Applications of dynamical projection-induced polarimetry in global 21-cm measurement

Bang Nhan

Department of Astronomy

University of Virginia

NRAO Central Development Lab (CDL)

Email: bnhan@nrao.edu

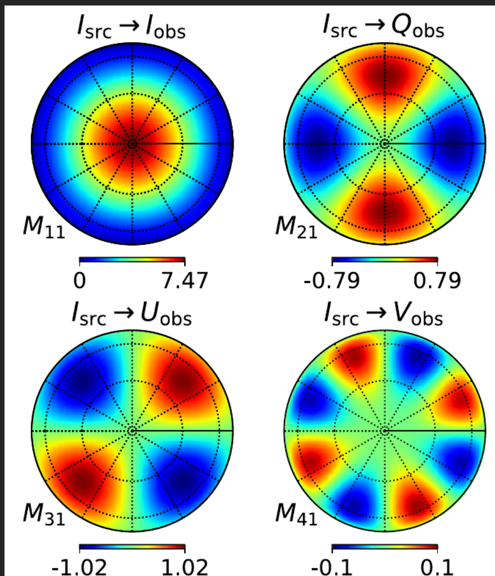
Credit: A. Loeb

Motivations

- Constrain the foreground *empirically*, with minimal dependence on fitting models

- Improve *robustness & uniqueness* in signal extraction with statistical training sets of instrumental & observational systematics

Projection-induced Polarization Effect (PIPE) (aka Dynamical Polarimetry)

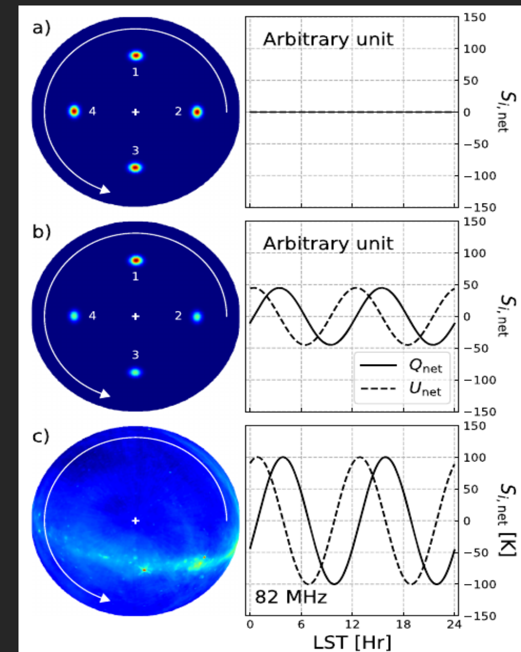


$$I_{\rm net}(t_{\rm LST}, \nu) = \frac{\int_\Omega M_{11}(\Omega, \nu) I_{\rm src}(t_{\rm LST}, \Omega, \nu)\, d\Omega}{\int_\Omega M_{11}(\Omega, \nu)\, d\Omega},$$

$$Q_{\rm net}(t_{\rm LST}, \nu) = \frac{\int_\Omega M_{21}(\Omega, \nu) I_{\rm src}(t_{\rm LST}, \Omega, \nu)\, d\Omega}{\int_\Omega M_{21}(\Omega, \nu)\, d\Omega},$$

$$U_{\rm net}(t_{\rm LST}, \nu) = \frac{\int_\Omega M_{31}(\Omega, \nu) I_{\rm src}(t_{\rm LST}, \Omega, \nu)\, d\Omega}{\int_\Omega M_{31}(\Omega, \nu)\, d\Omega},$$

$$V_{\rm net}(t_{\rm LST}, \nu) = \frac{\int_\Omega M_{41}(\Omega, \nu) I_{\rm src}(t_{\rm LST}, \Omega, \nu)\, d\Omega}{\int_\Omega M_{41}(\Omega, \nu)\, d\Omega},$$



Nhan+ 2019, *ApJ*

Conventional total-power experiments

$$I_{\rm uncal}(t, \nu) = \langle \widetilde{V}_X \widetilde{V}_X^* \rangle + \langle \widetilde{V}_Y \widetilde{V}_Y^* \rangle,$$

$$Q_{\rm uncal}(t, \nu) = \langle \widetilde{V}_X \widetilde{V}_X^* \rangle - \langle \widetilde{V}_Y \widetilde{V}_Y^* \rangle,$$

$$U_{\rm uncal}(t, \nu) = \langle \widetilde{V}_X \widetilde{V}_Y^* \rangle + \langle \widetilde{V}_X^* \widetilde{V}_Y \rangle,$$

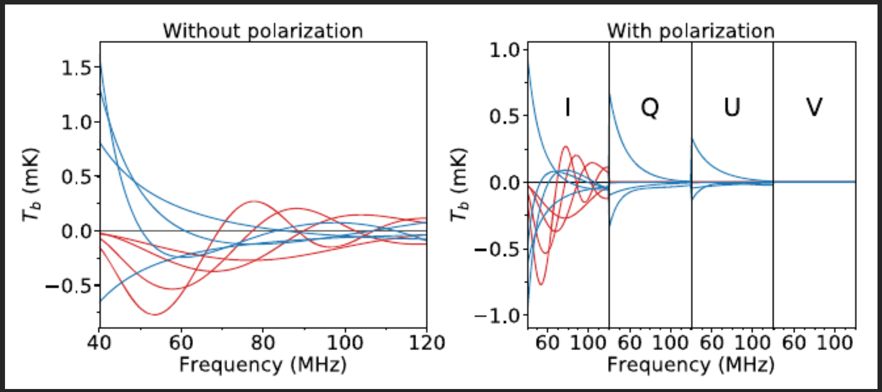
$$V_{\rm uncal}(t, \nu) = i(\langle \widetilde{V}_X \widetilde{V}_Y^* \rangle - \langle \widetilde{V}_X^* \widetilde{V}_Y \rangle).$$

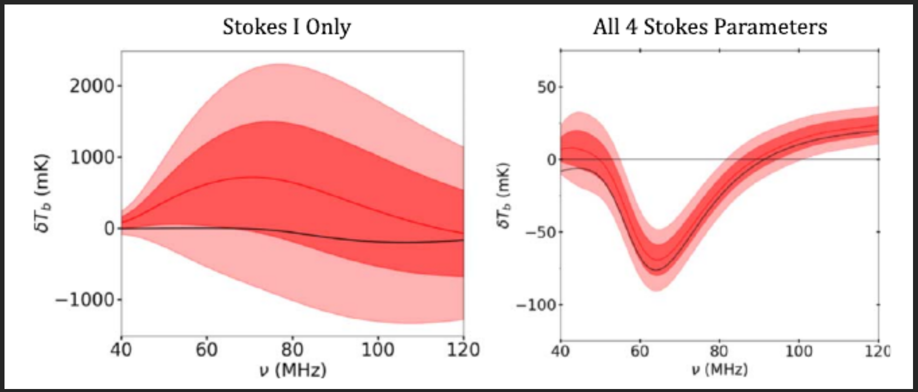
Full Stokes

PIPE is ***NOT*** *intrinsic* polarization from foreground!!!

Why bother? *“Isn’t total-power alone enough?”*

- **Extra handles** on underlying systematics
- Simultaneous measurement → **Uniqueness**

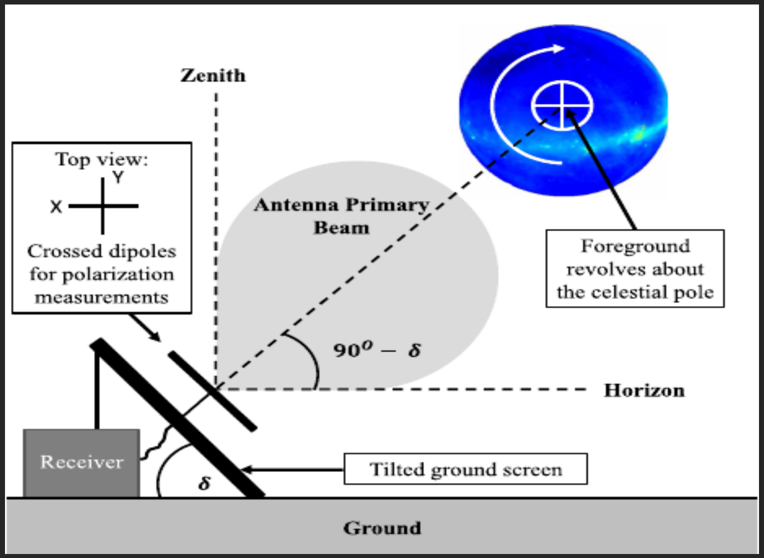




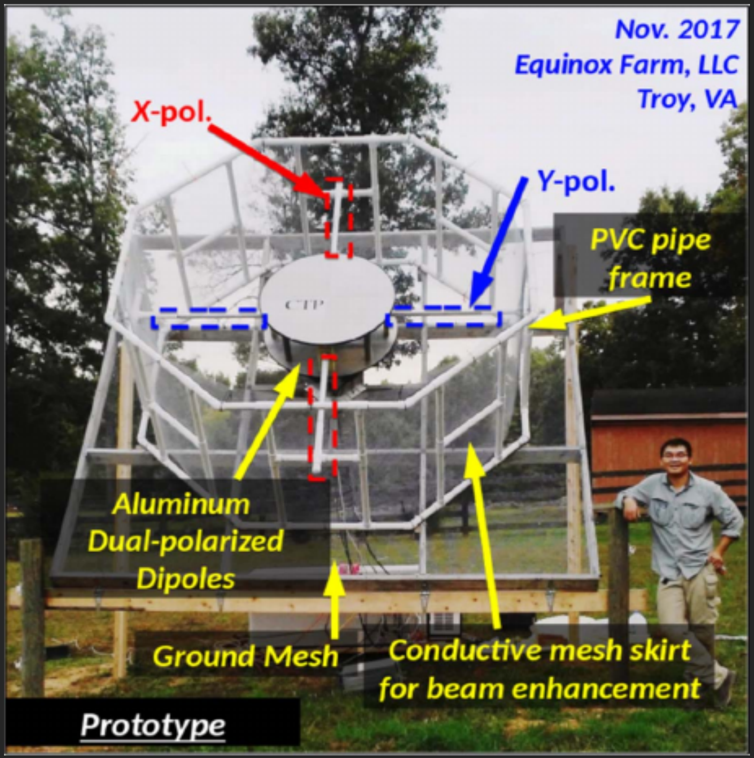
Nhan+ 2019, ApJ & Tauscher+ 2018, ApJ
(https://bitbucket.org/ktausch/pylinex & ARES)

- Help **constructing training sets** for each signal components (e.g., foreground, beam, electronics response, ionosphere, intrinsic polarization)

Cosmic Twilight Polarimeter (CTP) prototype

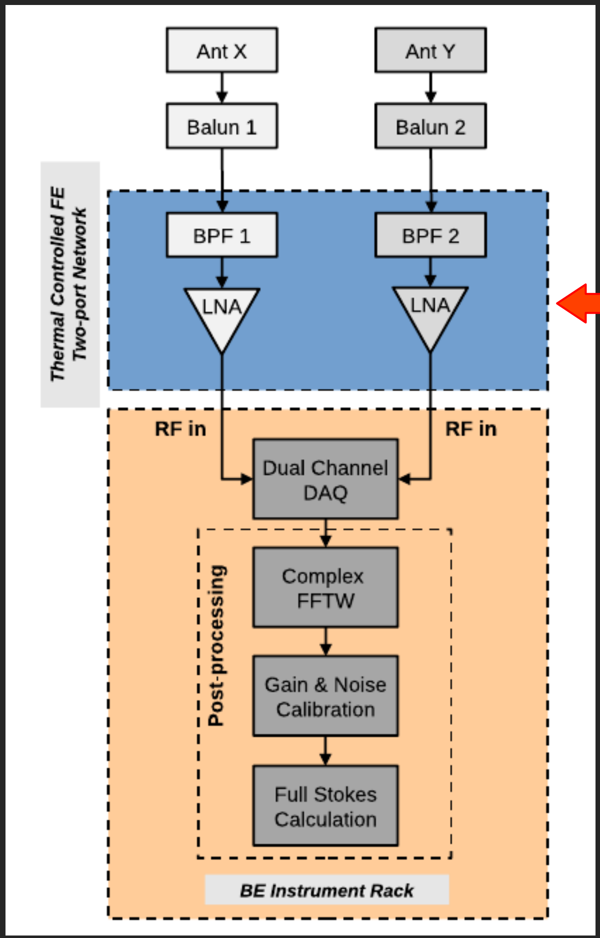


Nhan+ 2017, *ApJ*

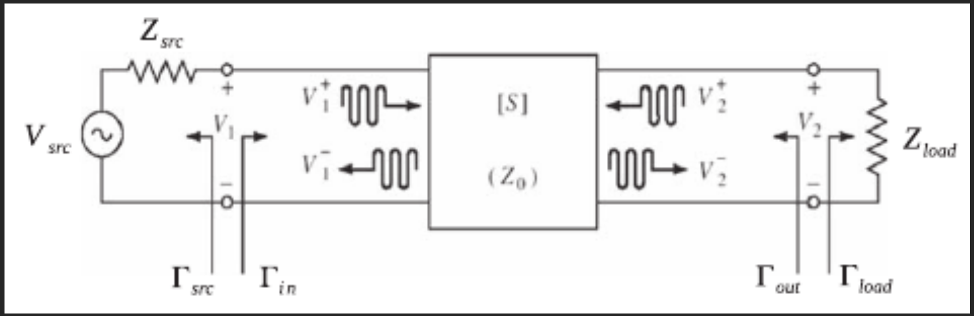


Nhan+ 2019, *ApJ*

CTP – Network-theory based calibration



- Two-port Network



- Transducer gain with S-parameters:

$$G_T(\nu) = \frac{(1 - |\Gamma_{\rm src}|^2)(1 - |\Gamma_{\rm load}|^2)|S_{21}|^2}{|(1 - S_{11}\Gamma_{\rm src})(1 - S_{22}\Gamma_{\rm load}) - S_{12}S_{21}\Gamma_{\rm src}\Gamma_{\rm load}|^2},$$

- Noise temperature with noise-parameters:

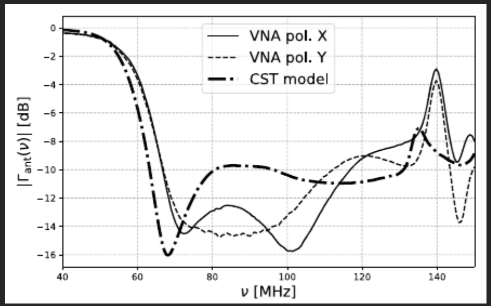
$$T_n(\nu) = T_{\rm min} + \frac{4NT_0|\Gamma_{\rm src} - \Gamma_{\rm opt}|^2}{|1 + \Gamma_{\rm opt}|^2(1 - |\Gamma_{\rm src}|^2)},$$

- **Caveat:** Both are functions of Z_{source}(freq) - Depends on inputs!

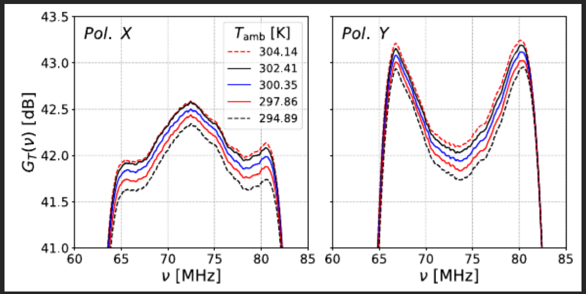
  Instead, use **S-** **&** **noise parameters** (***Network Intrinsic!***)

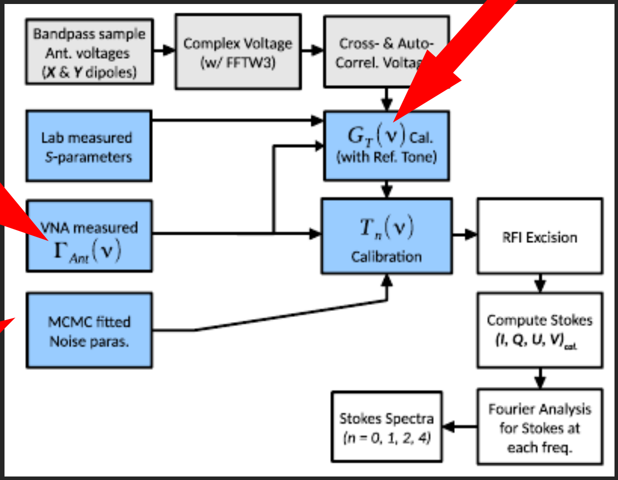
$$\{T_{\rm min}(\nu), {\rm Re}[\Gamma_{\rm opt}(\nu)], {\rm Im}[\Gamma_{\rm opt}(\nu)], N(\nu)\}$$

CTP - Calibration procedures & pipeline

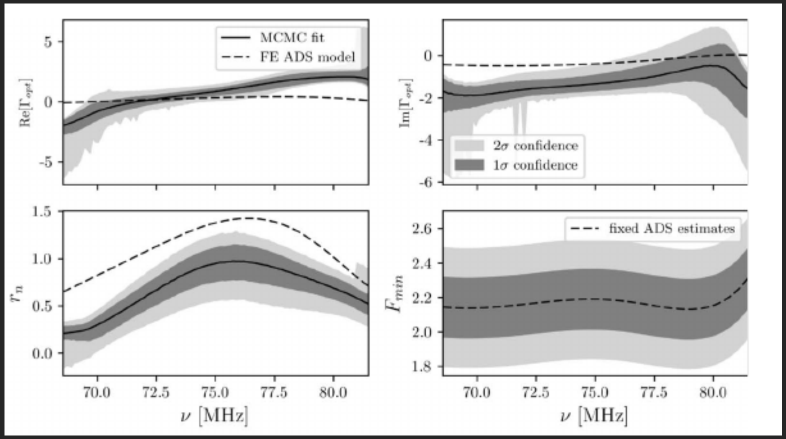


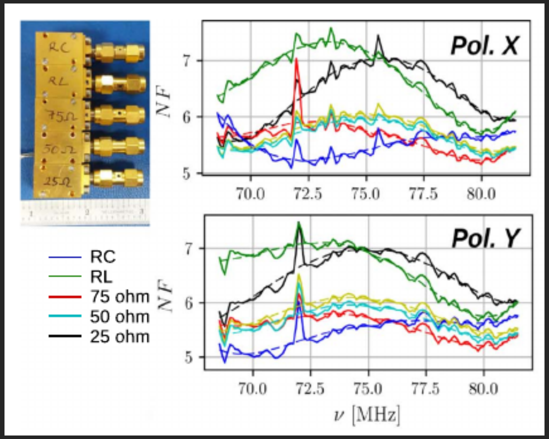
- S-parameters as function of temperature @ 50 Ohm (w/ VNA) → Gain (T_{amb})





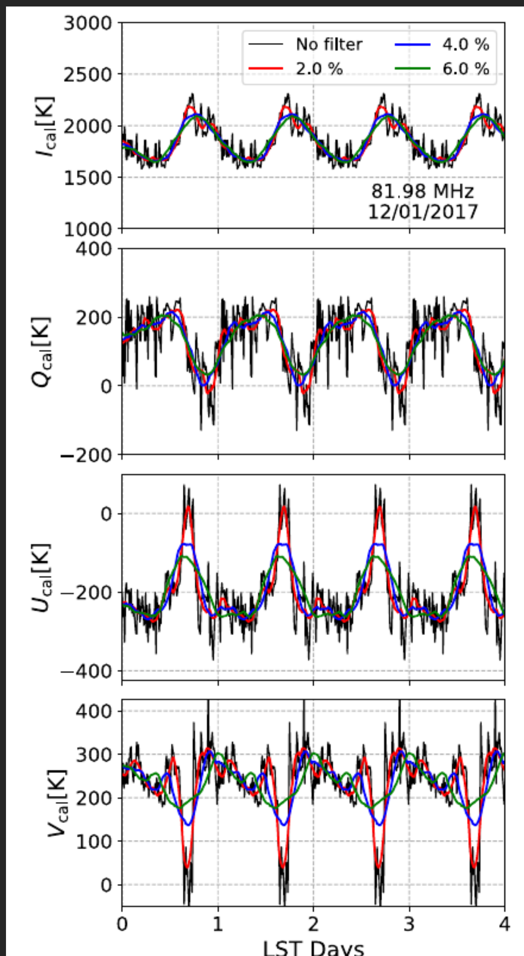
Nhan+ 2019, ApJ



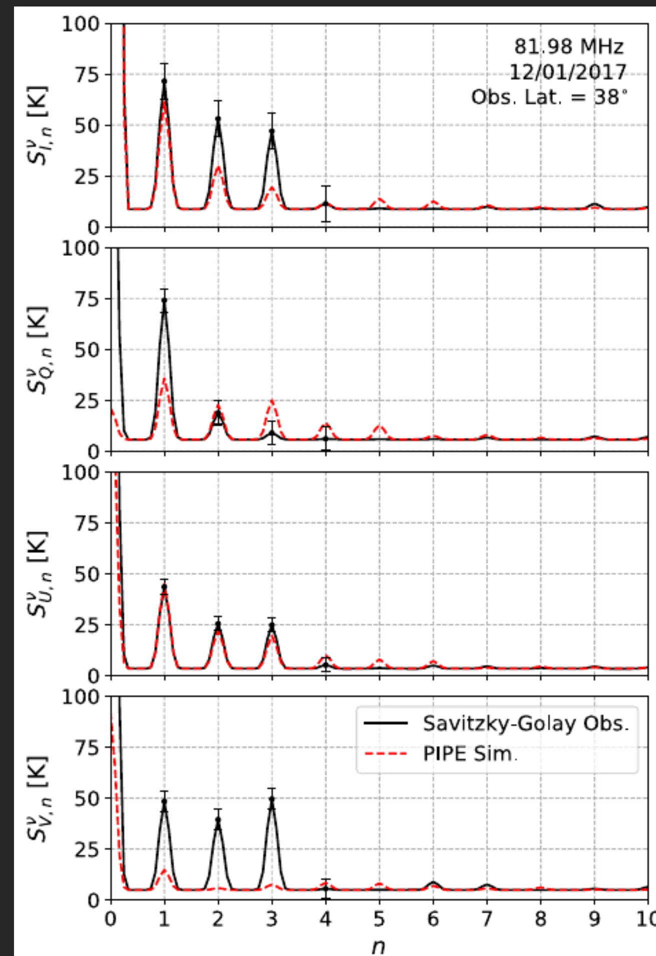


CTP low band – Result & Sim

Single day of cleanest data, duplicate and concatenate for FFT resolution



FFT

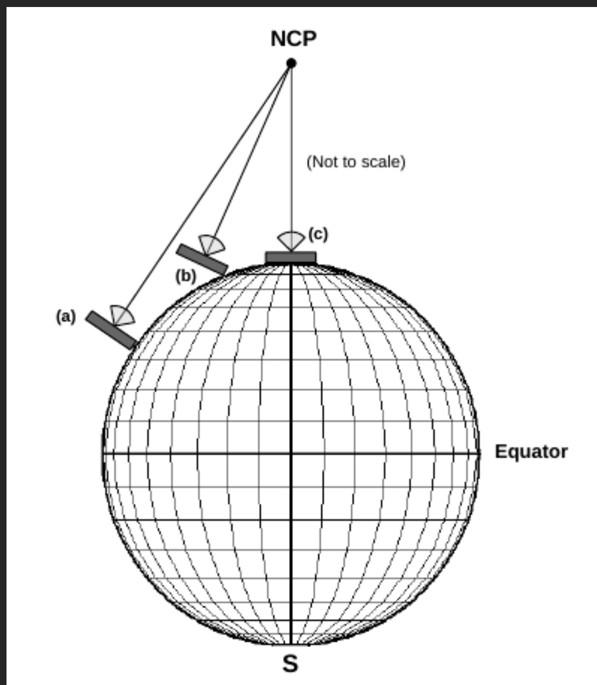


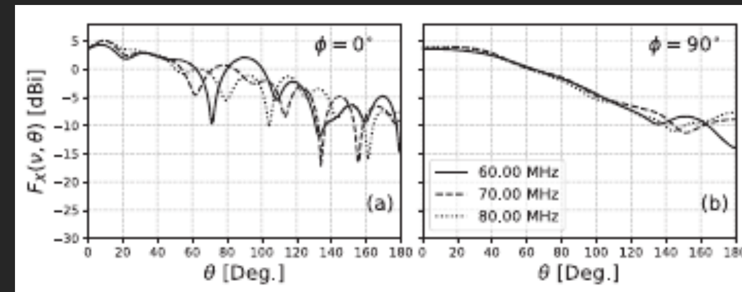
Nhan+ 2019, *ApJ*

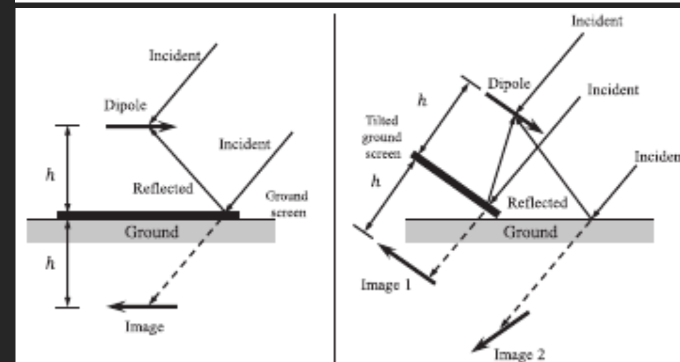
Lessons learned

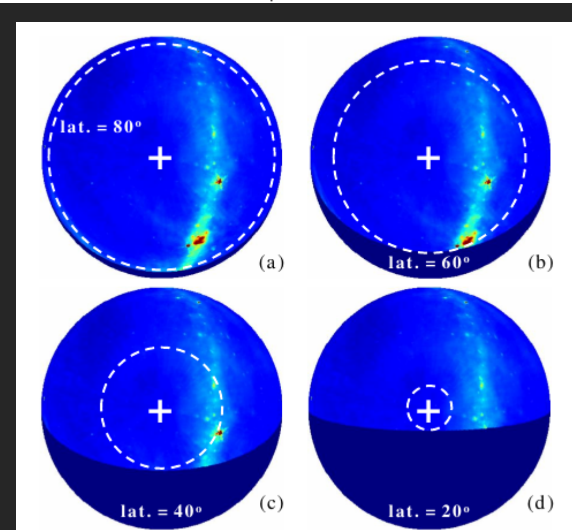
1)Tilting the beam at low lat.:

- Compromise beam smoothness
- Horizon obstruction









Strong RFI (Not surprising)

- Only few channels ~ 81 MHz
- Limited dataset
- Need better self-shelfing

CTP high band test (Summer-Fall 2019)

Team: David Bordanave (UVA), Ellie White (Mashall U), BN, Rich Bradley (NRAO)

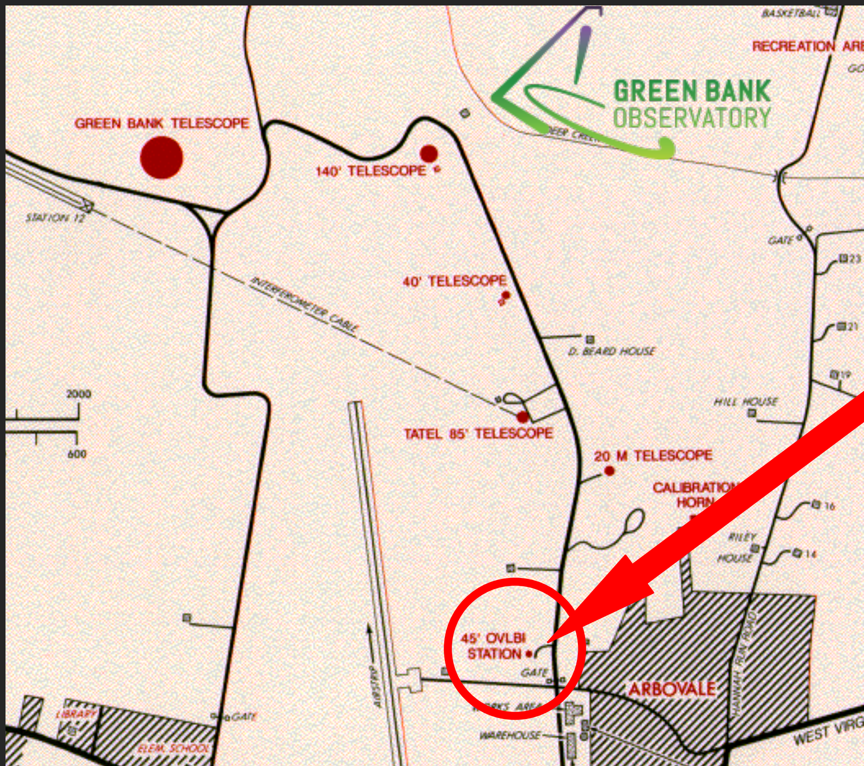


Photo Credit: Pat Klima (CDL)

- Zenith pointing (No horizon effects & beam distortion)
- GBO
  - Clean band between 168-172 MHz
  - Passed RFI shielding test in anechoic chamber

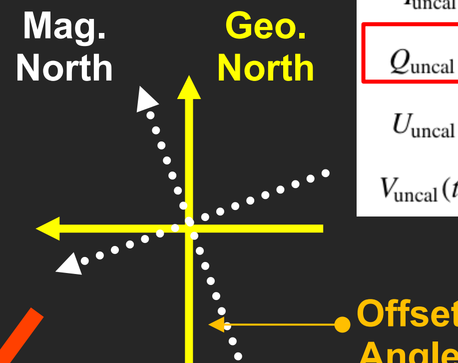
CTP high band test - Results

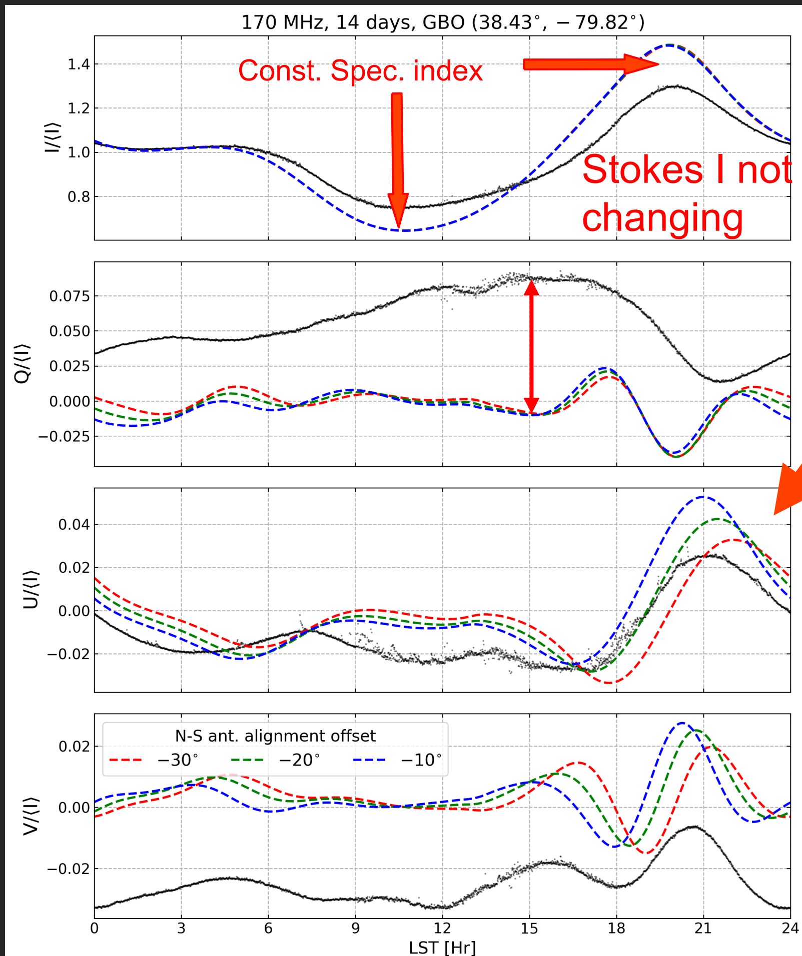
$$I_{\rm uncal}(t,\nu) = \langle \widetilde{V}_X \widetilde{V}_X^* \rangle + \langle \widetilde{V}_Y \widetilde{V}_Y^* \rangle,$$

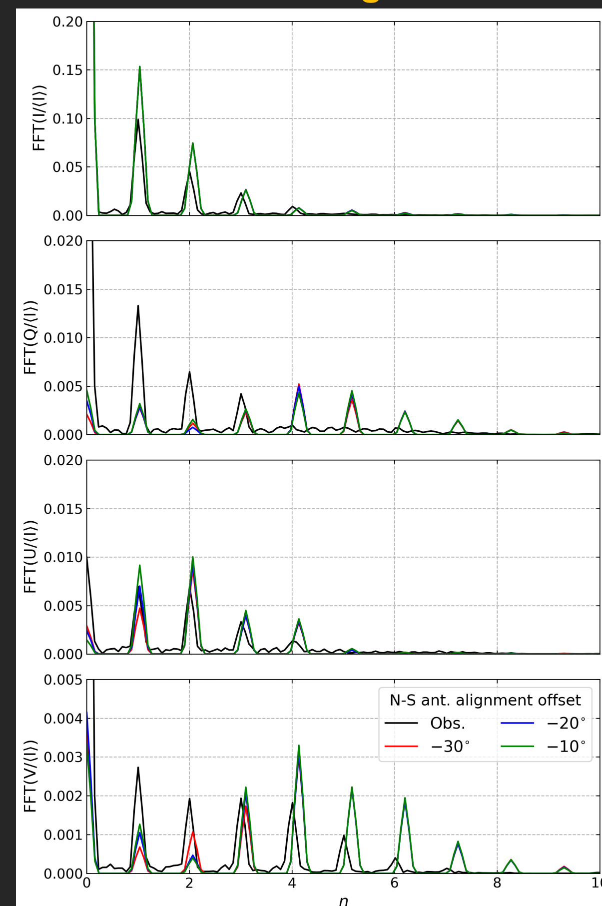
$$Q_{\rm uncal}(t,\nu) = \langle \widetilde{V}_X \widetilde{V}_X^* \rangle - \langle \widetilde{V}_Y \widetilde{V}_Y^* \rangle,$$

$$U_{\rm uncal}(t,\nu) = \langle \widetilde{V}_X \widetilde{V}_Y^* \rangle + \langle \widetilde{V}_X^* \widetilde{V}_Y \rangle,$$

$$V_{\rm uncal}(t,\nu) = i(\langle \widetilde{V}_X \widetilde{V}_Y^* \rangle - \langle \widetilde{V}_X^* \widetilde{V}_Y \rangle).$$







Preliminary:

- LST averaged
- Uncalibrated, normalized to mean Stokes I
- Narrow band (~ 2 MHz)

Underway

- Develop better circuit models for calibrations
- Constrains detailed CEM models with ant beam maps
- Understand effects of intrinsic polarizations & spectral index
- Evaluate SVD with CTP-high band data

In-situ Beam Mapper (IBeaM) Platforms

ORBCOMM Satellites

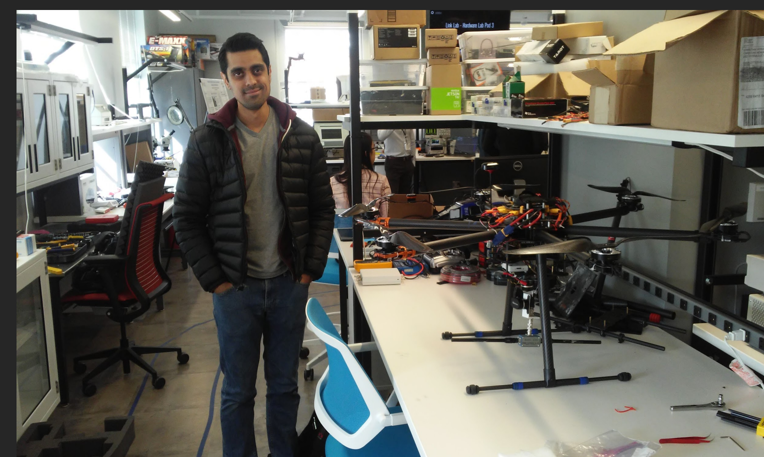
BN (Astro-UVA / NRAO)

137-138 MHz

Operational:
- OG1 (**10/35**)
- OG2 (**16/18**)

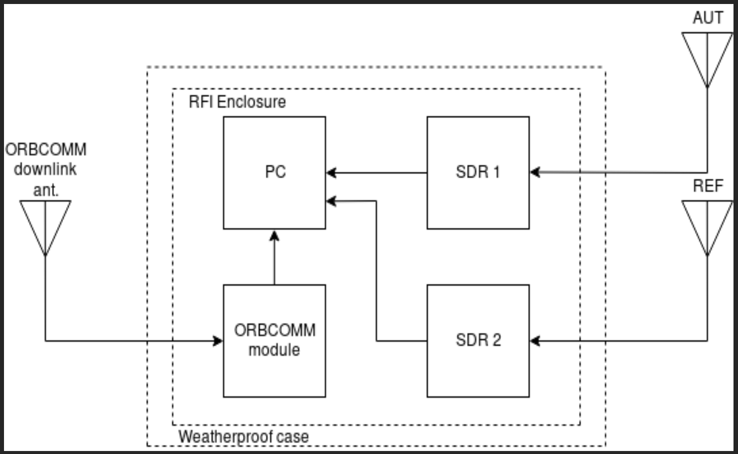
Drone

Krishna Makhija &
Varundev Suresh Badu
(EE-UVA)



GORDON AND BETTY MOORE FOUNDATION

IBeaM-ORBCOMM

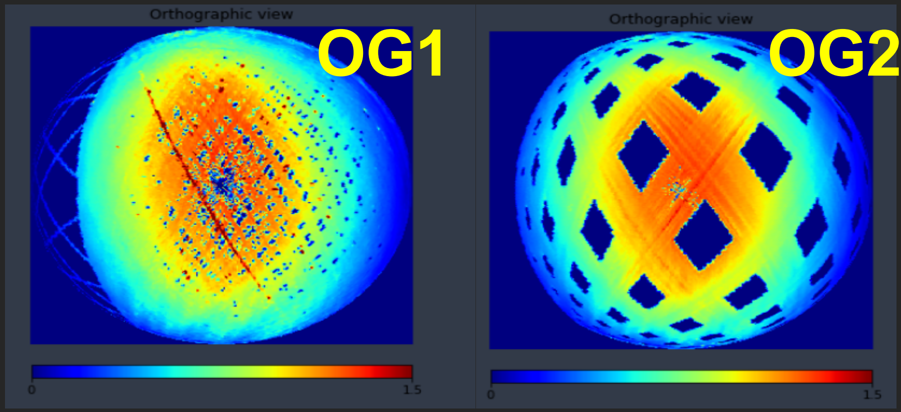


$$P_{\text{ref}} = B_{\text{ref}} F$$
$$P_{\text{AUT}} = B_{\text{AUT}} F$$

$$B_{\text{AUT}} = P_{\text{AUT}} B_{\text{ref}} / P_{\text{ref}}$$

Neben+ 2015

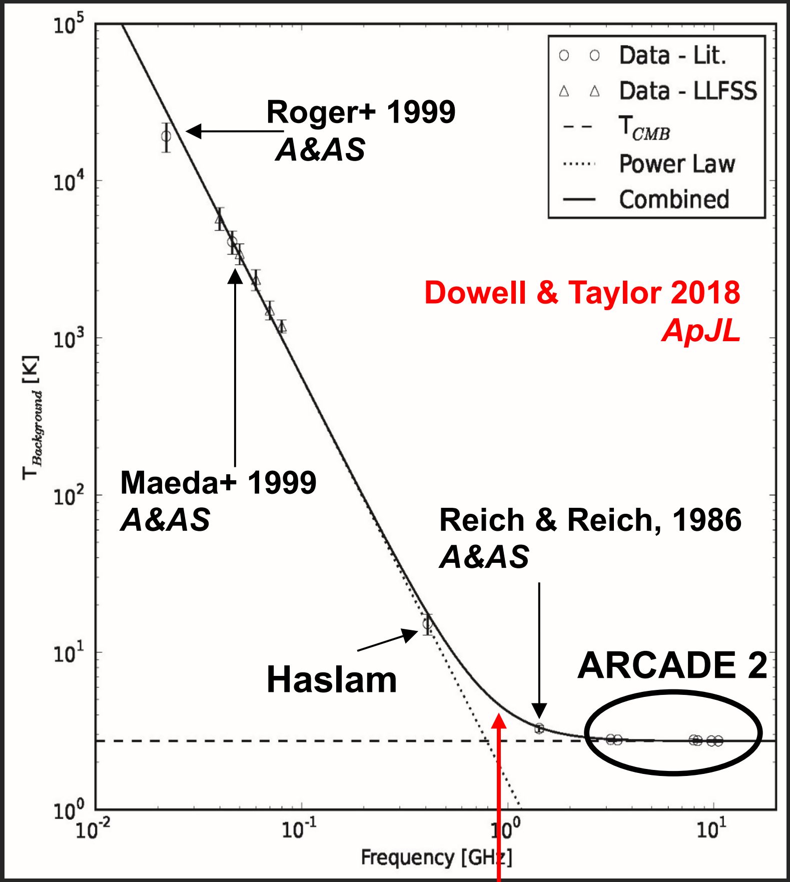
- Software-defined radio (SDR) based receiver system (*Configurable & Low cost)*
- RFI shielded & weather proof enclosure for site deployment
- Direct interface to antenna under test (AUT) at site

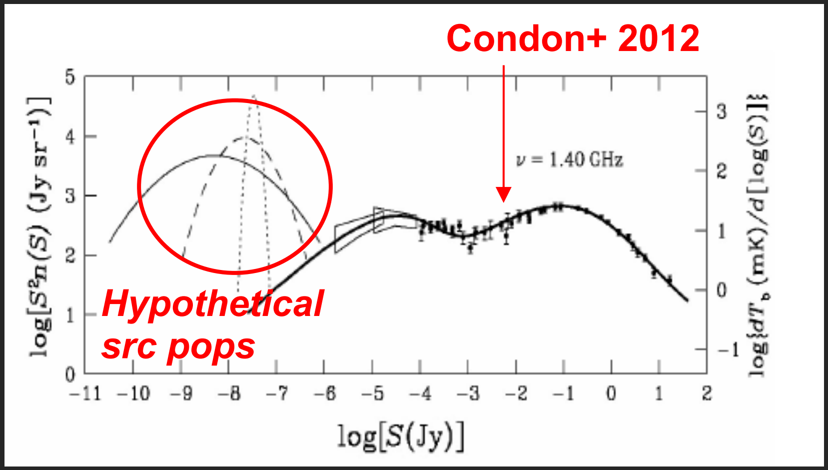


- Failing OG1 satellites (Longer run)
- Ununiform OG2 orbital coverage
- Limited in frequency

- Ideal for:
  - Spot check/beam diagnostics
  - Constraint for beam model @137 MHz

Excess Foreground Synchrotron Emission





$$T_{\mathrm{B}}(\mathrm{K}) = 24.1 \pm 2.1\mathrm{K}\,(\nu/310\ \mathrm{MHz})^{-2.6\pm0.04}$$

- Synch. rad. dominates diffuse radio sky <0.5 GHz
- Observed synch bkgnd brighter than can be explained by diffuse high-latitude Galactic emission + extragal. srcs.

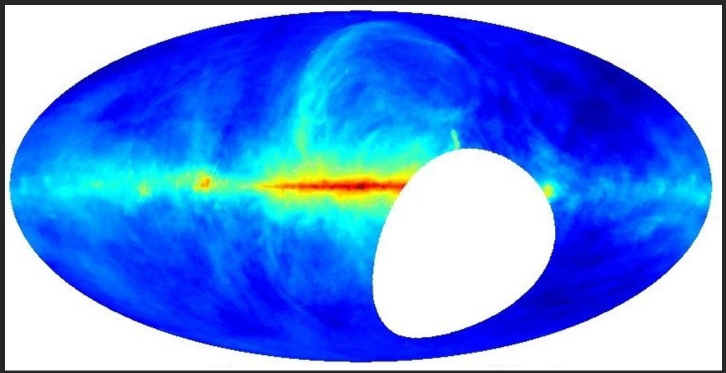
Publications of the Astronomical Society of the Pacific, 130:036001 (21pp), 2018 March https://doi.org/10.1088/1538-3873/aaa6b0

The Radio Synchrotron Background: Conference Summary and Report

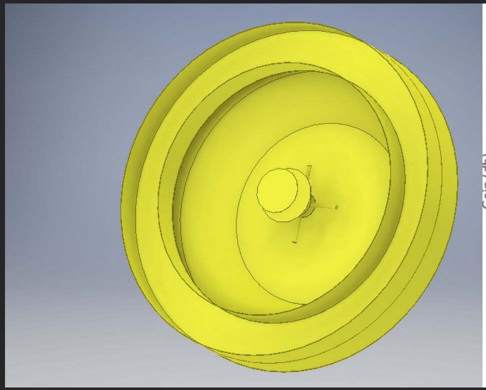
J. Singal[1], J. Haider[1], M. Ajello[2], D. R. Ballantyne[3], E. Bunn[1], J. Condon[4], J. Dowell[5], D. Fixsen[6], N. Fornengo[7], B. Harms[8], G. Holder[9], E. Jones[1], K. Kellermann[4], A. Kogut[6], T. Linden[10], R. Monsalve[11,12,13], P. Mertsch[14], E. Murphy[4], E. Orlando[15], M. Regis[7], D. Scott[16], T. Vernstrom[17], and L. Xu[16]

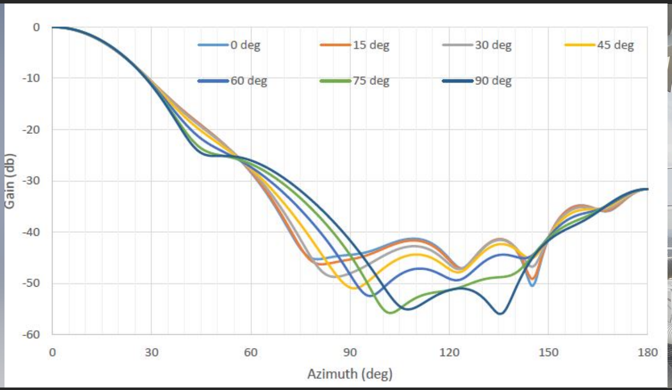
GBT 310 MHz Feed & Receiver Development

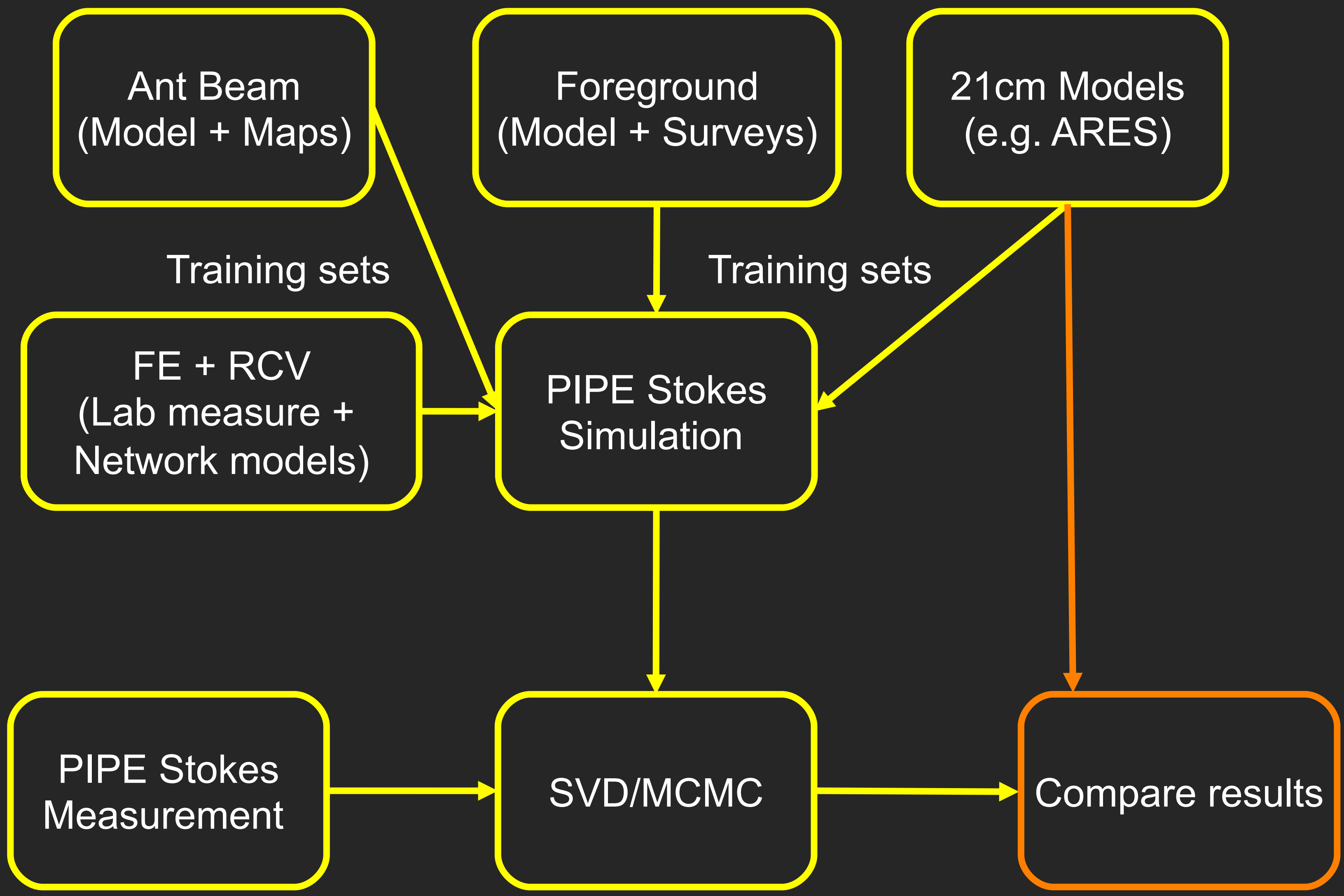
Team: U. Richmond, VA - J. Singal (PI)
NRAO: J. Condon (Co-PI), R. Bradley (Co-PI), S. Srikanth, A. Symmes, P. Klima, K. Kellermann, C. Salter
UVA: D. Bordenave, K. Makhija, B. Nhan
NASA: A. Kogut, E. Wollack



- Absolutely calibrated zero-level map
- GBT → High resolution (FWHM < 2 Deg)
- Custom feed (low spillover)
- Custom receiver (absolute gain & noise calibration)
- **Approved <u>24hr</u> of observing time for preliminary map**







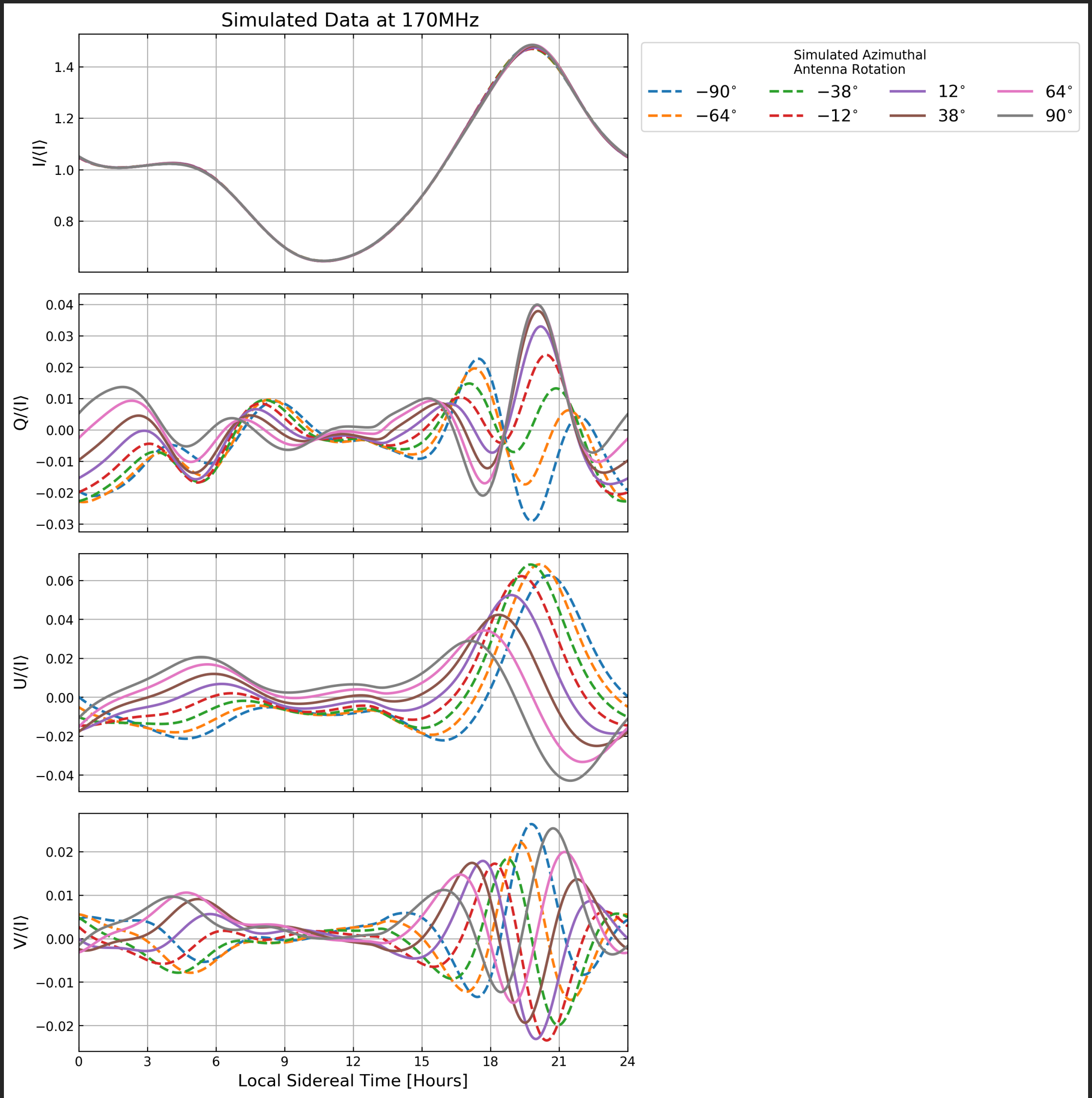
Ant Beam (Model + Maps)
Foreground (Model + Surveys)
21cm Models (e.g. ARES)
Training sets
Training sets
FE + RCV (Lab measure + Network models)
PIPE Stokes Simulation
PIPE Stokes Measurement
SVD/MCMC
Compare results

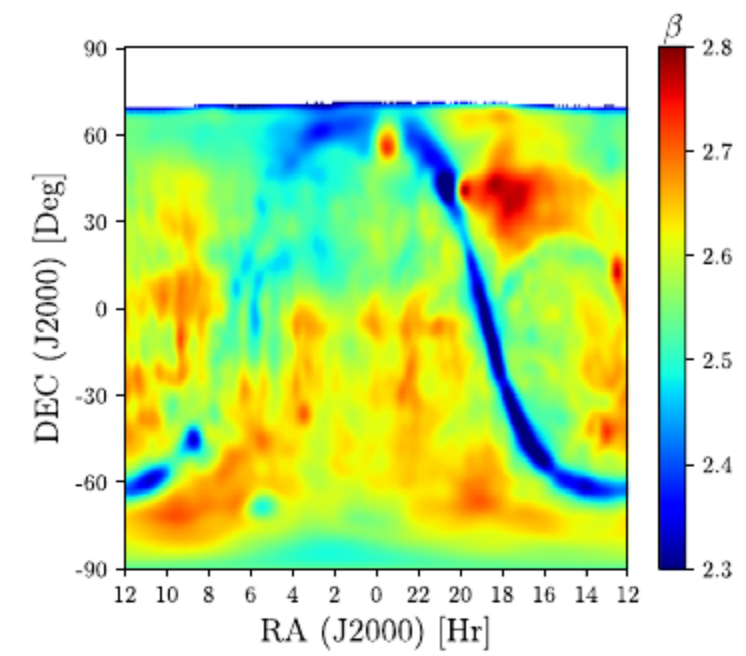
Take aways

- *Add values* to total-power measurement (1 vs 4 Stokes)
- Using *standard formulation* in network & noise theory for calibration
- Constrain systematics with detailed *models bounded by measurements*
- *Statistical & simultaneous* constraints on different signal components/eigenmode with SVD with the training sets

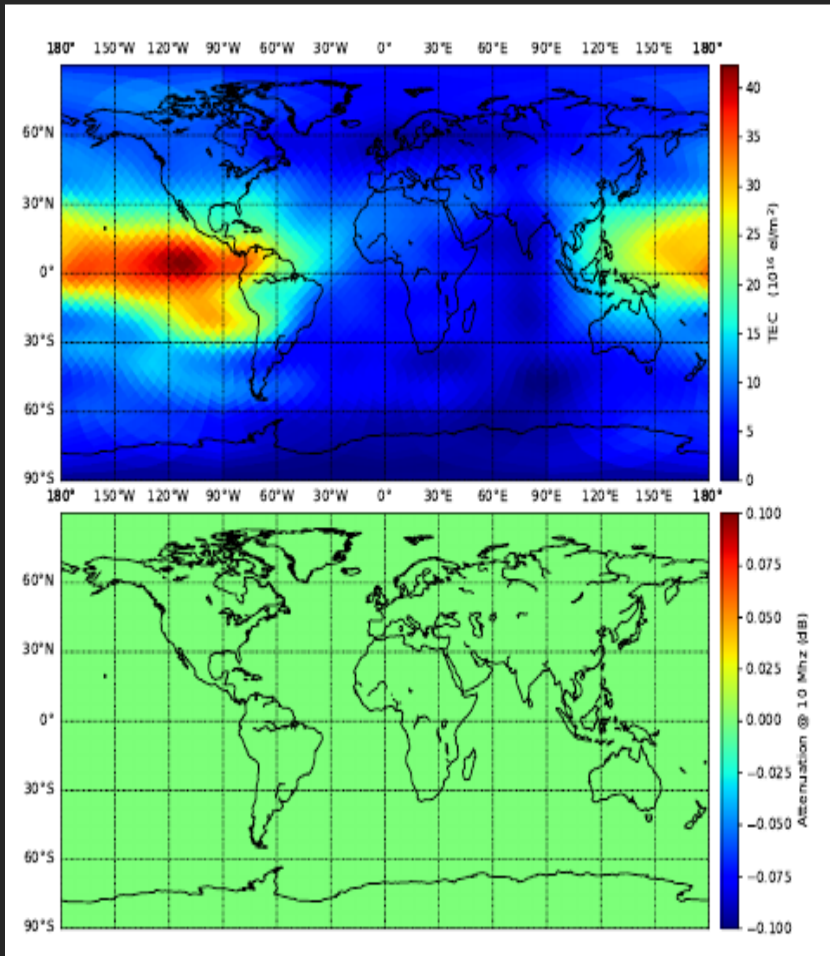
Supplementary slides

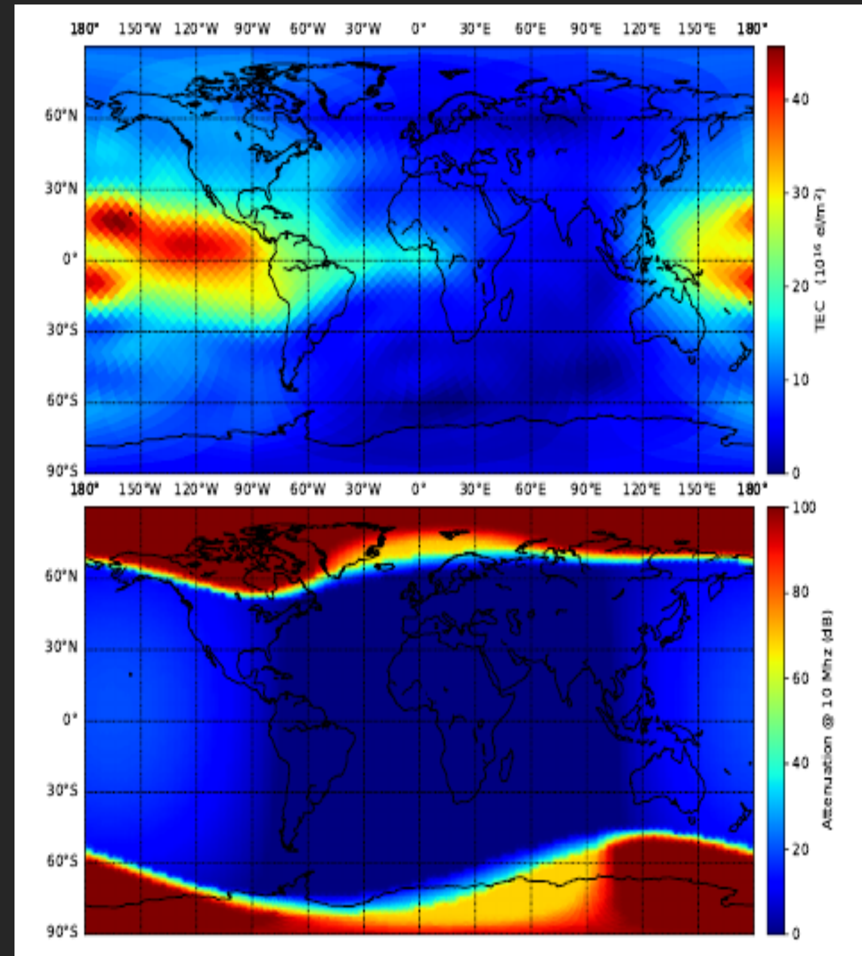
Example of training set: David's beam rotation for CTP high band





DEC (J2000) [Deg]
90
60
30
0
-30
-60
-90
12 10 8 6 4 2 0 22 20 18 16 14 12
RA (J2000) [Hr]
β
2.8
2.7
2.6
2.5
2.4
2.3





[19] Data provided by the Center for Orbit Determination in Europe (CODE), fetched by the Python script `radionopy` provided by Prof. James Aguirre from the University of Pennsylvania, https://github.com/UPennEoR/radionopy.

[20] Attenuation maps are based on Sauer & Wilkinson (2008) data, acquired from the National Oceanic and Atmospheric Administration (NOAA): https://www.swpc.noaa.gov/content/global-d-region-absorption-prediction-documentation.

Space applications
(DAPPER – Dark Ages Polarimeter PathfindER)