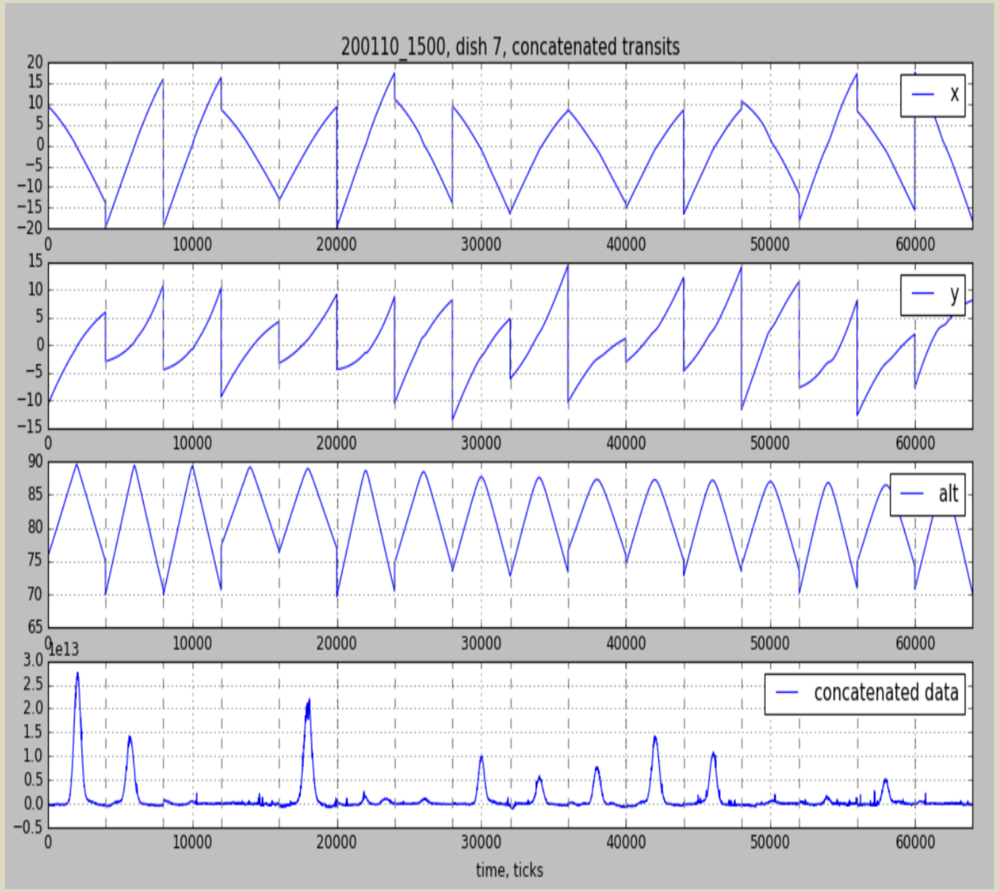
Method

- Integrate measured single-dish power over GNSS band from 1100 to 1378 MHz.
- Remove DC offsets
- Define 1-hour time windows centered around transits of up to 16 GNSS satellites (one day at a time).
- Assemble “stitched” data:
  - Data set is predicted [$\theta_x(t)$, $\theta_y(t)$], signal(t).
- Jointly fit 2D Gaussian beam model having parameters amplitude, beam pointing center and width (θ_{x0}, $\theta_{y0,}$ σ_x, σ_y).

Joint fit

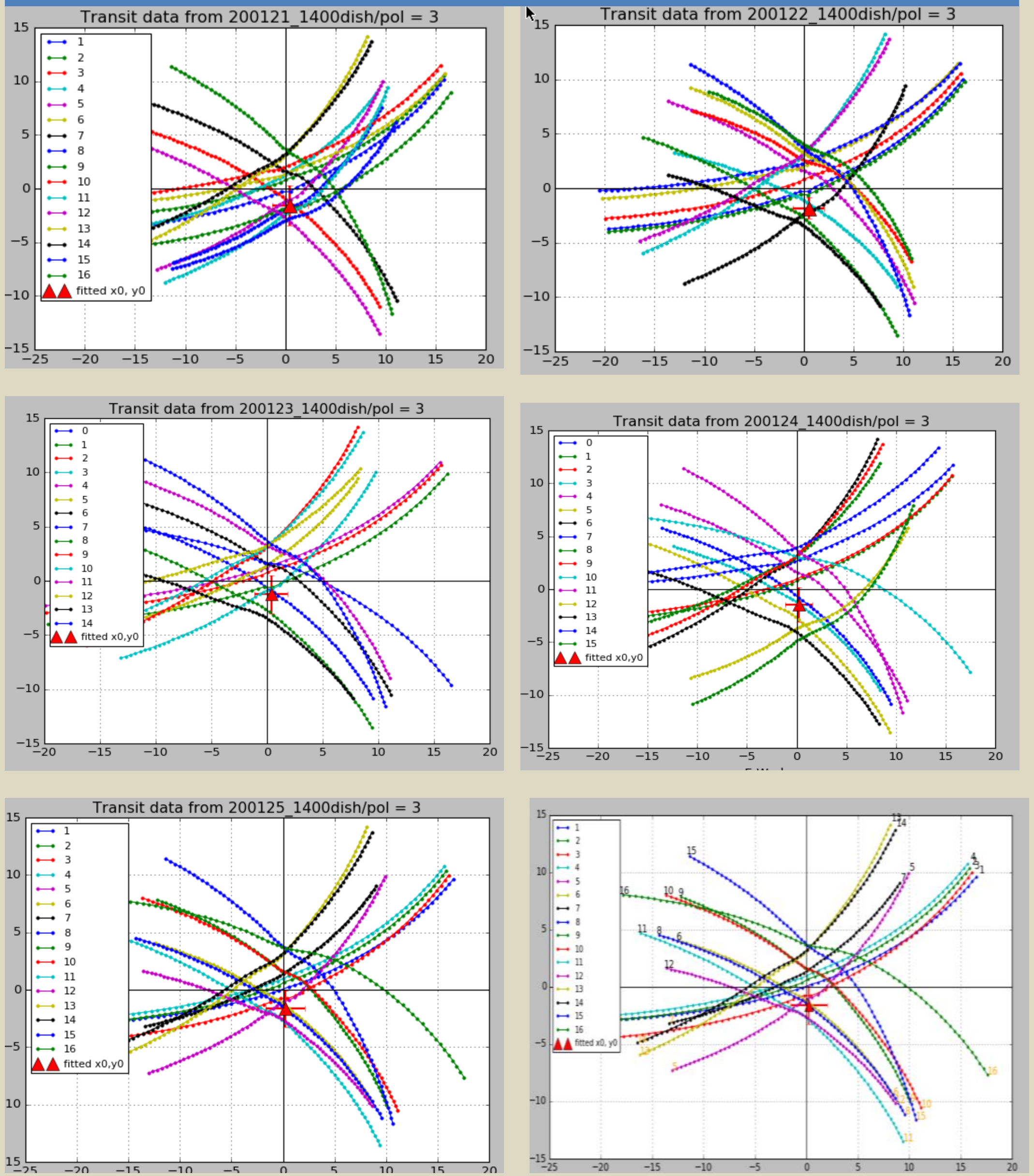


Concatenated input data set (16 satellites on 1/10/2020)



Fitted beam parameters over 21-25 Jan. 2020. Data for W dish, Y polarization

Tracks (red triangle = fit)

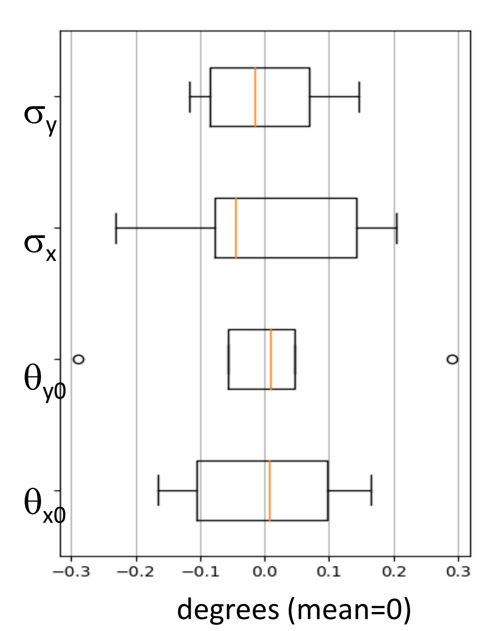


beam parameter	mean	st. dev.
θ_{x0}	0.3639	0.1229
θ_{y0}	-1.5392	0.1863
σ_x	1.5953	0.1568
σ_y	1.7222	0.1030
	deg	deg

pointing direction (θ_{x0}, θ_{y0})

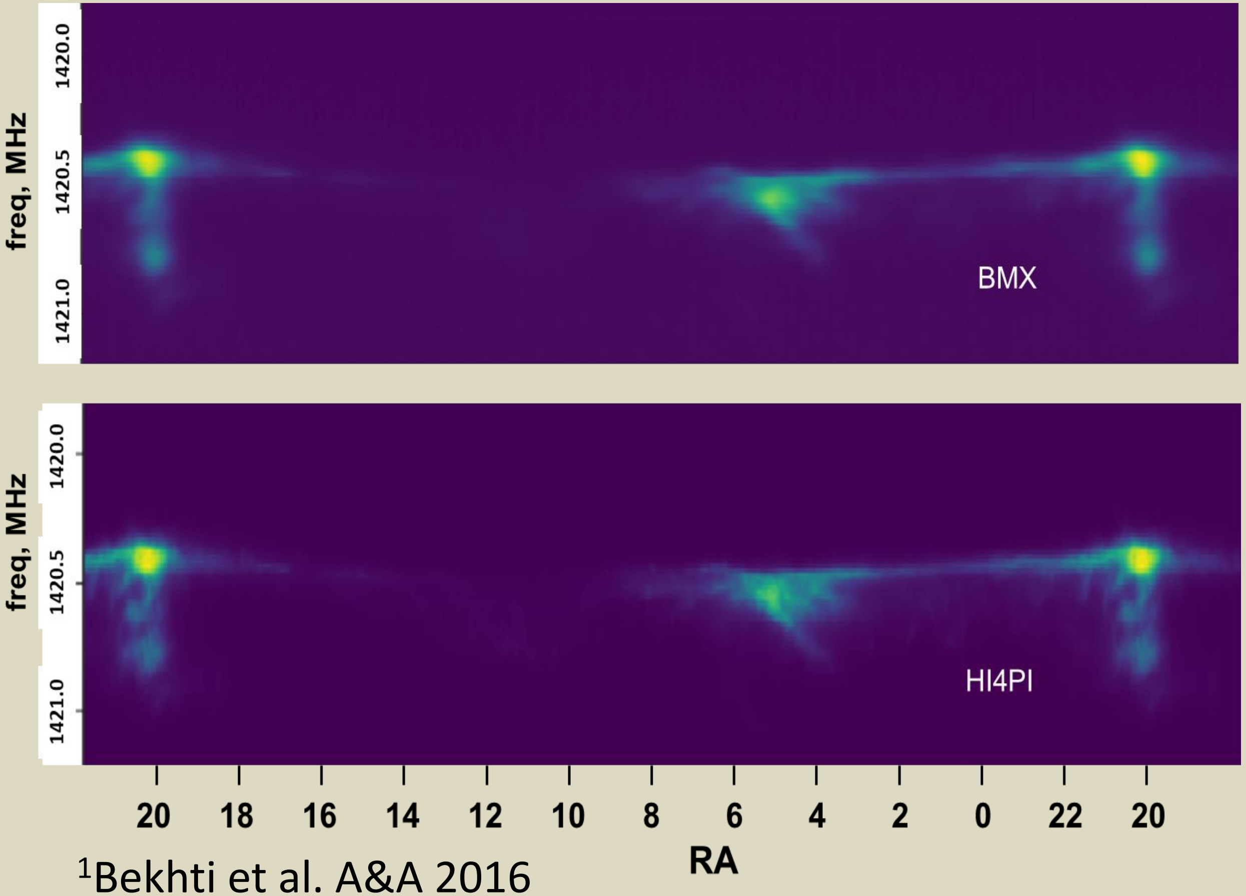
beam width (σ_x, σ_y)

statistics (mean subtracted)



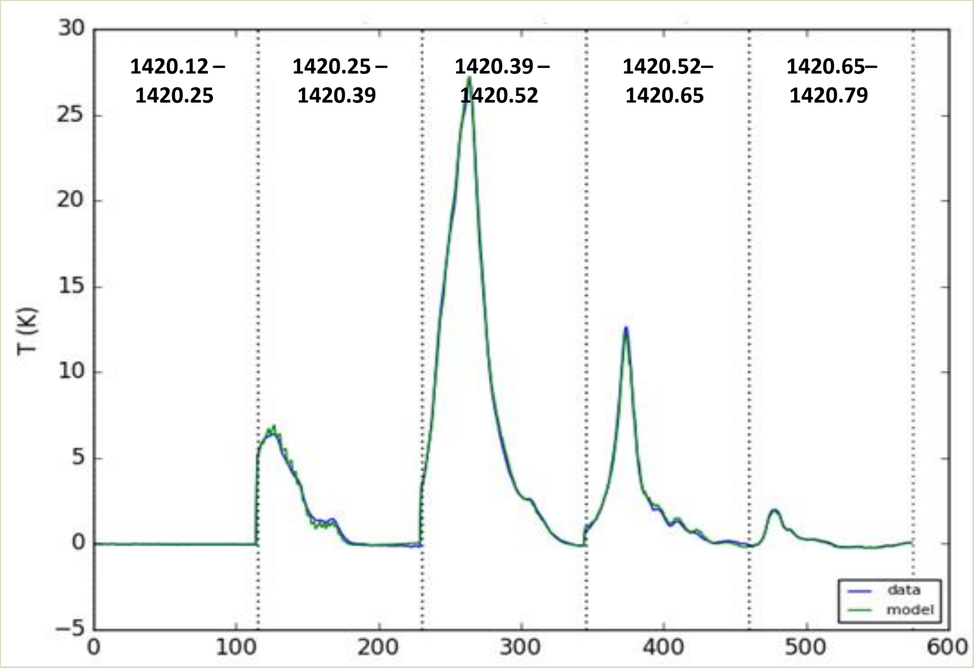
21cm clouds in Milky Way

Milky Way map in RA and frequency for the BMX strip. Top map is BMX data, bottom is rebinned data from the HI4PI survey[1]. Note, both maps start at 18h RA (left). After 24 hours, the BMX map extends to 22h the following day while the HI4PI map simply wraps around. Obs. Start: 21:45 UTC 20 October 2020.



[1]Bekhti et al. A&A 2016

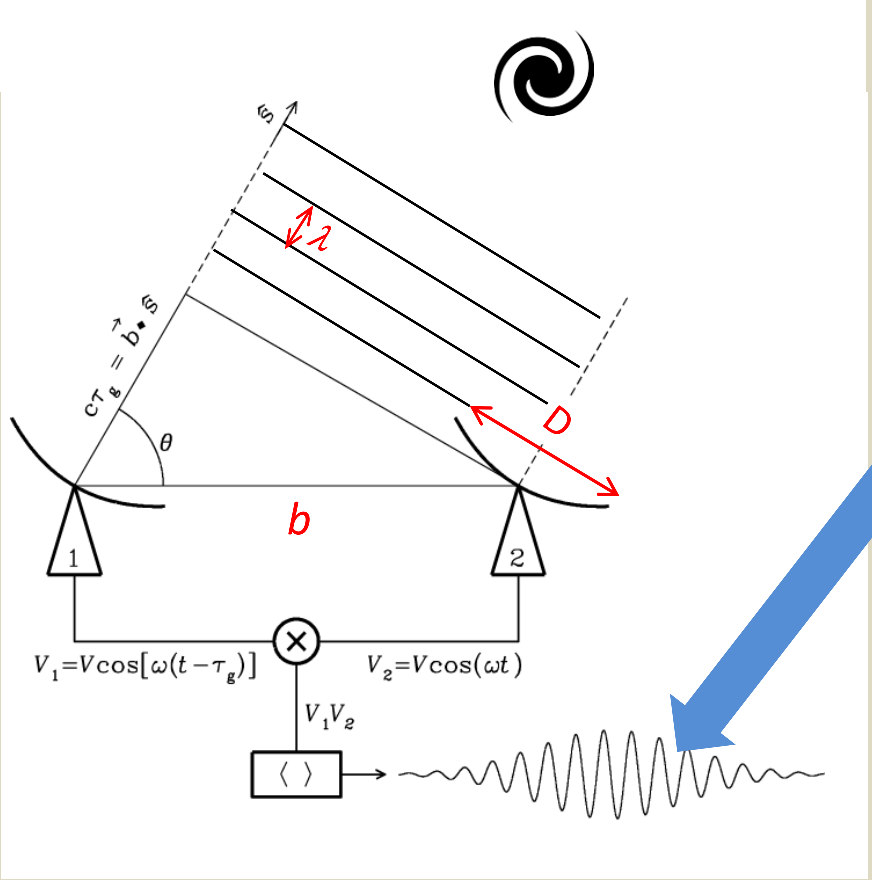
Detail of galactic HI structure. Each of the five sub-panels shows BMX spectrometer data in adjacent 130kHz frequency bins during the MW transit of 1 Dec 2017. The x-axis in each sub-panel covers the same ~100 degrees of RA. After transforming frequencies to a Local Standard of Rest (LSR) which takes into account motions of the Earth and Sun, data is fit to a Gaussian beam model (shape, pointing, frequency offset) with the HI signal predicted by the HI4PI map.



Analysis by C. Sheehy

Instrument design: radio interferometer

One baseline (N_{dish} = 2)



NRAO

Phase of the interference fringes encodes angle to source (θ):

$$R = B(\theta) \cdot e^{-i\phi}$$

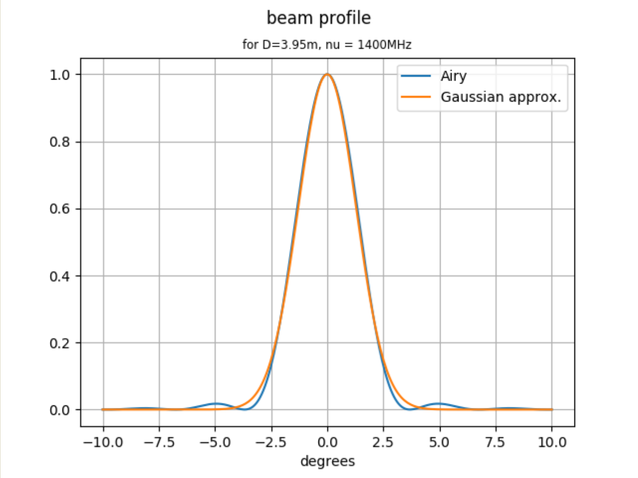
$$\phi = \frac{2\pi(\vec{b}\cdot\vec{s})}{\lambda} = \frac{2\pi|b|\cos\theta}{\lambda}$$

B(θ) = angular response of dish primary beam

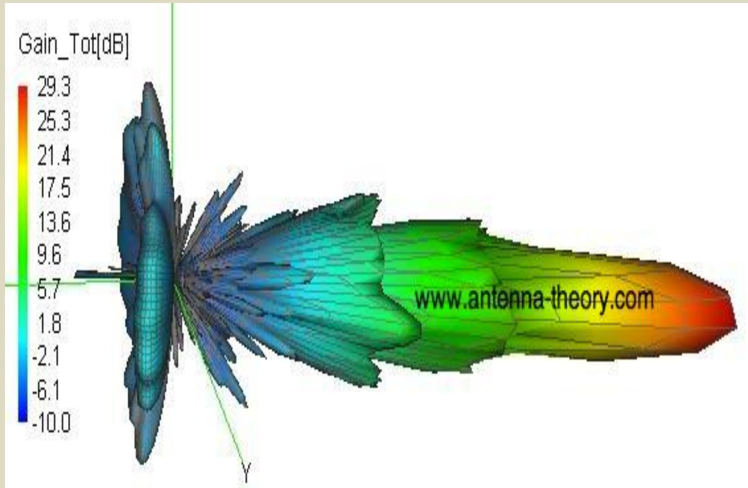
Interference fringes based on path length difference between 2 stations

- Angular resolution λ/|**b**|
- Angular field of view **λ/D "primary beam"**
- Collecting area **$\pi D^2 N_{dish}/4$**

Airy disc and Gaussian approximation



EM sim (not BMX!)



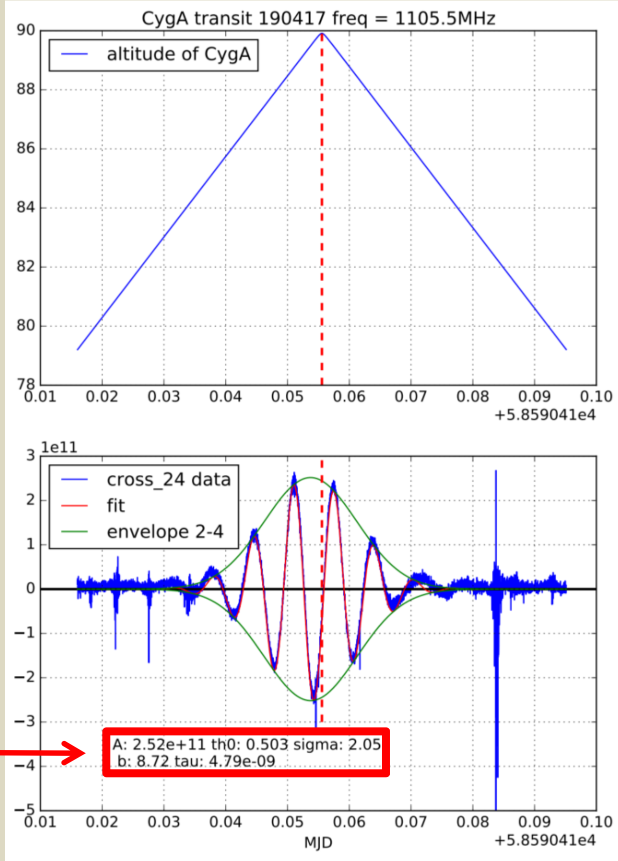
Cygnus A transit interference fringes

- BMX DAQ records cross-correlations of each pair of dishes (baselines) across the full frequency band
- Fringes with SNR ~200 are seen during transit of pointlike CygA source
- For every baseline and polarization, fit observed fringes to 1-D model having parameters: amplitude, pointing offset from zenith, width of (composite) beam in Gaussian approximation, projected baseline length in E-W direction, and time delay between signal transmission paths. Position of CygA in horizon coordinates known to high precision.
- Repeat fit for several frequency bins, avoiding regions likely to be contaminated by nearby GNSS passes.

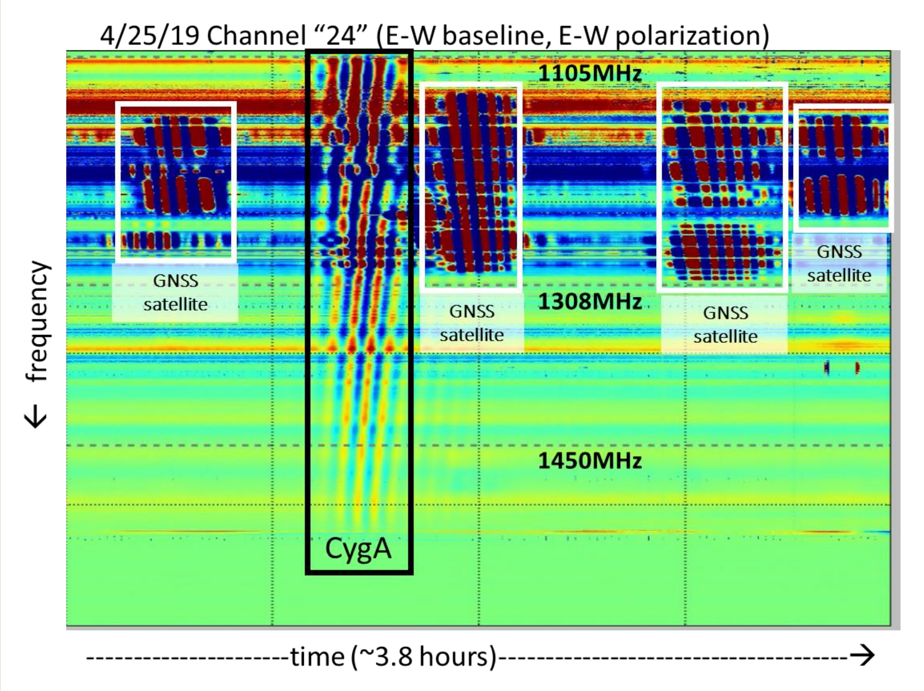
Altitude of CygA

E-W baseline b24
Fringes at 1105MHz
Data (blue), fit (red), envelope (green)

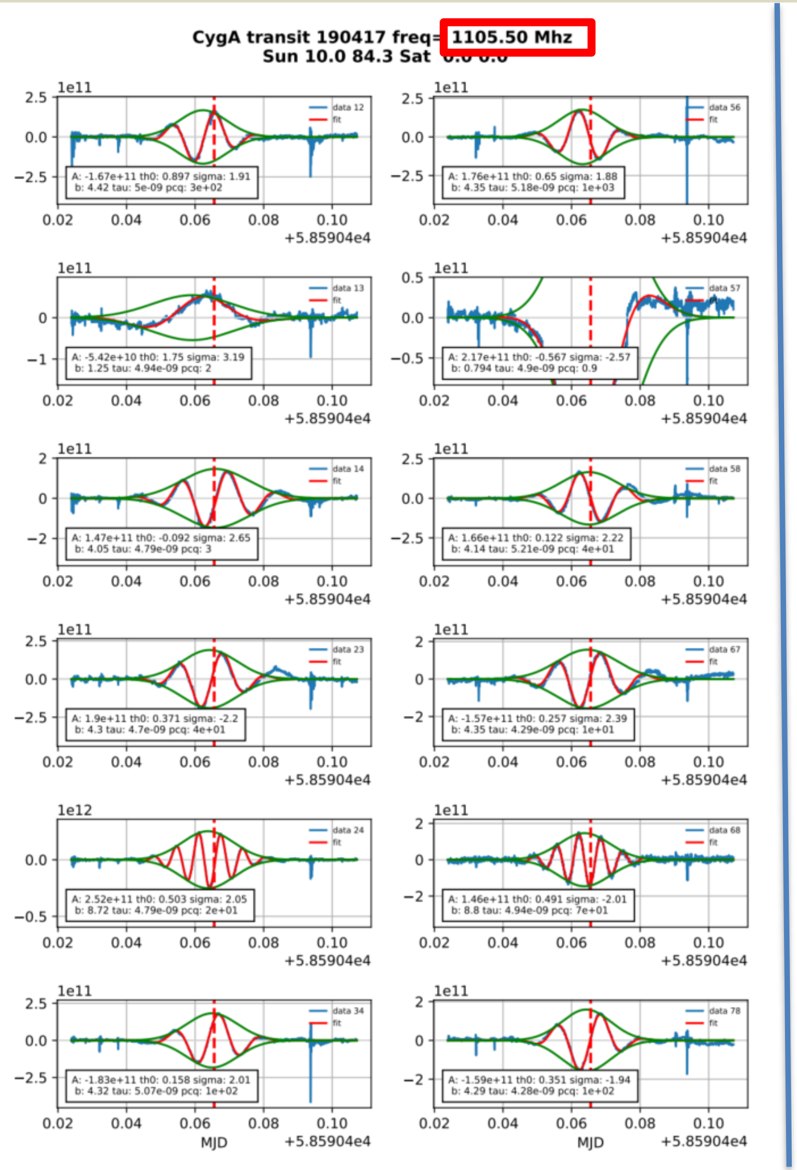
Fitted parameters →

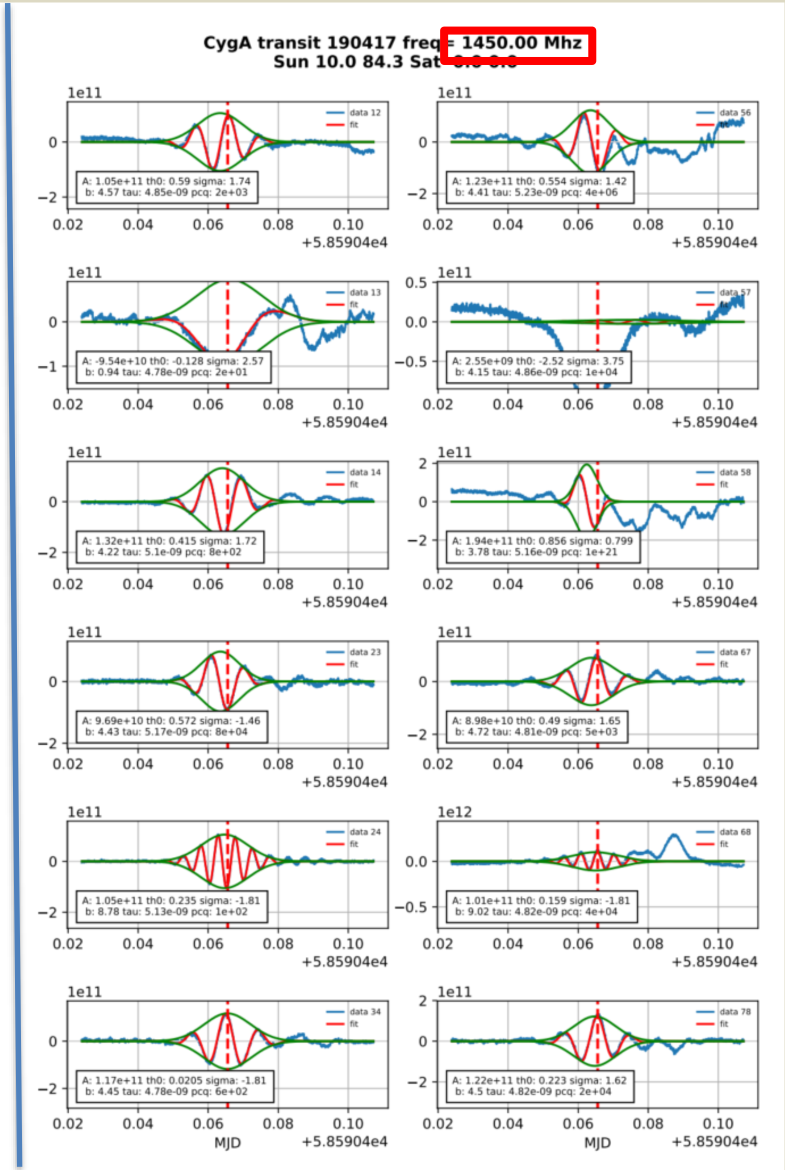


GNSS interference



Fringes from transit of 17 April 2019





$\vec{b}_{12}$

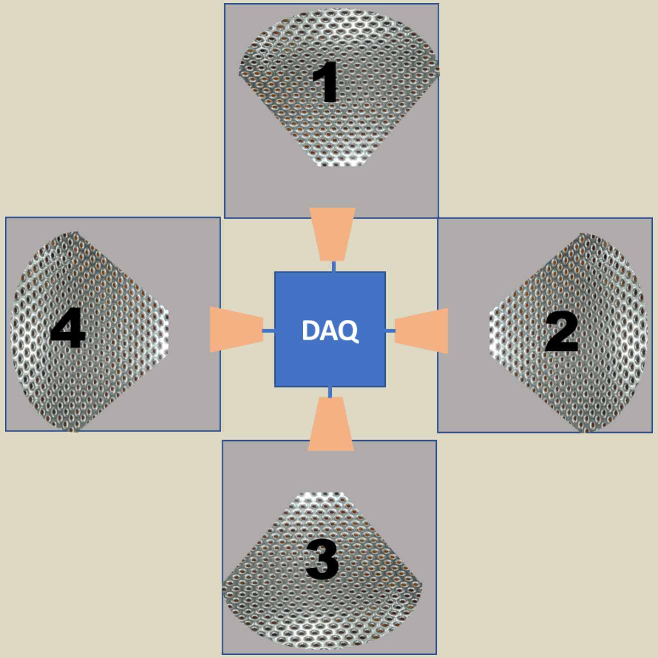
$\vec{b}_{13}$

$\vec{b}_{14}$

$\vec{b}_{23}$

$\vec{b}_{24}$

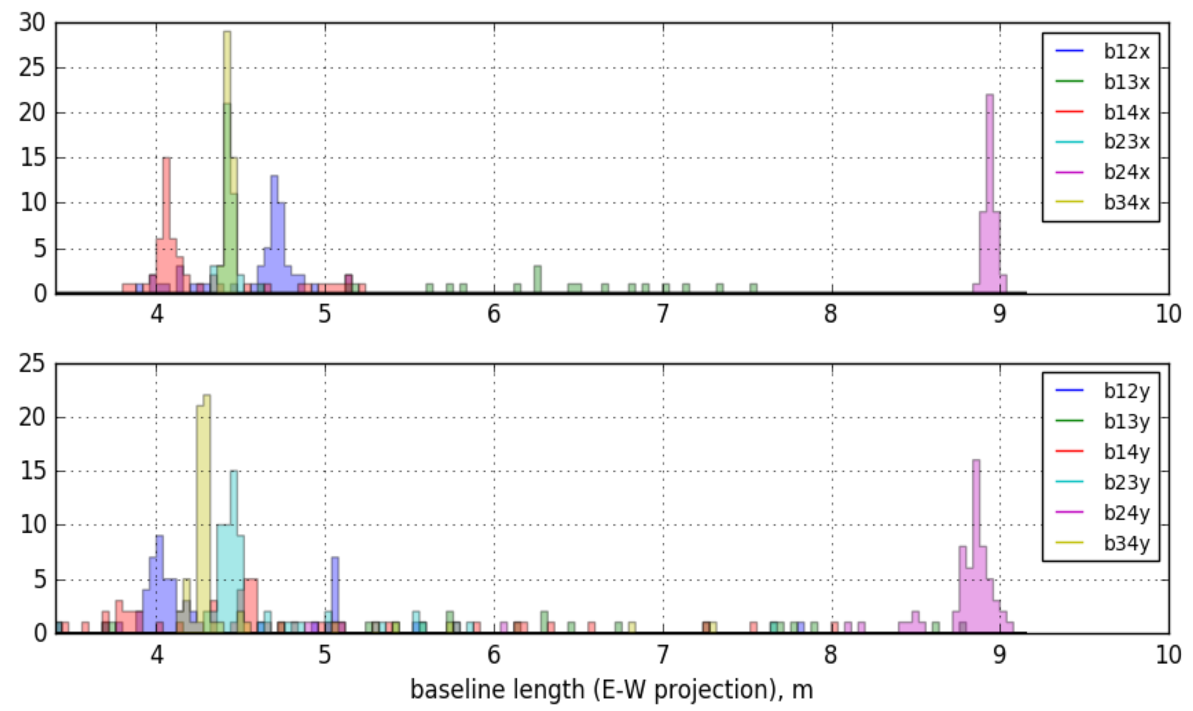
$\vec{b}_{34}$



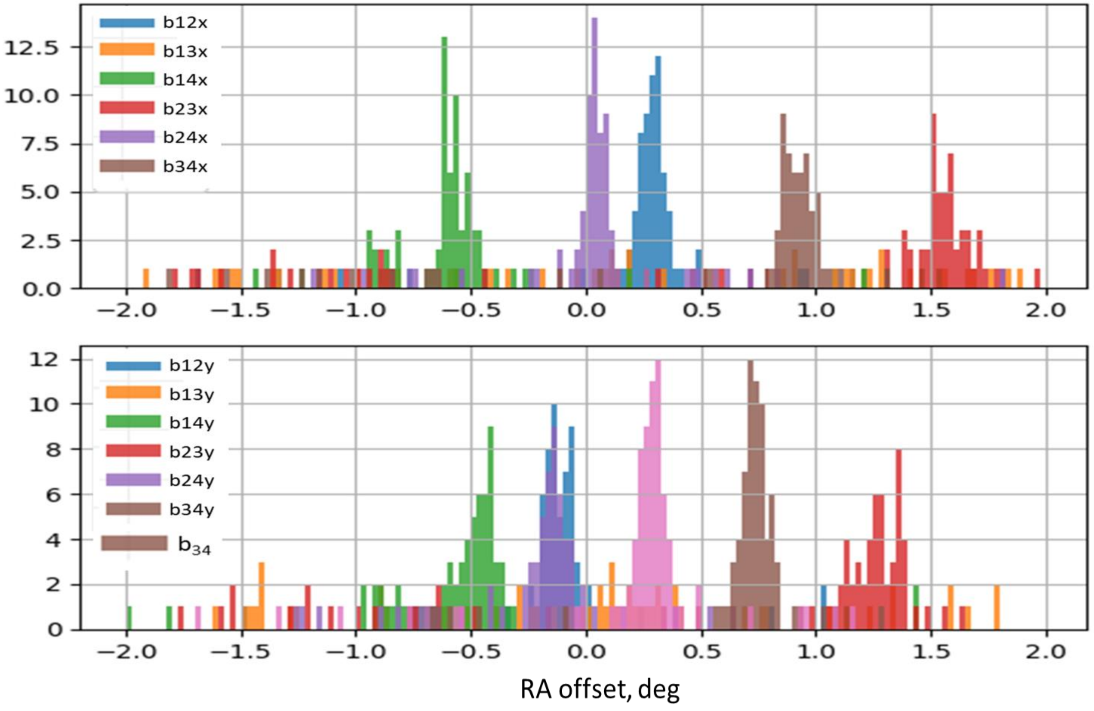
polarization Y polarization X polarization Y polarization X

Results for fit to CygA fringes

Baseline lengths (E-W projection)



RA pointing offsets

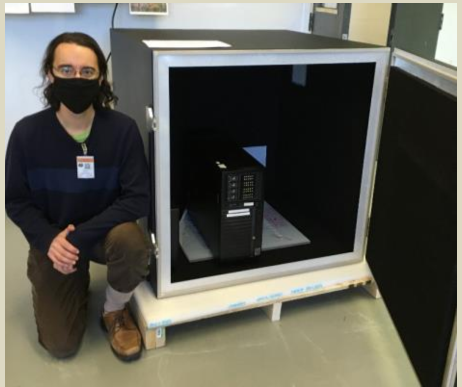


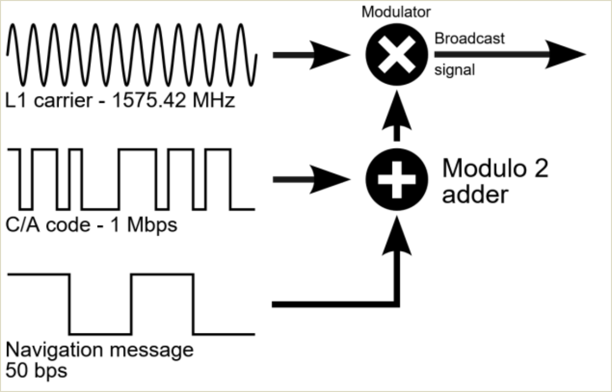
	b12	b13	b14	b23	b24	b34
X-pol	4.478 ± 0.066	2.594 ± 2.671	4.021 ± 0.075	4.277 ± 0.042	8.745 ± 0.072	4.347 ± 0.057
Y-pol	4.317 ± 0.103	1.919 ± 2.556	4.260 ± 0.071	4.301 ± 0.096	8.776 ± 0.095	4.283 ± 0.059

Note b12+b14 = b23+b34 = b24 within error

Future plans

- **BMX "tune up":**
  - Improve self-RFI environment at BMX site
  - Align beams (adjust dish and horn positions)
- **Fixed-wing drone**
- **EM Sims of beam shape**
- **Analysis improvements**
- **Replace digitizer + channelizer with RFSoC-based platform**
- **GPS navigation message decoding**
- **Acquire stable data for ~months**
  - detect cosmic 21cm signal at $0 < z < 0.3$ in cross-correlation with galaxy survey





Summary

- BMX is an R&D test bed for 21cm line intensity mapping
- During 2019 – present we have been investigating beam and array calibrations
- Calibrators include UAV, satellite, and astrophysical sources
- Post-COVID plans for additional telescope upgrades and UAV flight campaigns
- Calibration R&D is on the critical path for assessing feasibility of a future large scale survey

Acknowledgement:
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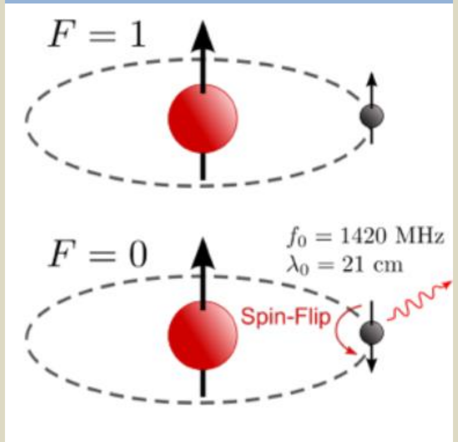
BNL Instrumentation Division
OHEP KA-25 program
BNL Office of Educational Programs
Mar. 2020 UAV flight campaign conducted with support from Yale Physics

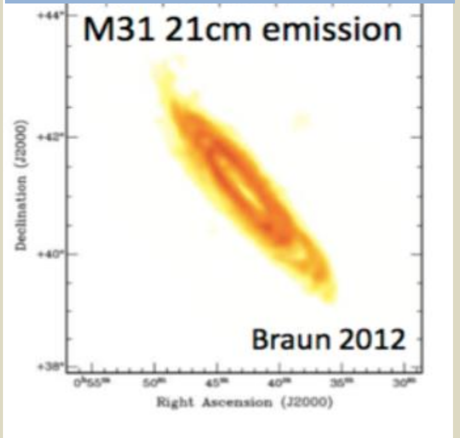
BACKUP MATERIAL

Origin and ubiquity of 21cm emission

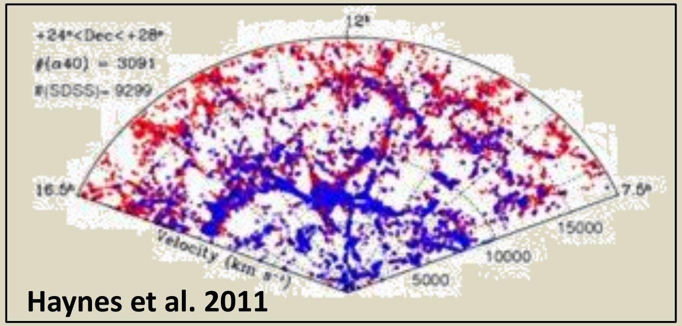
Spin-flip transition of neutral hydrogen



Nearby galaxy M31 imaged in 21cm

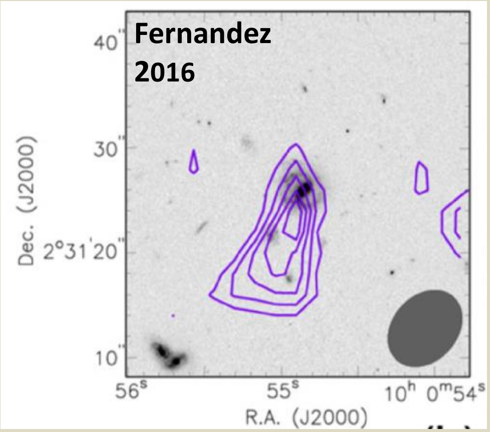


21cm and optical surveys detect similar structure to z ~ 0.07



Red: SDSS optical
Blue: ALFALFA 21cm

Highest redshift detection (z = 0.376)



Grey: optical
Purple: 21cm

Spectral line at 21cm rest-frame wavelength is ***sharp*** and ***isolated***
→ Once detected, provides ***precise redshift***

Intensity Mapping technique

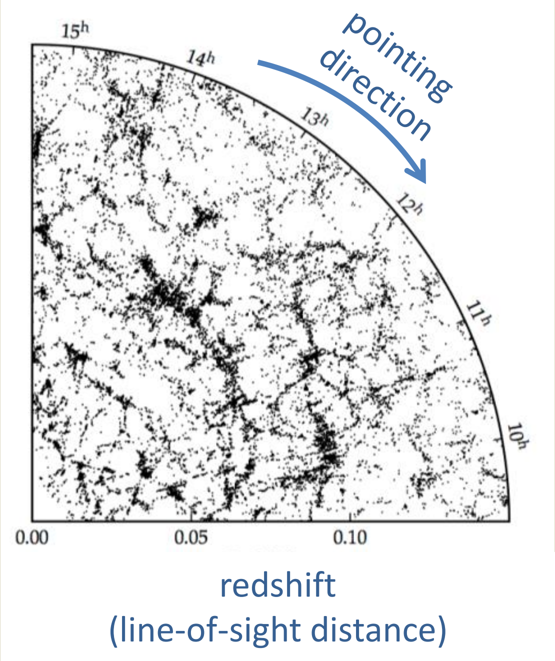
Traditional galaxy survey:

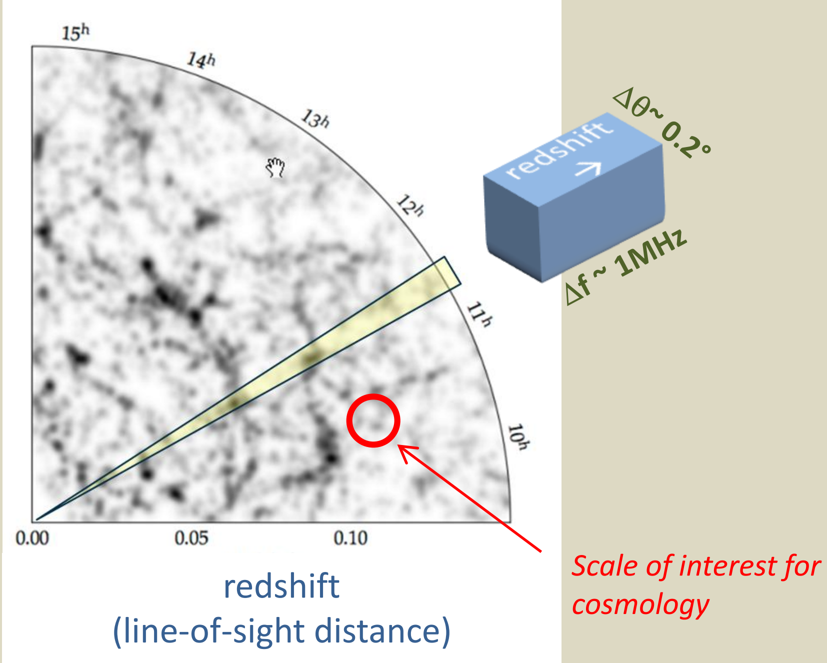
- individual sources observed, one at a time with spectrograph

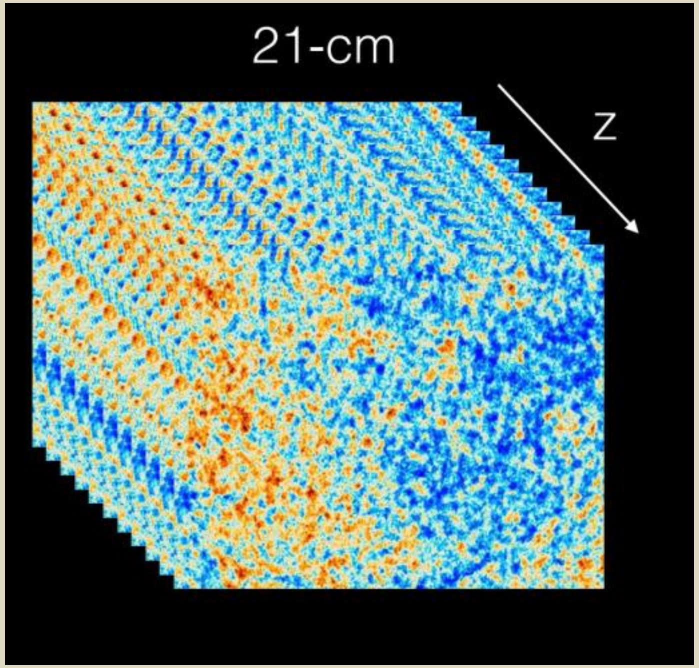
Intensity mapping survey:

- integrated emission observed as a function of frequency (redshift)
- choose $\Delta\theta$, Δf to be sensitive to scales of interest to cosmology

Build up tomographic reconstruction of density field across large volume of space





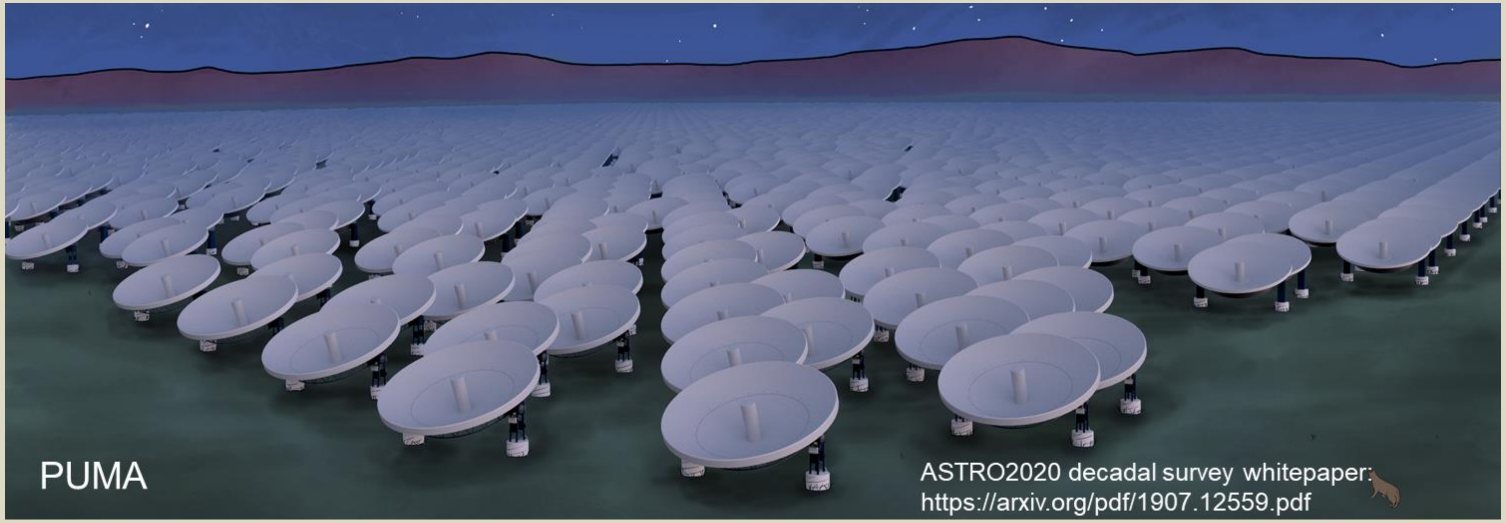


- Several 1st-generation IM dark energy experiments online, under construction, and proposed: CHIME (Canada), HIRAX (S. Africa), BINGO (Brazil), TIANLAI (China)
- US participation minimal at this time

A concrete example: Packed Ultrawideband Mapping Array (PUMA)

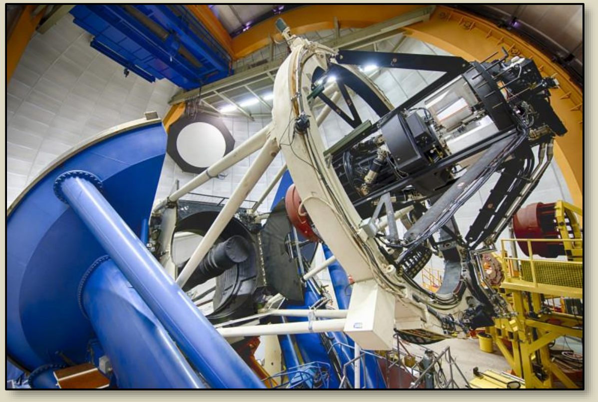
- A next-generation cosmic survey using intensity mapping of the 21-cm emission from neutral hydrogen
- Proposal submitted to the ASTRO2020 Decadal Survey and Snowmass LOI call
- Interferometric array of 32,000 (5,000) six-meter dishes closely packed
- Redshift range 0.3 < z < 6 corresponding to 1100 < ν < 200 MHz
- Primary science goals:
  - ***Probing physics of dark energy in the pre-acceleration era***
  - ***Searching for signatures of inflation***
  - ***Probing the transient radio sky (fast radio bursts and pulsars)***

PUMA
packed ultra-wideband mapping array



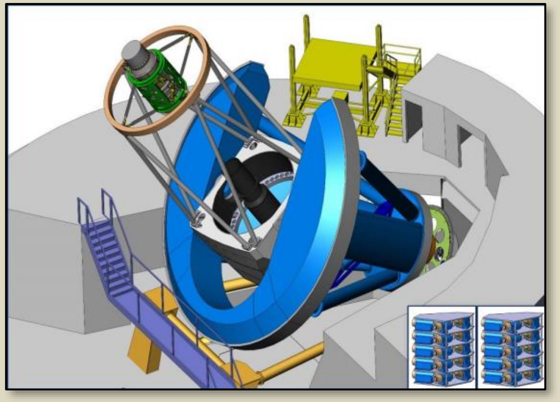
Current/Upcoming OHEP-sponsored cosmic surveys

Dark Energy Survey (DES)



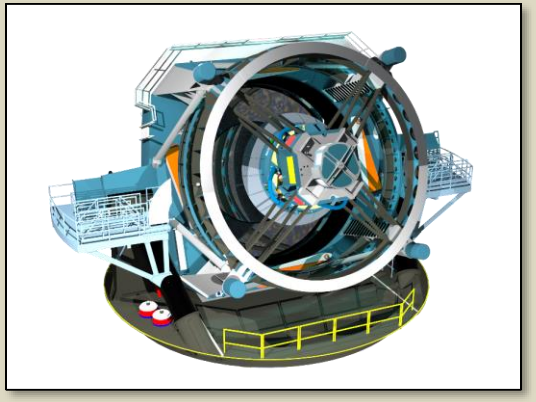
Galaxy Imaging, broadband filters
504 Mpix CCD Focal Plane
Operations 2014 - 2019

Dark Energy Spectroscopic Instrument (DESI)



Galaxy Spectra
5000 Fiber Focal Plane
Operations 2019- 2024

Large Synoptic Survey Telescope (LSST)



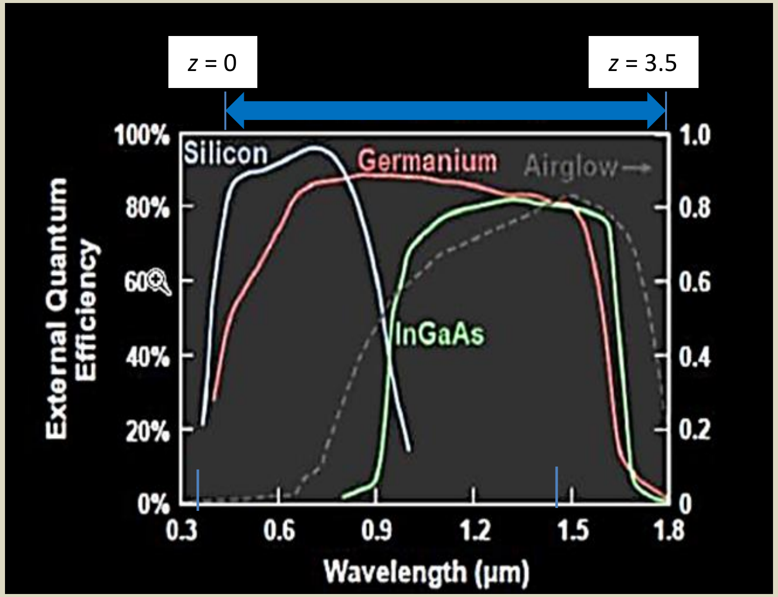
Galaxy Imaging, broadband filters
3.2 Gpix CCD Focal Plane
Operations 2023 - 2033

?

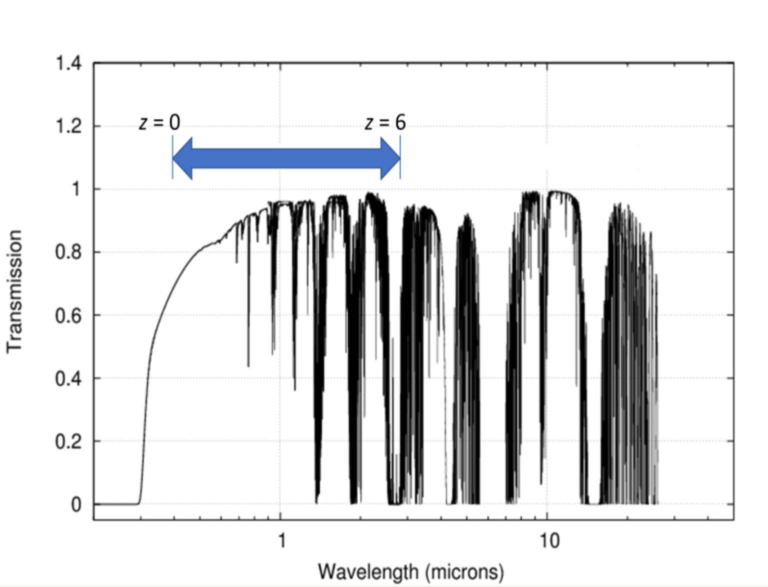
- Power of a cosmic survey to measure cosmological parameters is limited by
  - ***redshift range and accuracy***
  - ***sensitivity (number of sources)***
  - ***scale***
- Improved statistics has to come from increasing ***survey speed*** and/or increasing ***sensitivity to fainter/redder*** sources, while preserving redshift accuracyr.

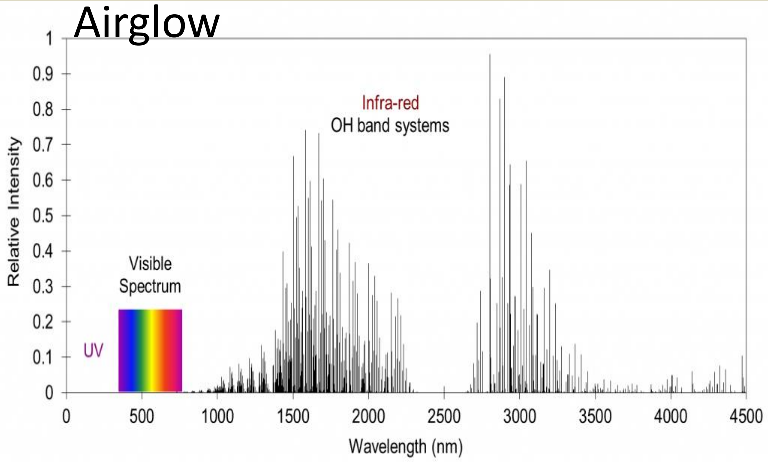
Obstacles to scaling optical surveys

Detector technology for IR

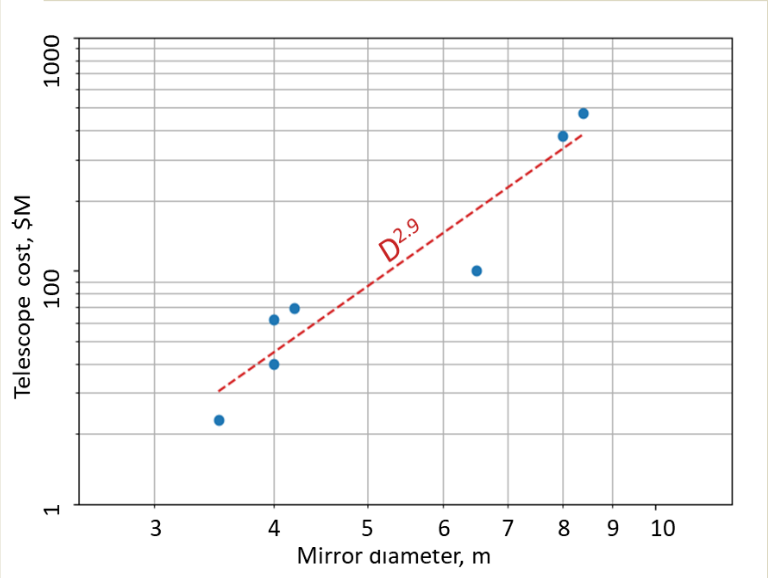


Atmospheric transparency in IR





Telescope cost scaling



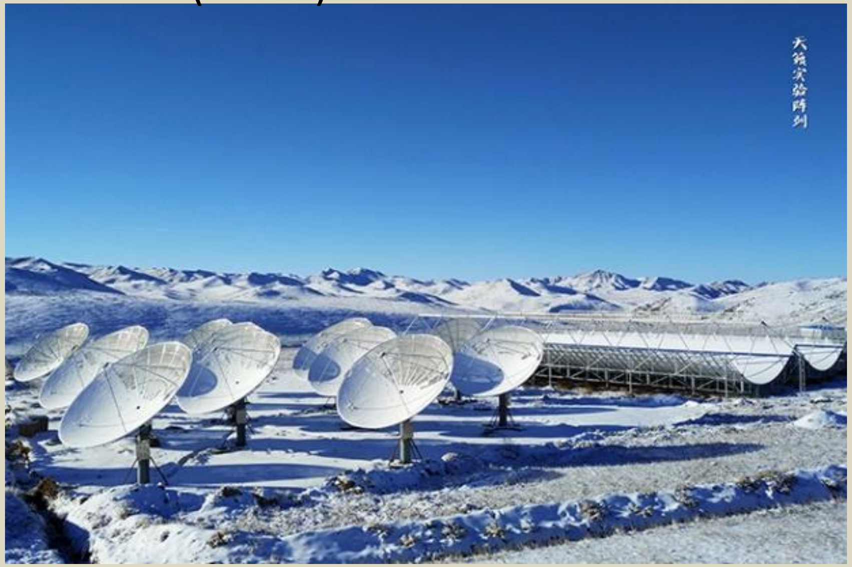
Let's consider another wavelength range…

21cm intensity mapping experiments (0.8 < *z* < 2.6)

CHIME (Canada)

HIRAX (S. Africa)

TIANLAI (China)

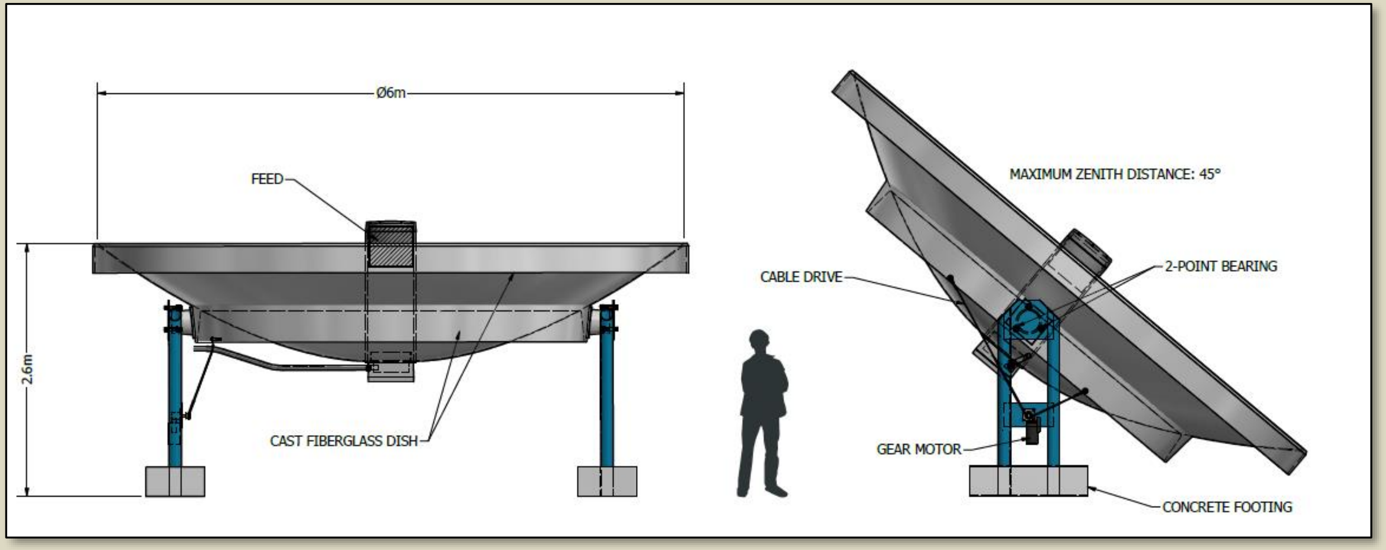


PAON-4 (France)

Low-cost dish construction methods

BMX dish

Notional PUMA dish



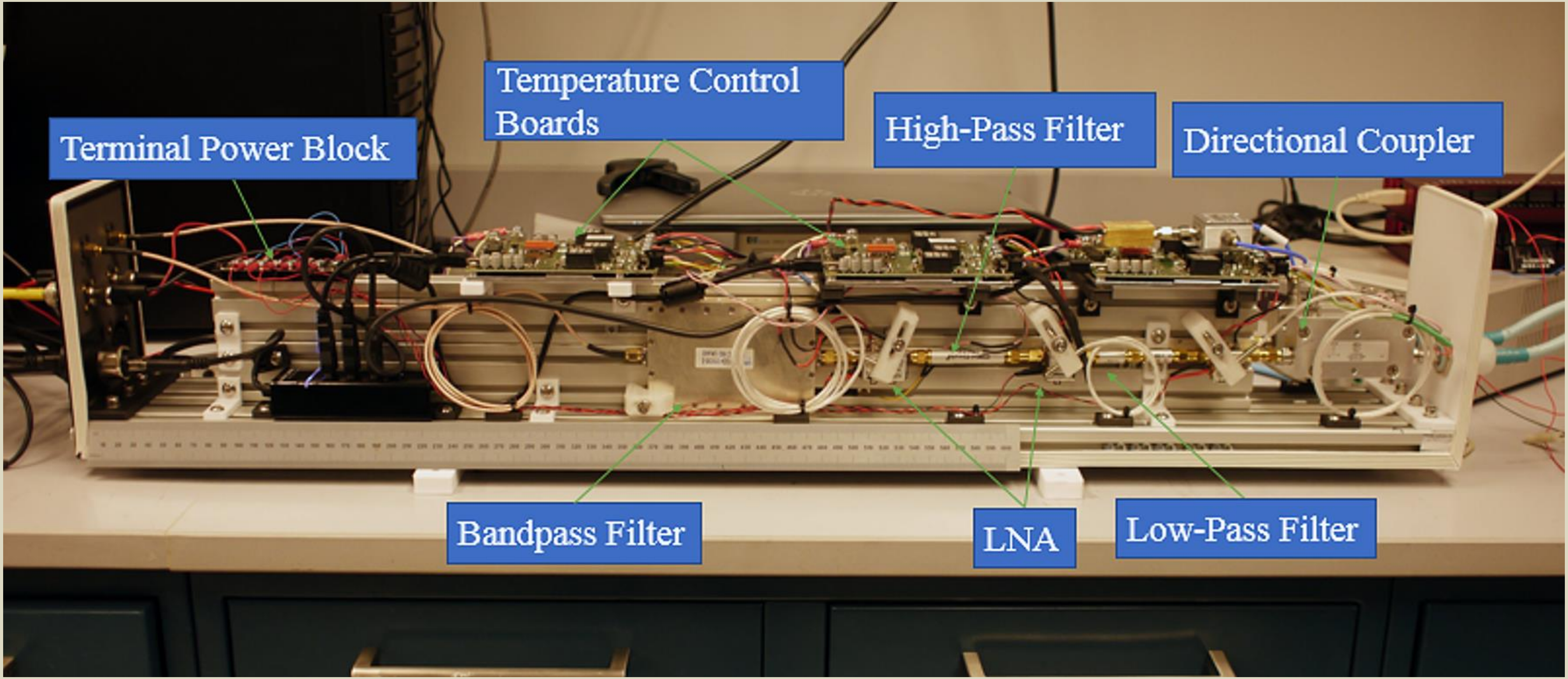
Composite dish construction

CHORD

HIRAX

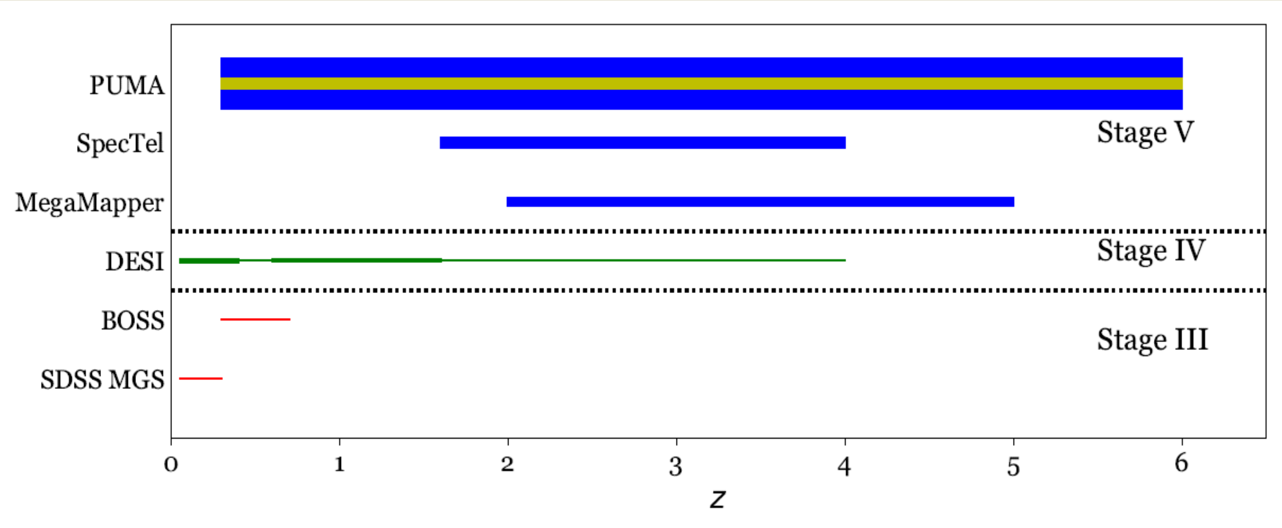
SKA

FEE box

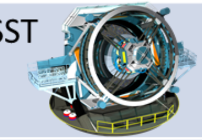
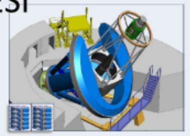


Temperature Control Boards
Terminal Power Block
High-Pass Filter
Directional Coupler
Bandpass Filter
LNA
Low-Pass Filter

Galaxy statistics and redshift range vs. optical galaxy surveys



Length of bar = redshift range
Area of bar = effective galaxy number

Instrument	Survey duration	# Galaxies observed	Redshift accuracy	Redshift range
LSST 	10 yrs	4B	Modest	0.3 < z < 3
DESI 	5 yrs	35M	High	0 < z < 3
PUMA 	**5 yrs**	**2.9B effective**	**High**	**0.3 < z < 6**

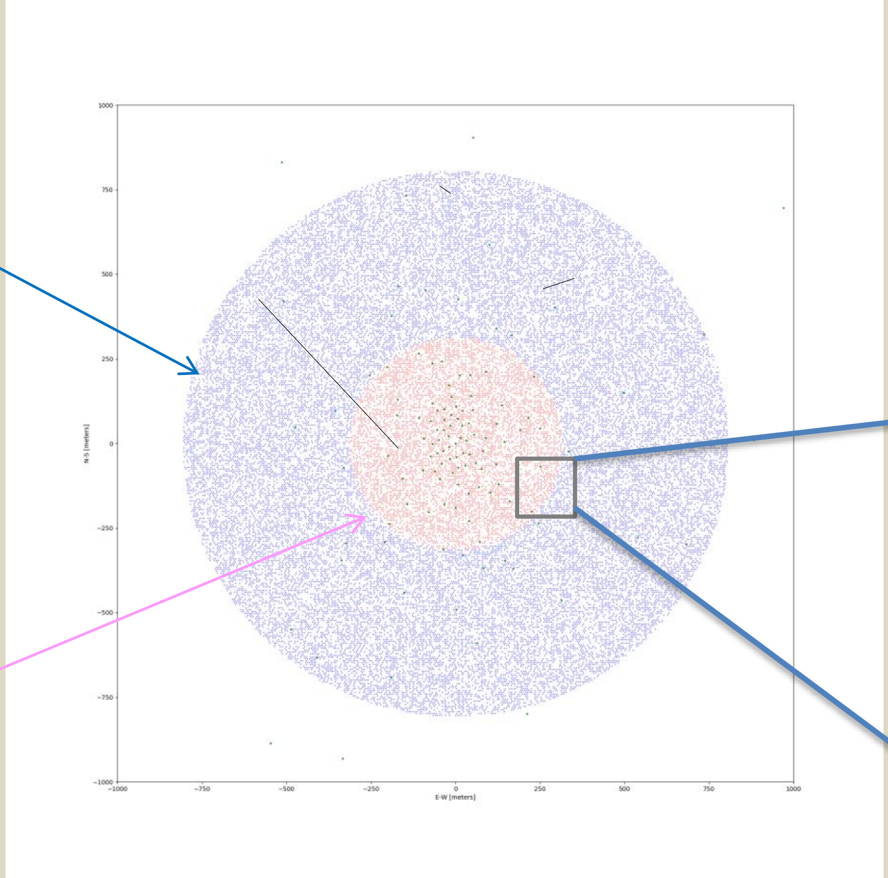
Speed of LSST, accuracy of DESI

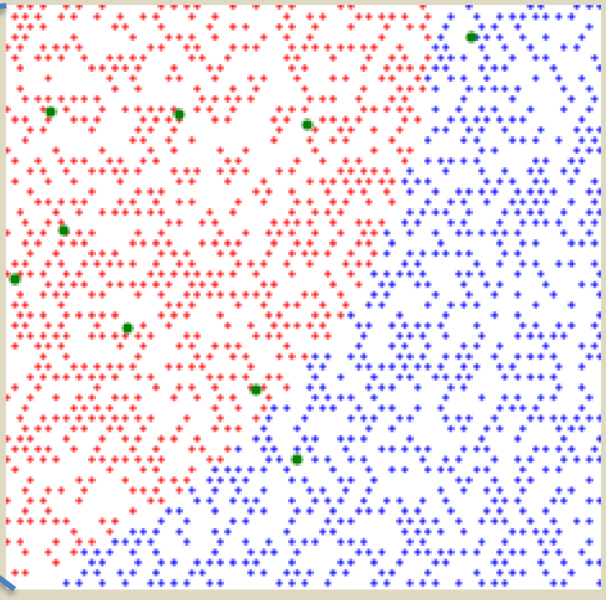
Instrument design: radio interferometer (large-N)

Many baselines (N_{dish} = 5000/32000)

PUMA 32K

PUMA 5K





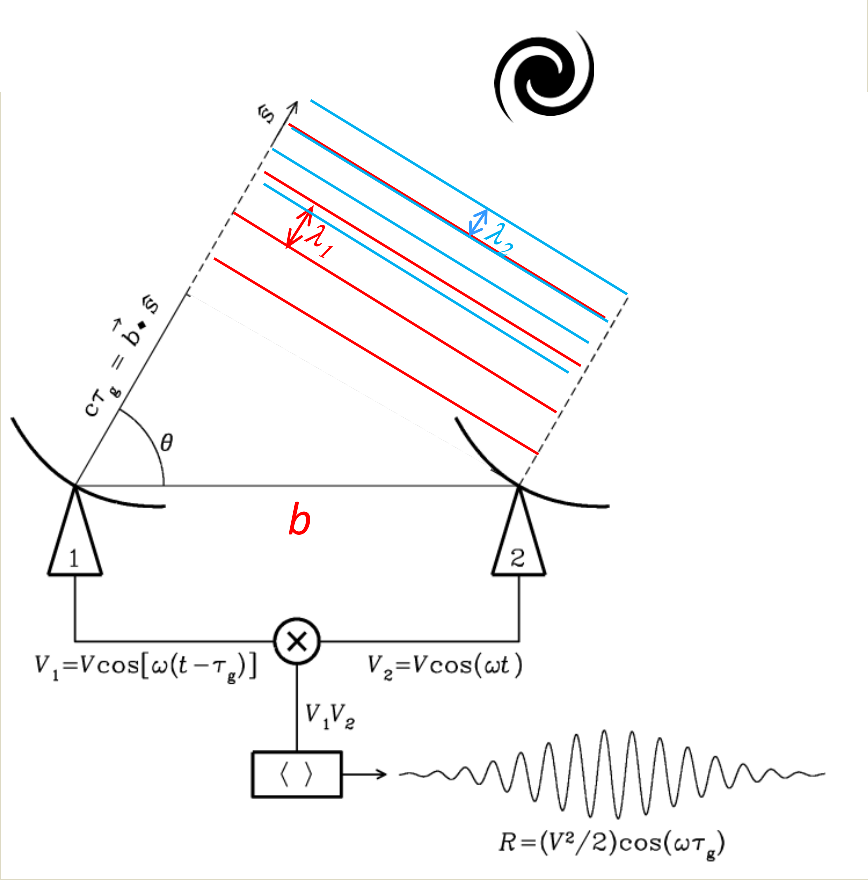
Every pair of stations provides a baseline

$N_{baselines} = N_{dish}(Ndish - 1)/2$

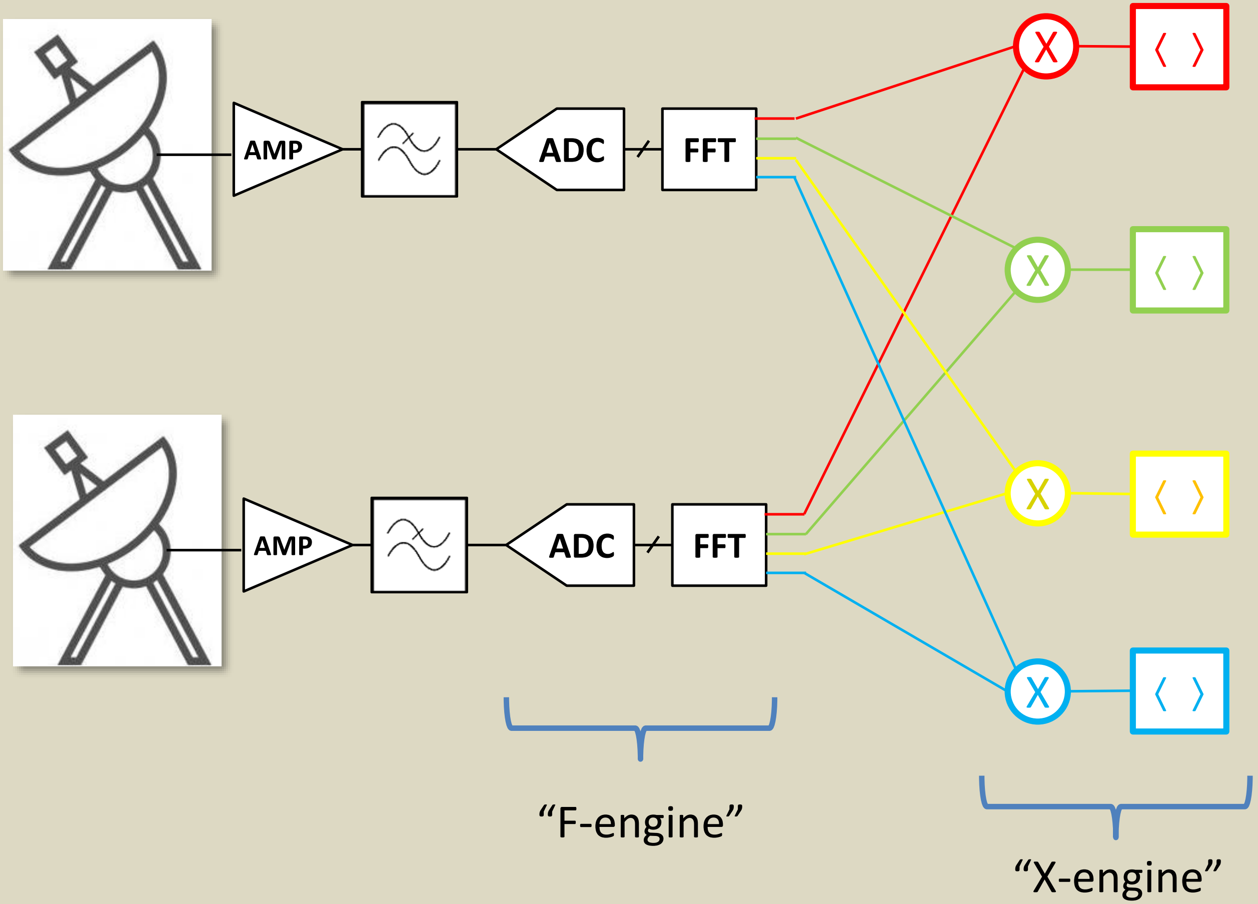
Each baseline probes a corresponding spatial frequency

Instrument design: radio interferometer (polychromatic)

One baseline (N_{dish} = 2)



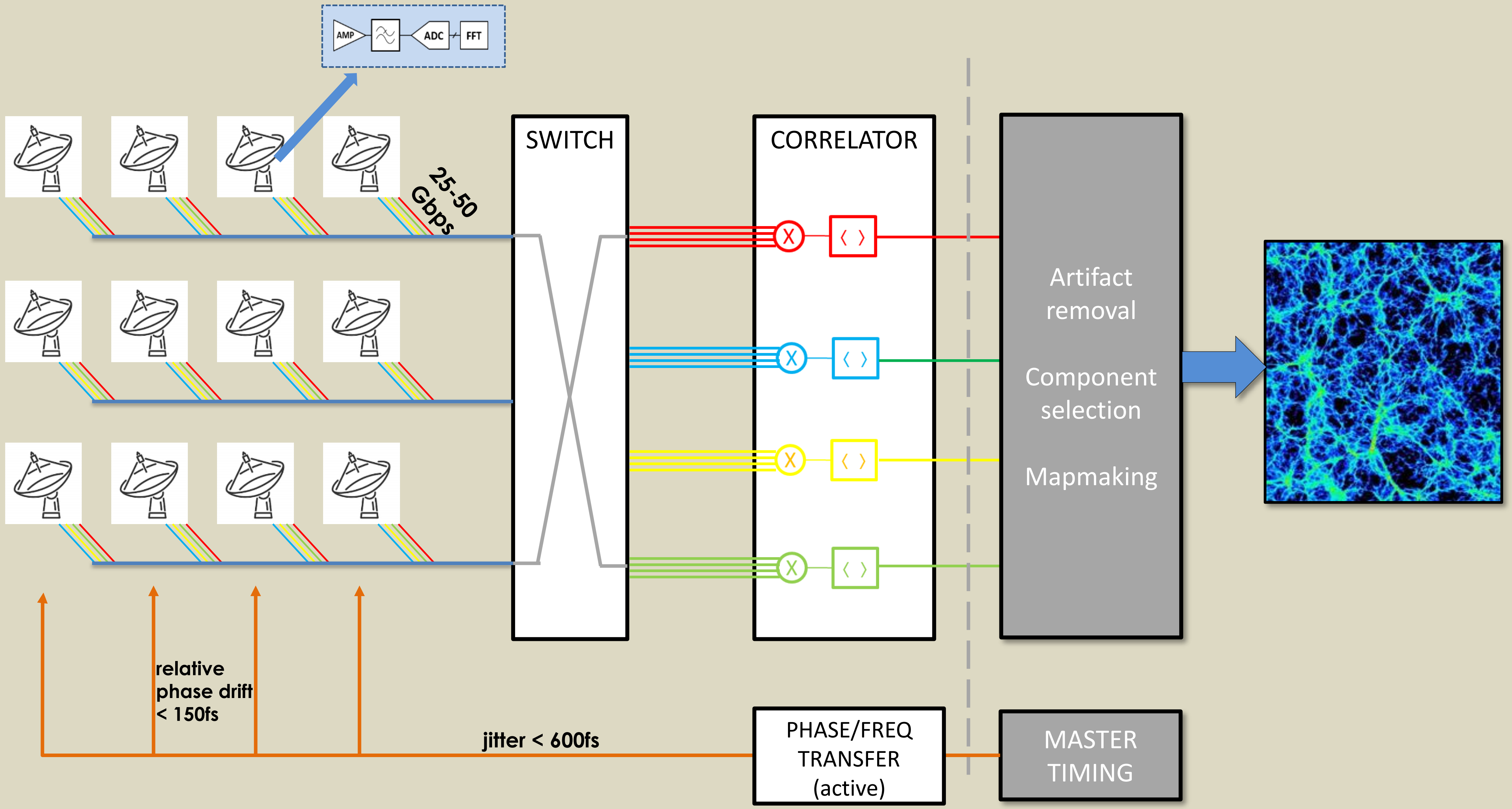
NRAO



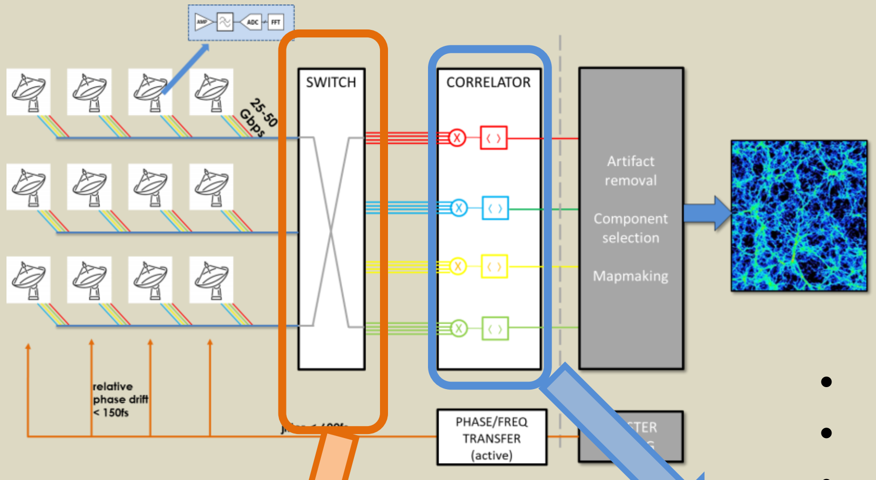
Interference fringes based on path length difference between 2 stations

- Collecting area **$\pi D^2 N_{dish}/4$**
- Angular resolution **λ/b**
- Angular field of view **λ/D**

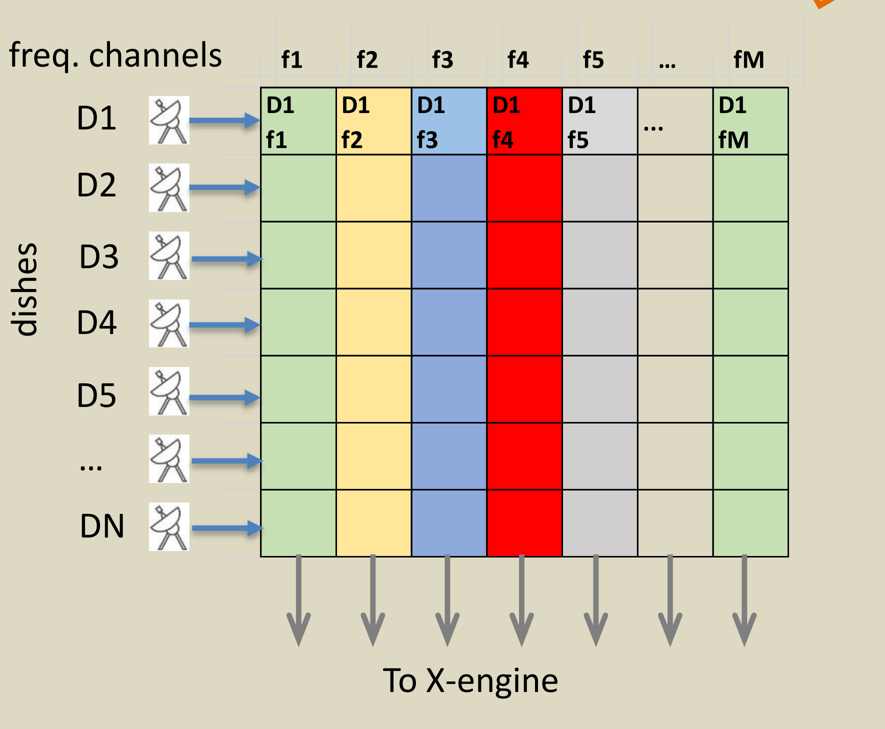
Full array network



Switch and X-engine details

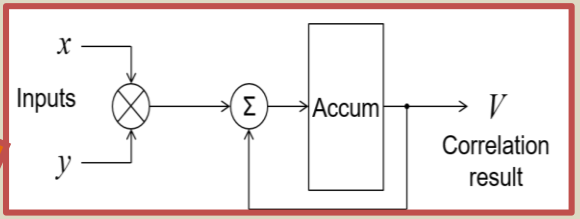


- Re-organize inputs, group by frequency channels
- Send to X-engine



- Perform all auto- and cross-correlations (realtime)
- Average redundant baselines
- Integrate results

	D1 fi	D2 fi	D3 fi	D4 fi	D5 fi	...	DN fi
D1 fi	A						
D2 fi	X	A					
D3 fi	X	X	A				
D4 fi	X	X	X	A			
D5 fi	X	X	X	X	A		
...						...	
DN fi	X	X	X	X	X	...	A



By the numbers…

DATA

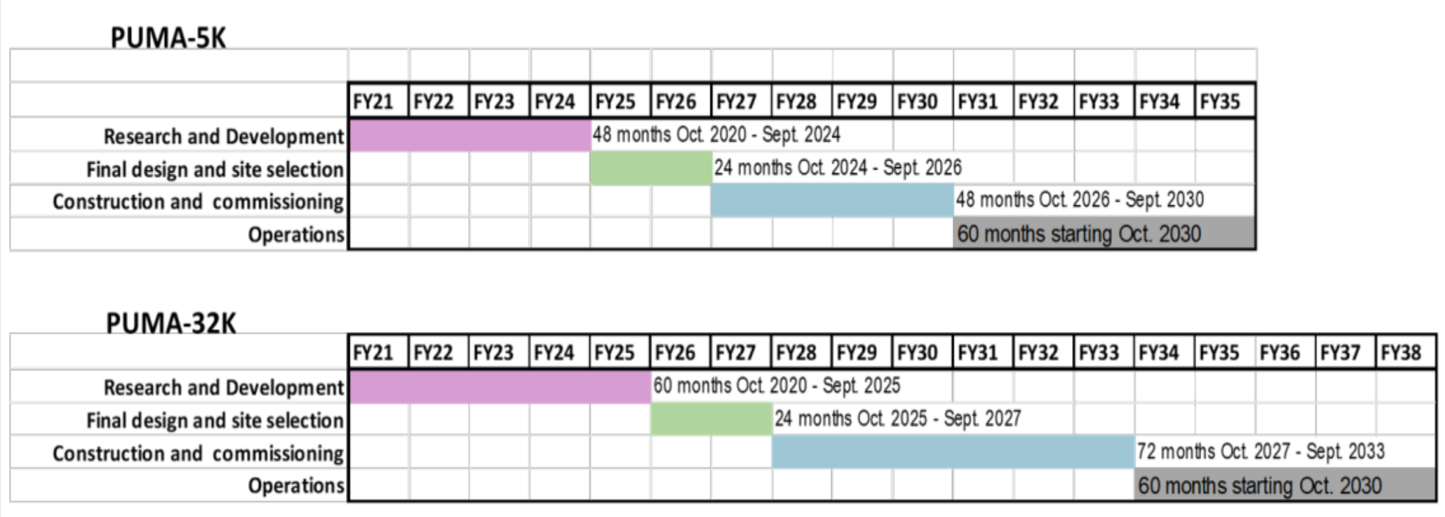
	PUMA-5K	PUMA-32K	
Raw data rate	240	1500	Tbit/s
Real-time computation	15	100	PFLOP
Output data rate	13	82	GB/s
Data volume	0.9	5.7	PB/day
Power *	.23	1.5	MW

*no ASIC

DOLLARS

	PUMA-5K				PUMA-32K			
Phase	Years	U.S. Federal ($M)	Non-federal ($M)	Total ($M)	Years	U.S. Federal ($M)	Non-federal ($M)	Total ($M)
R&D	FY 21-24	15.0	5.0	30.0	FY 21-25	26.3	8.8	35.0
Final design and site acquisition	FY 25-26	8.0	2.0	10.0	FY 26-27	8.0	2.0	10.0
Construction and commissioning	FY 27-30	55.9	2.9	58.8	FY 28-33	354.7	18.7	373.4
Operations	FY 34-30	15.9	1.8	17.7	FY 34-38	100.8	11.2	112.0
Science	FY 31-35	12.4	4.1	16.5	FY35-38	78.4	26.1	104.5
TOTAL	FY 21-35	**107.1**	**15.8**	**133.0**	FY 21-38	**568.2**	**66.8**	**634.9**

DEVELOPMENT TIMELINE



SUMMARY

- 21cm intensity mapping is a new, cost-efficient observational technique that is ***complementary to optical and CMB*** surveys.
- It opens the largely unexplored redshift range $2.5 < z < 6$ where ***beyond-ΛCDM*** physics can be studied - dynamic DE, modified GR, inflationary relic signatures.
- ***Leverages industry advances*** (wireless, AI) and requires no specialized detector environments (cryo, radiation).
- Research needs center on ***DAQ architectures*** (with 2030-era electronics), and on ***calibration methods,*** including sub-picosecond phase synchronization.
- BMX can serve as an early pathfinder to a future large project such as PUMA
  - well-matched to HEP expertise and is ***synergistic with many emerging trends in EF and IF electronics***.