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

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Laura Newburgh, Maile Harris, Emily Kuhn, Annie Polish, Will Tyndall (Yale)
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 $\sim 10^4$ 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 extragalactic 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 instrument

Off-axis configuration of single dish + receiver

- Analog front end electronics
- Low-voltage power and RF signal
- Support tower
- Weather shelter
- Computer and electronics
- Dish focus
- Parabolic Reflector Dish (fixed)
- Dish platform

Parent paraboloid

EM Sim of illumination pattern on dish

Front end electronics

- COUPLER
- AMP1
- Highpass Filter
- AMP2
- Lowpass Filter
- AMP3
- Bandpass Filter

Calibrated noise diode
BMX field of view on sky

Horizon coordinates

FOV unwrapped superimposed with radio source map
## Calibrators

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

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

Location of the beam centers

Beam widths

First Airy disc null for 3.95m aperture at 1500MHz

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

Analysis by G. Troiani
GNSS satellites: constellations, passes over BMX

**orbits**

**GPS**
- 6 Orbital planes
- 24 Satellites + Spares
- 55° Inclination Angle
- Altitude 20,200km

**Galileo**
- 3 Orbital planes
- 27 Satellites + 3 Spares
- 56° Inclination Angle
- Altitude 23,616km

**GLONASS**
- 3 Orbital planes
- 21 Satellites + 3 Spares
- 64.8° Inclination Angle
- Altitude 19,100km

**Angular rates by constellation**

**Predicted tracks over BMX**

**Angular rates and headings**
GNSS passes over BMX on 1/3/2020 (13 satellites observed in 4 constellations)
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 \([\theta_x(t), \theta_y(t), \text{signal(t)}]\).
• Jointly fit 2D Gaussian beam model having parameters amplitude, beam pointing center and width \((\theta_x, \theta_y, \sigma_x, \sigma_y)\).

<table>
<thead>
<tr>
<th>beam parameter</th>
<th>mean</th>
<th>st. dev.</th>
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<tbody>
<tr>
<td>$\theta_{x0}$</td>
<td>0.3639</td>
<td>0.1229</td>
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<tr>
<td>$\theta_{y0}$</td>
<td>-1.5392</td>
<td>0.1863</td>
</tr>
<tr>
<td>$\sigma_x$</td>
<td>1.5953</td>
<td>0.1568</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>1.7222</td>
<td>0.1030</td>
</tr>
</tbody>
</table>

- **pointing direction**: 
  - $\theta_{x0}$
  - $\theta_{y0}$

- **beam width**: 
  - $\sigma_x$
  - $\sigma_y$

**statistics (mean subtracted)**
21 cm 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. 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.

Detail of galactic HI structure. Each of the five sub-panels shows BMX spectrometer data in adjacent 130 kHz 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 ($N_{\text{dish}} = 2$)

Interference fringes based on path length difference between 2 stations

- Angular resolution $\lambda/|b|$  
- Angular field of view $\lambda/D$ “primary beam”  
- Collecting area $\pi D^2 N_{\text{dish}}/4$

Phase of the interference fringes encodes angle to source ($\theta$):

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

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

$B(\theta) =$ angular response of dish primary beam

Airy disc and Gaussian approximation

EM sim (not BMX!)

$V_i = V \cos(\omega(t - \tau_i)) \quad V_2 = V \cos(\omega t)$
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

4/25/19 Channel "24" (E-W baseline, E-W polarization)
Fringes from transit of 17 April 2019

polarization Y  polarization X  polarization Y  polarization X
Results for fit to CygA fringes

### Baseline lengths (E-W projection)

<table>
<thead>
<tr>
<th></th>
<th>b12</th>
<th>b13</th>
<th>b14</th>
<th>b23</th>
<th>b24</th>
<th>b34</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-pol</td>
<td>4.478 ± 0.066</td>
<td>2.594 ± 0.075</td>
<td>4.021 ± 0.075</td>
<td>4.277 ± 0.042</td>
<td>8.745 ± 0.072</td>
<td>4.347 ± 0.057</td>
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<tr>
<td>Y-pol</td>
<td>4.317 ± 0.103</td>
<td>1.919 ± 0.071</td>
<td>4.260 ± 0.071</td>
<td>4.301 ± 0.096</td>
<td>8.776 ± 0.095</td>
<td>4.283 ± 0.059</td>
</tr>
</tbody>
</table>

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

### RA pointing offsets

**Baseline lengths (E-W projection) and RA offset, deg**

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
• 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:
BNL LDRD 19-022
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

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

Nearby galaxy M31 imaged in 21cm

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

Highest redshift detection (z = 0.376)

Fernandez 2016

Haynes et al. 2011

Red: SDSS optical
Blue: ALFALFA 21cm
Grey: optical
Purple: 21cm

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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

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 $\Delta \theta$, $\Delta f$ to be sensitive to scales of interest to cosmology

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

Scale of interest for cosmology
• 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 $1100 < \nu < 200$ 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)
Current/Upcoming OHEP-sponsored cosmic surveys

- Dark Energy Survey (DES)
- Dark Energy Spectroscopic Instrument (DESI)
- Large Synoptic Survey Telescope (LSST)

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

Galaxy Spectra
5000 Fiber Focal Plane
Operations 2019- 2024

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 accuracy.
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

2.5m CHORD

6m HIRAX

15m SKA
Galaxy statistics and redshift range vs. optical galaxy surveys

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

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Survey duration</th>
<th># Galaxies observed</th>
<th>Redshift accuracy</th>
<th>Redshift range</th>
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<tr>
<td>LSST</td>
<td>10 yrs</td>
<td>4B</td>
<td>Modest</td>
<td>0.3 &lt; z &lt; 3</td>
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<tr>
<td>DESI</td>
<td>5 yrs</td>
<td>35M</td>
<td>High</td>
<td>0 &lt; z &lt; 3</td>
</tr>
<tr>
<td>PUMA</td>
<td>5 yrs</td>
<td>2.9B effective</td>
<td>High</td>
<td>0.3 &lt; z &lt; 6</td>
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</tbody>
</table>

Speed of LSST, accuracy of DESI
Instrument design: radio interferometer (large-N)

Many baselines \( (N_{\text{dish}} = \frac{5000}{32000}) \)

Every pair of stations provides a baseline
\[
N_{\text{baselines}} = N_{\text{dish}}(N_{\text{dish}} - 1)/2
\]
Each baseline probes a corresponding spatial frequency

PUMA 32K

PUMA 5K
Instrument design: radio interferometer (polychromatic)

One baseline ($N_{\text{dish}} = 2$)

Interference fringes based on path length difference between 2 stations

- Collecting area $\pi D^2 N_{\text{dish}} / 4$
- Angular resolution $\lambda/b$
- Angular field of view $\lambda/D$
Full array network

- Relative phase drift < 150 fs
- Jitter < 600 fs
- 25-50 Gbps

- SWITCH
  - Artifact removal
- CORRELATOR
  - Component selection
  - Mapmaking
- MASTER TIMING
  - PHASE/FREQ TRANSFER (active)
Switch and X-engine details

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

freq. channels

<table>
<thead>
<tr>
<th>dishes</th>
<th>f1</th>
<th>f2</th>
<th>f3</th>
<th>f4</th>
<th>f5</th>
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<tbody>
<tr>
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</tbody>
</table>

To X-engine

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

![Diagram of Switch and X-engine details]

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

freq. channels

<table>
<thead>
<tr>
<th>dishes</th>
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</table>

To X-engine

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- Average redundant baselines
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![Diagram of Switch and X-engine details]
By the numbers…

**DATA**

<table>
<thead>
<tr>
<th></th>
<th>PUMA-5K</th>
<th>PUMA-32K</th>
</tr>
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<tbody>
<tr>
<td>Raw data rate</td>
<td>240</td>
<td>1500</td>
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<tr>
<td>Real-time computation</td>
<td>15</td>
<td>100</td>
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<tr>
<td>Output data rate</td>
<td>13</td>
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<tr>
<td>Data volume</td>
<td>0.9</td>
<td>5.7</td>
</tr>
<tr>
<td>Power *</td>
<td>.23</td>
<td>1.5</td>
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</table>

*no ASIC

**DEVELOPMENT TIMELINE**

**DOLLARS**

<table>
<thead>
<tr>
<th></th>
<th>PUMA-5K</th>
<th>PUMA-32K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>Years</td>
<td>U.S. Federal ($M)</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>FY 21-24</td>
<td>15.0</td>
</tr>
<tr>
<td>Final design and site acquisition</td>
<td>FY 25-26</td>
<td>8.0</td>
</tr>
<tr>
<td>Construction and commissioning</td>
<td>FY 27-30</td>
<td>55.9</td>
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<tr>
<td>Operations</td>
<td>FY 34-30</td>
<td>15.9</td>
</tr>
<tr>
<td>Science</td>
<td>FY 31-35</td>
<td>12.4</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td>FY 21-35</td>
<td><strong>107.1</strong></td>
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</table>

<table>
<thead>
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<th></th>
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<tr>
<td><strong>TOTAL</strong></td>
<td>FY 21-38</td>
<td><strong>568.2</strong></td>
</tr>
</tbody>
</table>

* no ASIC
• 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.