Probing the Cosmic Dawn: SCI-HI in South Africa

Collaboration Members: University of KwaZulu-Natal (UKZN), Carnegie Mellon University (CMU), Instituto Nacional de Astrofísica, Optica y Electrónica (INAOE)

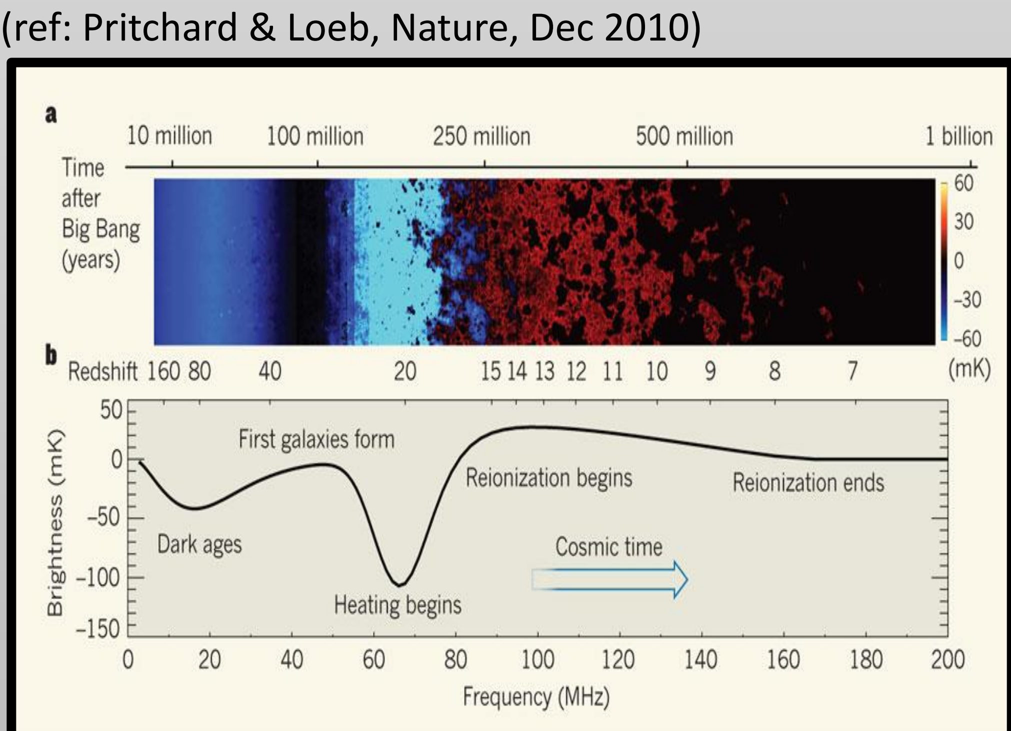
Theory:

In the early history of our universe, when the first stars began to form; they were surrounded by a material called the intergalactic medium (IGM). Primarily made up of neutral hydrogen (HI) gas, the IGM provides an opportunity to study a part of the universe that is not well understood. Measurement can be made by taking advantage of a sharp feature in the spectrum of HI gas at 21-cm (1420 MHz). This 21-cm signal has an intensity proportional to the brightness temperature of the HI gas producing the signal (see equation below, where the Cosmic Microwave Background, CMB, is a well understood background signal). By measuring the intensity of the "21-cm" signal at different frequencies, we obtain the redshifted signal; giving a brightness temperature profile over time.

$$T_b \propto \left[\frac{T_S - T_\gamma}{T_S}\right]\sqrt{\frac{z+1}{10}}$$

T_s is the 21-cm spin temperature, T_γ is the CMB temperature, and z is the redshift

The evolution of the brightness temperature as a function of redshift provides information about the first stars, as they will cause changes in the IGM. In particular, some models of star formation expect a sharp feature, a decrease in the brightness temperature of 10-200 mK centered around redshift z ~ 20. The figure below shows one such theoretical model (ref: Pritchard & Loeb, Nature, Dec 2010)



SCI-HI Experimental Setup:

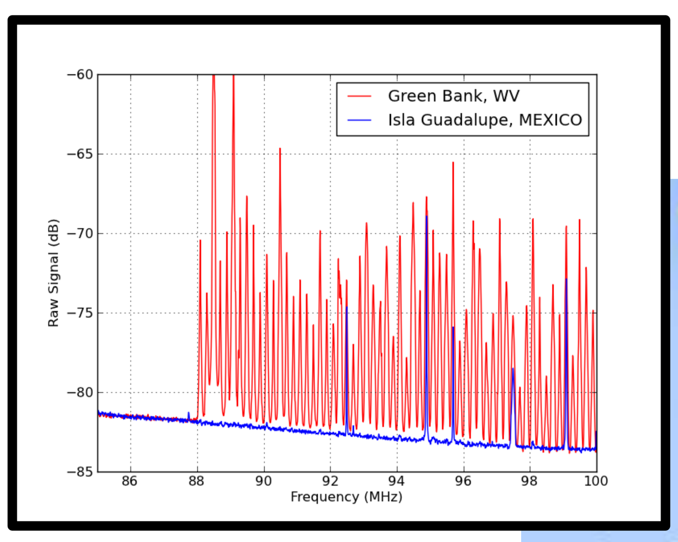
The "Sonda Cosmológica de las Islas para la Detección de Hidrógeno Neutro" (SCI-HI) Experiment uses a single antenna and attendant sampling system. It is optimized to work from 40-130 MHz, with two scaled antennas providing over 90% antenna coupling efficiency from 50-120 MHz.

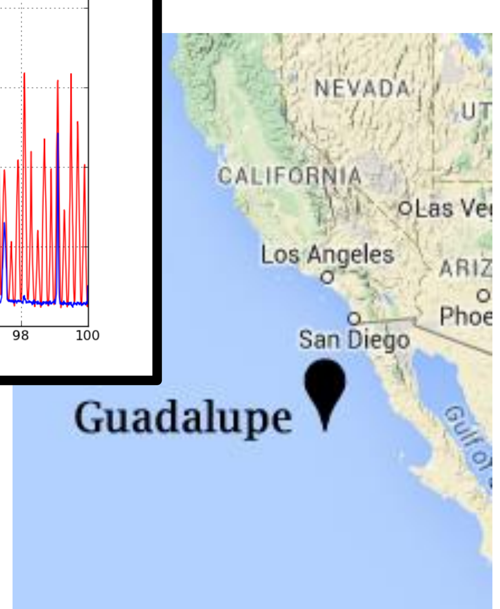
HIbiscus Antenna:

Antenna design started with the need to observe over an octave of frequency. Using FEKO, a finite element simulation, a four-square antenna was modified by dividing the square plates into inclined trapezoidal sections. A scale model was tested in the CMU antenna range to determine the real antenna bandwidth impedance and beam shape compared to simulation. The antenna is fixed and points to zenith, with a roughly uniform 55° beam at its center frequency. Scaled antennas were constructed with center frequencies at 70 MHz and 100 MHz.

Sampling System:

The signal from the antenna passes through a series of electronic stages, including amplifiers and filters. Using an electromechanical switch, spectra are also collected from terminators of known temperature (50Ω, 100Ω, and Short). Signals are sampled by a digitizer board at 500 MSamples/sec with 12 bits of resolution, after which Fourier transform routines integrated into the sampling software are used to generate power spectra from 0-250MHz. The system is placed inside a Faraday Cage with RF filters to minimize self-generated noise contamination.





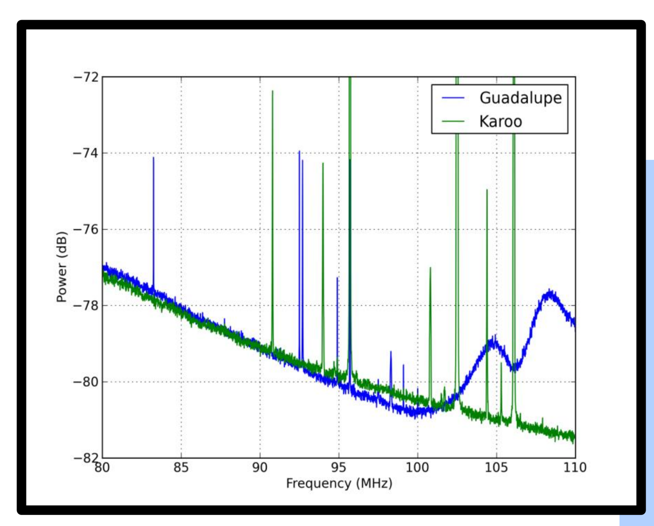
Experimental Sites:

One major noise contribution in this frequency range is terrestrial RFI. In particular, FM radio stations transmit in our band. In order to bring RFI down below the level of the expected signal, it is necessary to operate the instrument at an extremely remote radio-quiet location.

The initial site selected for radio quiet qualities was Isla Guadalupe, a Mexican biosphere reserve 280 km off the Baja California peninsula. At this remote site remnant RFI about 0.1 dB in the FM band is still present.

Since Guadalupe was insufficient as a radio-quiet site, a new site was needed. The South African Antarctic Program (SANAP) has regular visits to Marion Island, whose isolated location makes it an excellent candidate for radio-quiet properties. Deployment to Marion is scheduled for April 2016.

Meanwhile, the SKA site in the Karoo is being utilized for field testing of the SCI-HI system. The site has similar RFI levels in the FM band to Guadalupe and possesses the infrastructure needed for testing. Deployment to the SKA site occurred in April 2015.



Data Calibration:

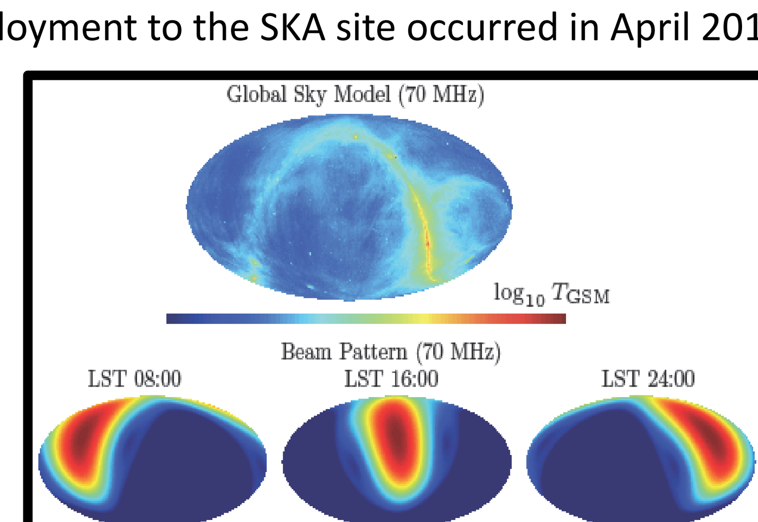
System gain is calculated for the SCI-HI data using the equation:

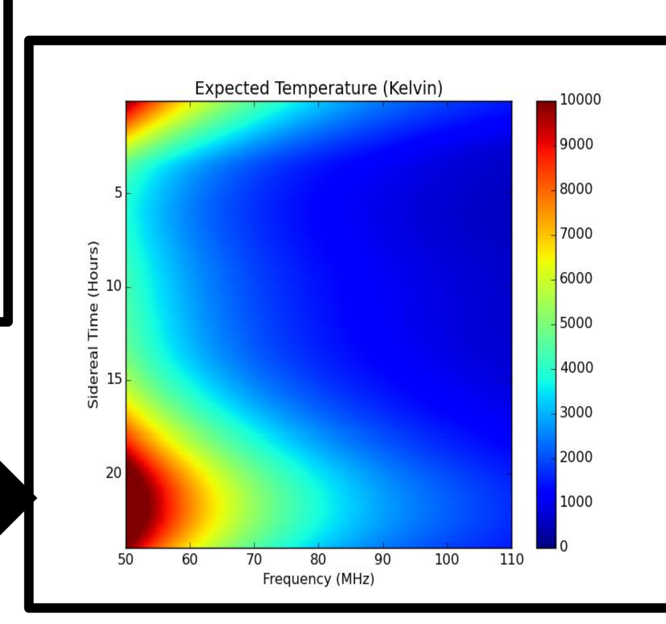
$$T_{meas}(t,\nu) = K(\nu)\left[\frac{P_{meas}(t,\nu) - P_{short}(\nu)}{\eta(\nu)}\right]$$

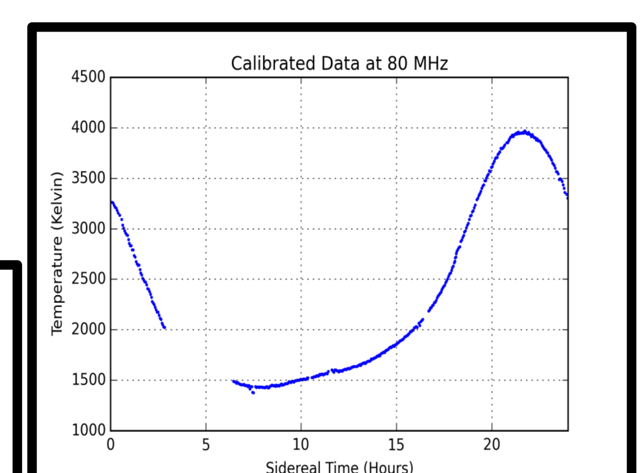
P_{short} gives the system noise and η is the measured antenna coupling efficiency.

In order to calculate K(ν), we use the Global Sky Model (GSM, ArXiv:0802.1525) and our simulated antenna beam. The beam averaged galaxy signal gives an expected sky temperature as a function of time, which has a wide variation as the Galactic plane crosses the antenna beam center. We fit this variation with the daily mean subtracted from the data to get K(ν) for each frequency.

$$\chi^2(\nu) = \sum_t [(T_{meas}(t,\nu) - \langle T_{meas}\rangle(\nu)) - (T_{GSM}(t,\nu) - \langle T_{GSM}\rangle(\nu))]^2$$







Guadalupe Results:

In order to measure T_b we need to first remove the foreground Milky Way Galaxy signal.

One way to do this is to use a simple model of the galaxy signal ($T_{GM}(\nu)$) and compare it to the average signal from a day of data $\langle T_{meas}\rangle_{DAY}(\nu)$ to get residuals:

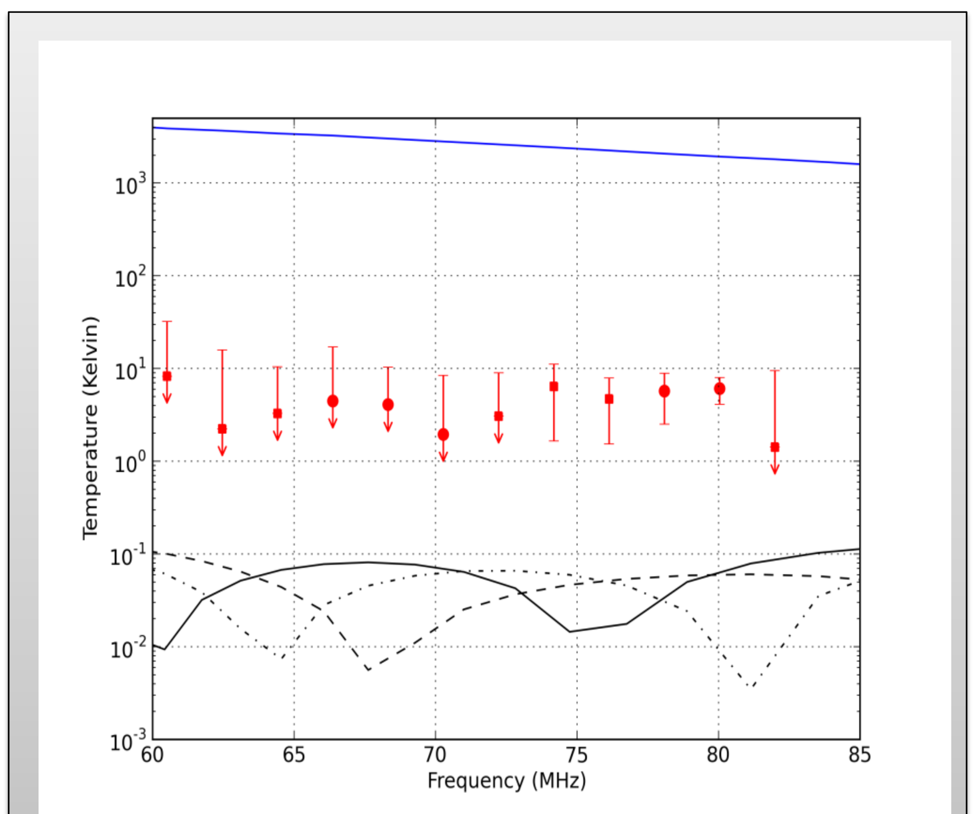
$$log_{10}T_{GM}(\nu) = \sum_{k=0}^{n} a_k\left[log_{10}\left(\frac{\nu}{70\ MHz}\right)\right]^k$$

$$\Delta T(\nu) = \langle T_{meas}\rangle_{DAY}(\nu) - T_{GM}(\nu)$$

These residuals are the combination of T_b, thermal noise, and any remaining Galaxy signal.

Results were analyzed for 9 days of observation on Isla Guadalupe totaling 4.4 hours of integration. With n=2, the residuals are <1% of the galaxy signal for the limited frequency band of 60-85 MHz.

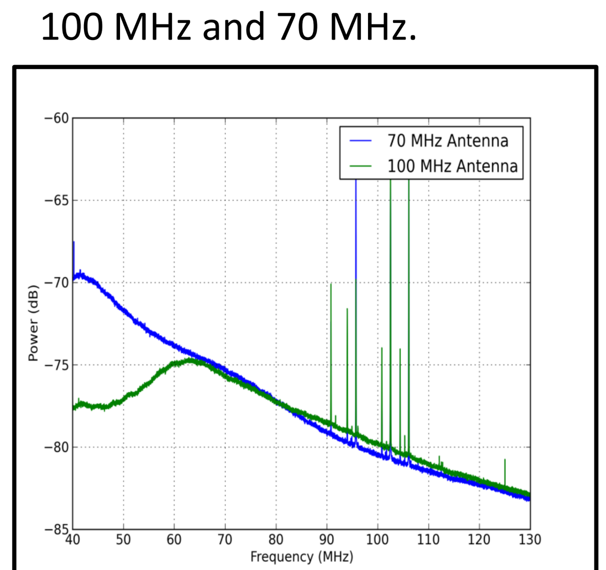
These results are discussed further in ArXiv:1311.0014



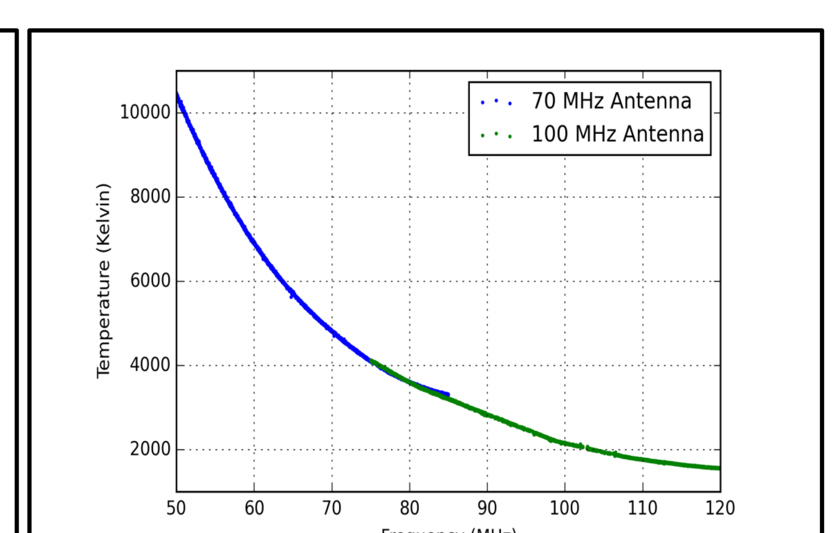
Guadalupe results from 2013. In the plot, blue is foreground signal, red is residuals, and black are different 21-cm signal models.

Preliminary Karoo Results:

Data was collected in April 2015 with the HIbiscus antennas scaled to both 100 MHz and 70 MHz.



One second integration of uncalibrated data with both antennas. RFI has not yet been masked out in the data.



Two minute integration of calibrated data with RFI masked out in the data. 70 MHz antenna data shown for <85 MHz, 100 MHz antenna data shown for >75 MHz.