Calibration sources for the Tianlai 21 cm Polar Cap Survey

(Dated: July 24, 2018)

We request observing time with two different receivers to calibrate 67 radio sources for use as calibrators for a 21-cm intensity-mapping survey with a new instrument – the Tianlai Dish Array. Specifically, we request 1.75 hours to calibrate these sources in the 700–800 MHz band with the GBT PF1 (0.68 - 0.92 GHz) receiver, and 1.75 hours in the 1170–1270 MHz band with the GBT L (1.15 1.73 GHz) receiver. To our knowledge, these sources have not been calibrated in these bands before.

21 CM INTENSITY MAPPING

Neutral hydrogen intensity-mapping has developed over the past decade as a possible means to measure large-scale structure in the Universe in a relatively inexpensive way [1–5]. Traditionally, large-scale structure is measured with galaxy redshift surveys, a time-consuming process that requires detecting a large number of individual galaxies and determining their positions and redshifts. The fundamental idea behind 21 cm intensity-mapping is to measure the combined neutral hydrogen emission from many galaxies at once, simultaneously reducing the required angular resolution of the telescope and increasing the signal-to-noise ratio.

The most significant challenge to 21 cm intensity-mapping is extracting the HI signal from strong Galactic foregrounds that are $\sim$ 1000 times greater. In principle, the foregrounds should be separable from the signal because the spectra are very different: the foregrounds are dominated by synchrotron radiation and free-free emission, which have smooth, power-law spectra, while the HI signal from clumps of HI emitting at different redshifts forms a 'spikey' spectrum. In practice, instrumental effects introduce structure into the spectra. The first measurements of the HI power spectrum using 21 cm intensity-mapping, reported beginning in 2010, were made with the GBT at $z \sim 0.8$. HI maps were cross-correlated with maps of galaxy number counts from the DEEP2 and WiggleZ galaxy redshift surveys [4, 6–8]. The goal for future surveys is to detect the 21 cm signal directly, without cross-correlation with known structures.

To survey large swaths of the sky with adequate signal-to-noise requires dedicated instrumentation. Both single dish and interferometric approaches are being developed. Although single-dish instruments like the GBT may have less chromatic response than do interferometers, and hence have a significant advantage for the removal of foregrounds and instrumental effects, it has proved difficult to increase the mapping speed of single-dish instruments to compete with that of large-N interferometers. As a result, most 21 cm intensity-mapping instruments are interferometers [9–13] and include cylindrical reflectors (Pittsburgh CRT[14], CHIME[15], the Tianlai cylinder array[16]) as well as arrays of single dishes (Tianlai dish array and HIRAX[17]).

THE TIANLAI 21 CM POLAR CAP SURVEY

Over the last decade our team has been developing the Tianlai Dish Array, which is specifically designed for 21 cm intensity mapping. It consists of sixteen, 6 m diameter dish antennas located in a radio-quiet part of northwest China ($44°9'9.66''$ N $91°48'24.72''$ E). The dishes can be pointed electronically, but for science surveys they operate in drift-scan mode. The receivers can be tuned to observe in bands of width 100 MHz in the range from 600 MHz to 1420 MHz ($1.36 > z > 0$). The dish array saw first light in 2016 and we are now commissioning the instrument.

The dish array's first science surveys will be of the North polar cap in two different frequency bands: 700 − 800 MHz ($1.03 > z > 0.78$) and 1170 − −1270 MHz ($0.21 > z > 0.12$). The low redshift survey will overlap with an existing photometric optical galaxy survey of the polar cap. We are attempting to commission a spectroscopic optical survey of the same region to obtain redshifts for this sample of galaxies. This survey will be used for a cross-correlation analysis with the Tianlai dish survey. The high redshift Tialai dish survey will explore new territory, without the benefit of a corresponding optical survey.

Restricting our observations to this limited region of the sky (the dishes have FWHM of 3.0° at 750 MHz and 1.8° at 1220 MHz) will allow us to integrate to the expected level of the 21 cm signal in TBD days. However, there are no bright radio sources in the polar cap, and, because sky rotates so slowly there, the relatively dim point sources in the field will modulate the observed visibilities very slowly. For these reasons the observations and calibration of the polar cap survey will occur in a two-step process for each of the two frequency bands.

1. Before observing the polar cap itself, we will observe bright radio sources in a strip at the declination of Cygnus-A for a period of several days. These bright sources will allow us to measure the shape of the beams with high signal-to-noise and to study the stability of the calibration over periods from a few hours to 24 hours.

2. We will observe the polar cap itself for a period of TBD days. We will use brightest known point

sources in this field to calibrate the array in the course of the observations.

PROPOSED GBT OBSERVATIONS

We have identified a total of 67 radio sources to calibrate in the two frequency bands in the Cygnus strip and the polar cap itself. Each frequency band requires a different receiver. As justified below, we plan to use 60 second integration times for each source, with the exception of Cygnus-A which will feature a 5 minute integration time. This will bring the uncertainty of Cygnus-A down to $\sim 0.05\%$, for both frequencies. Additionally, the other major sources at the declination of Cygnus-A will be known to the 0.1% level. All polar cap sources will be known better than 1%. These numbers correspond to knowing most sources within one to tens of mJy.

The total integration time, considering position switching from sources to reference fields, and observations at both frequencies is 142 min. We estimate that the repointing time between each source will be around a minute, so the total time would be around 3.5 hrs.

Insert Trevor's table of sources here.

TECHNICAL JUSTIFICATION

We designed the calibration observations using the following parameters. The results of the GBT sensitivity calculator are attached for a typical source. For the observing time estimates we interpolate between flux densities measured for these sources in the NVSS catalog (1420 MHz) and the WENSS catalog (TBD MHz).

700–800 MHz observations Backend: VEGAS Mode: Spectral Line Receiver: PF1 (0.68 - 0.92 GHz) Polarization: Dual Bandwidth (MHz): 100 Switching mode: position switching Rest frequency: 750 Source contribution to system temp: (varies) Desired resolution: 0.2 MHz

1170–1270 MHz observations Backend: VEGAS Mode: Spectral Line Receiver: L (1.15 1.73 GHz) Polarization: Dual Bandwidth (MHz): 100 Switching mode: position switching Rest frequency: 1220 Source contribution to system temp: (varies) Desired resolution: 0.2 MHz

We prefer to observe at night, with higher elevation, in order to minimize RFI. Also with our well developed off-line data analysis code, we can flag out the remaining RFI, which is already been used in our previous analysis.

STUDENT TRAINING

There are currently a number of graduate students working on the Tianlai program in the US, France, and China. One of them, Trevor Oxholm, is the PI of this proposal. He is starting his second year in the Ph.D. program in physics at UW-Madison and is focusing on the North Polar Cap Survey for his first Ph.D. project. This will be his first use of the GBT but he is advised by experienced GBT users, including his thesis advisor, Co-I Peter Timbie.

CONCLUSION

Subtracting the strong foregrounds requires exquisite knowledge of the response of the instrument: *i.e.* calibration. For this reason, we are requesting GBT observing time to calibrate bright sources in our observing bands in and near the North polar cap.

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Sources:

RAJ2000 deg	DEJ2000 deg	Int. time min
299.868	**40.734**	**5**
48.10975	39.27514	1
48.68192	43.23472	1
49.56983	41.90489	1
49.95067	**41.51169**	1
51.67025	41.85911	1
52.61350	41.02836	1
62.01883	42.99917	1
64.56571	**38.01386**	1
65.05600	38.82881	1
65.82875	40.89275	1
65.87654	43.50978	1
65.93704	40.07692	1
65.98325	41.83417	1
66.52071	41.44861	1
66.94179	41.55022	1
67.31900	42.53019	1
67.94308	44.69642	1
68.15171	41.64142	1
69.04983	39.04778	1
70.03279	42.74469	1
71.57429	39.75083	1
72.26617	45.02678	1
72.38992	42.29661	1
246.49025	41.57811	1
247.15975	39.55000	1
247.22208	44.31811	1
247.80446	43.81111	1
248.51229	39.00017	1
248.75987	37.37167	1
248.81462	38.13467	1
249.51725	37.88533	1
249.69387	42.56003	1
250.12358	39.77947	1
250.13379	38.44494	1
250.33212	38.04656	1
250.37562	42.15717	1

250.74487	**39.81028**	1
250.77471	37.49289	1
251.26067	40.17692	1
251.52408	37.20878	1
251.62025	38.52044	1
251.73692	40.98811	1
251.85717	37.87178	1
252.00008	37.74158	1
252.02504	38.01831	1
252.12204	41.06828	1
252.17512	42.67375	1
252.20537	38.80397	1
252.22525	42.90019	1
253.46767	39.76017	1
253.64887	39.09978	1
254.59246	39.10708	1
3.15204	85.72039	1
17.68921	87.63953	1
19.38675	89.48019	1
35.64967	**86.29089**	1
35.70142	**86.31425**	1
95.52292	87.33019	1
140.06983	86.47942	1
197.04958	85.74022	1
244.91925	85.82256	1
249.85596	86.53167	1
279.30092	85.24706	1
285.96112	85.61333	1
295.40262	85.02739	1
341.812	85.9285	1