Developing a Focal Plane Array at the GBT for 21 cm Astronomy

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Abstract. Progress has been made on the design of a 9 receiver array in the 700 to 945 MHz range to replace the single receiver in that frequency range currently in use at the Green Bank Telescope (GBT) in West Virginia. The new array will increase the rate of data collection ~9x in ongoing 21 cm intensity mapping, and it should also be a valuable resource for other users of the GBT. The following paper describes the science of 21 cm intensity mapping and the work that has been done in designing the receiver for the focal plane array.

Cosmology with the 21 cm line of Neutral Hydrogen (HI)

It has been observed that, on the largest scales, the universe is quite symmetric. If one considers scales much larger than galaxy clusters, the universe looks the same in every direction (isotropic) and also the same at every point (homogeneous). This allows cosmologists to make the simplifying approximation that, again only on very large scales, the matter and radiation density of the universe are constant. Combining this simplification with the rules of general relativity (GR), one can derive the Friedmann Equation, a differential equation which determines how the universe expands as a function of four things: the matter density, the radiation density, the curvature of space, and a mysterious component called dark energy (which is, in the currently favored ΛCDM model, Einstein's cosmological constant). As the universe expands, the wavelength of light traveling through the universe expands with it. It has also long been known that velocity curves of galaxies are inconsistent with gravitation from the visible luminous matter: objects are traveling too fast for the amount of matter that is seen. Therefore, rather than completely abandon the highly successful GR theory of gravity, cosmologists now postulate that most matter is 'dark matter,' which does not interact with or produce light. Studying dark matter and dark energy are two main goals of modern cosmology.

Mapping the distribution of neutral hydrogen, using the 21 cm line, is a convenient way to study the distribution of dark matter and the equation of state of dark energy (to be discussed more fully later). Hydrogen's abundance makes it a good unbiased tracer of the underlying dark matter distribution (because of gravitational attraction, it should map the dark matter). The 21 cm line, being a (low energy) atomic transition, is always produced at a fixed wavelength (21 cm), and therefore any increase in wavelength over 21 cm is due to the expansion of the universe (cosmological redshift). The Friedmann equation allows one to use this redshift to calculate the radial position of the HI and the time in the past when the radiation was emitted. Aside from mapping the dark matter, the HI power spectrum should show the remnants of Baryon Acoustic Oscillations (BAO). BAOs were pressure waves in the primordial plasma of the early universe, created due to slight over densities and under densities in the matter of the universe (caused by random quantum fluctuations). Eventually the plasma cooled enough for photons to decouple with matter, the universe became transparent, and the pressure driving the propagation of the

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sound waves disappeared. The over/under density pattern of these waves, now vastly increased in size, became frozen in place. At that point, their size became tied to the expansion of the universe. Thus, if we can map the size of the BAOs over time, we can produce a history of the expansion of the universe. This precise history will provide higher precision tests of the nature of dark energy. For example, in co-moving coordinates (in which the expansion of the universe is factored out), the radial size of the BAO feature should be equal to the tangential size. Since the radial coordinate depends on the dark energy density, constraining these two dimensions to be equal can put limits on how the dark energy density varies with time (equation of state). The current ΛCDM model has a constant dark energy density, but there may be another more complicated equation of state.

Completed Intensity Mapping with the GBT

Mapping 21 cm HI emission in individual galaxies at high redshift is impossible with current single dish telescopes, due to the diffraction limit. However, it is possible to use large radio telescopes like the GBT to perform three dimensional intensity mapping by detecting the combined emission from the many galaxies that occupy large (1000~ Mpc^3) voxels [F. B. Abdalla and S. Rawlings (2005), S. Wyithe, A. Loeb, and P. Geil (2007), Y. Mao et al. (2008), H.-J. Seo et al. (2010)]. The use of such large voxels allows telescopes such as the Green Bank Telescope to reach up to z~2, conducting a rapid survey of large volumes. The BAO features are still visible on this scale.

The biggest challenges are RFI and foreground removal. The strongest foregrounds are synchrotron emitters, which produce approximately 1000 times more flux then the HI signal. Since synchrotron radiation is spectrally smooth and pointlike, whereas the HI signal should be uncorrelated in frequency along the line of sight. This makes foreground subtraction through Singular Value Decomposition (SVD) possible but difficult. Consequently, our collaboration has thus far only published results in cross-correlation with galaxy surveys. Auto-correlation results are not yet ready. First results, a cross-correlation with the DEEP2 galaxy survey at an average redshift of z~0.8 were published in 2008 [Chang et al. (2008)]. A second paper, cross-correlating with WiggleZ fields, has been submitted.

Design of new Focal Array for GBT

Efforts are underway to replace the 700-945 MHz GBT receiver with a 3x3 array in the focal plane of the GBT. The increase in the mapping speed is given by the radiometer equation, which says that the time required to reach desired signal to noise is proportional to the number of receiver elements divided by the square of the system temperature of those elements. The system temperature is a measurement of the inherent noise of an antenna, due to the electronic amplifier and unwanted radiation picked up from the ground and sky. We plan to limit the electronic noise by using a cryo-cooled low noise amplifier. The amount of radiation picked up from the ground is a function of the shape of the antenna's beam pattern and is quantified by the antenna spill temperature.

I have worked almost exclusively on the antenna design, and the rest of this report will follow my efforts with that. All antenna designs were modeled with CST's Microwave Studio.

The size constraints at the GBT focus limit us to a 3 meter by 3 meter array. This makes the current receiver, which has excellent system temperature, too large for even a 2x2 array. Several alternative designs were considered, but the best seemed to be the short backfire antenna (SBA), which is extremely compact and has a relatively narrow beam pattern. The SBA also has the advantage of using dipoles as exciting/receiving elements, whereas horn antennas require a fairly large and heavy OMT (Orthomode Transducer) to transition radiation from the antenna to modes that can properly excite dipoles. For a 9 element array of horn antennas, 9 OMTs would be required, whose size and bulk could quickly put us over our space and weight allowances. The original SBA design that was modeled (Fig. 1) was a scaled up version of a receiver already used at the GBT for higher frequencies (scaled up to match our lower frequency). Figure 2 shows the spill temperature for this antenna design, calculated for several frequencies.

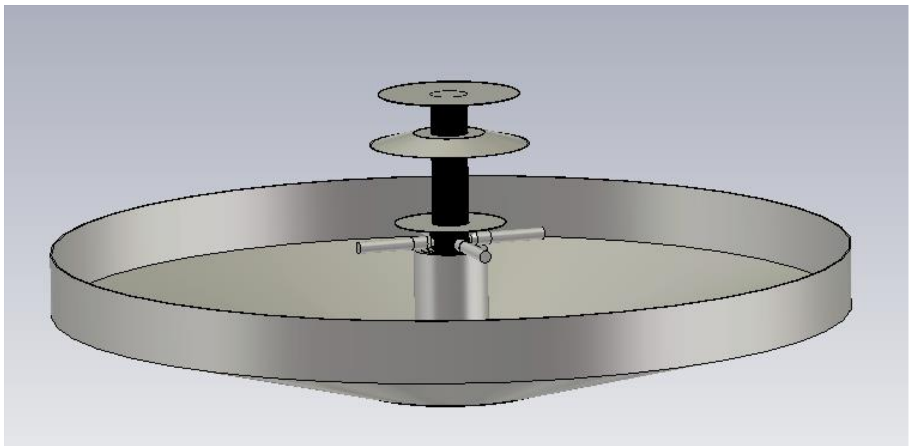

Figure 1: Original SBA design. The black cylinder is dielectric. The metallic cylinder beneath the dipoles is the cryogenic housing for the electronics. The diameter is 76 cm.

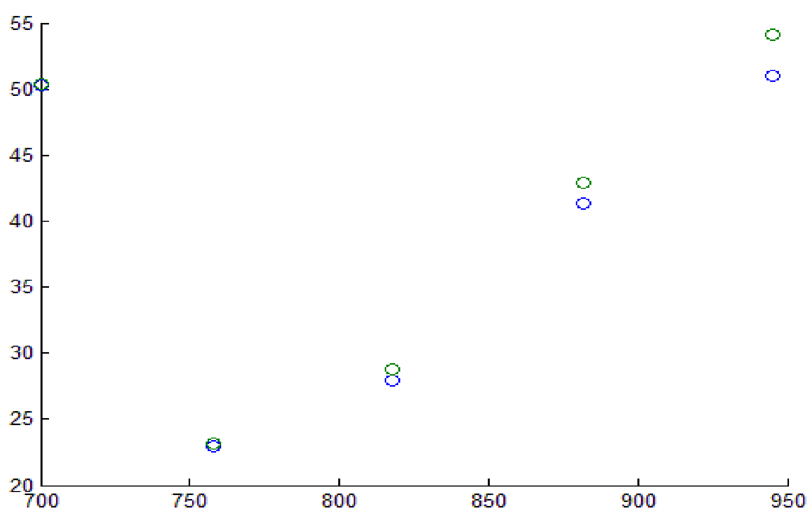

Figure 2: Spill temperature in Kelvin as a function of frequency in MHz for the original SBA design. The two circles at each frequency represent the two dipoles of the SBA. The temperature is decent at 758 MHz, but it is very high at 700 MHz and 882 MHz. The value at 945 MHz is high, but RFI in that portion of the band makes it practically unusable.

The design has gone through many iterations, but the current best design (Fig. 3) has a quarter wavelength outer corrugation, which has the effect of narrowing the beam-pattern [Kooi, Leong, Yeo (1979)]. To minimize the spill temperature over the bandwidth, the diameter was increased to 1.04 meters and then squared off at the edges to fit in a 1x1 square meter box. As shown in [Lee, Yang, et al. (2006)], squaring off the edges had only a small effect on the beam pattern. Fig. 4 shows the calculated spill temperature of the new SBA design, and Fig. 5 shows the proposed 3x3 array of receivers.

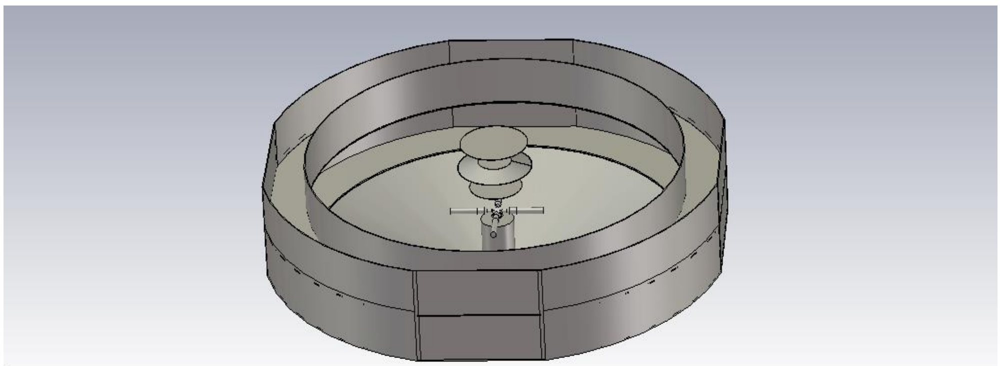

Figure 3: Current SBA design, with squared off corrugated rim. The length and width is 1 meter.

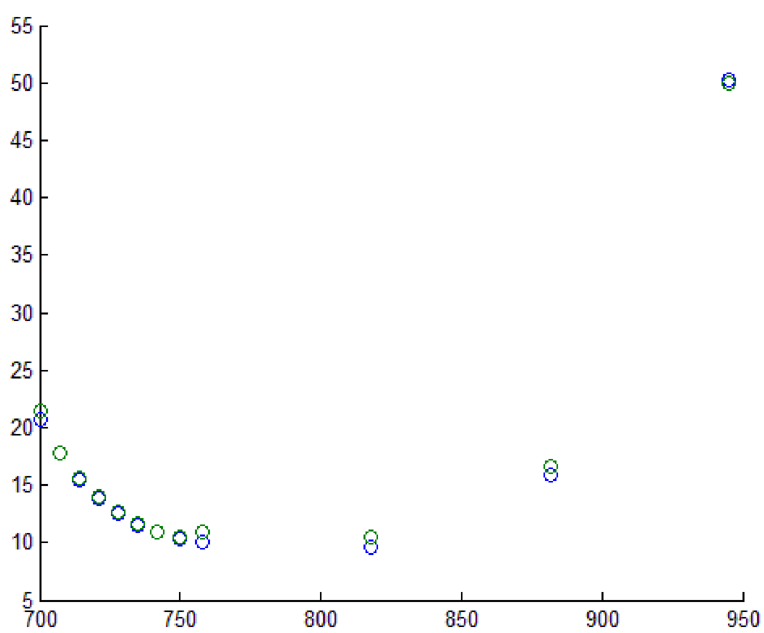

Figure 4: Spill temperatures for the current design of the SBA.

Figure 5: Visualization of propose 3x3 array to be installed at the GBT focal plane.

My adviser, Professor Timbie, and I believe the spill temperature is near optimal values. The only remaining difficulty is tweaking the position of the smaller sub-reflectors to minimize power loss in our desired frequency band (optimizing S-parameters). To minimize thermal noise in the wiring, the tip of the cryogenically cooled chamber for the electronic amplifier extends almost to the dipole antennas, and this has led to some difficulty in optimizing the S-parameters. We are confident that this will be overcome, perhaps with a slight sacrifice in spill temperature.

Conclusions and Future Work

This work is being conducted by a small international collaboration. Once the S-parameters are optimized, construction of the antenna and cryogenic system will begin in Taiwan. The completed antenna will then be shipped to the United States, where the amplifier will be integrated. We will then install a single prototype receiver on the GBT to test its noise temperature and beam pattern. The new array will be just part of our ongoing efforts in 21 cm intensity mapping. Our group is also pursuing intensity mapping in a higher redshift range with another GBT receiver and lower redshift intensity mapping using the Parkes telescope in Australia. We hope that our work will inspire enthusiasm and funding in the burgeoning field of 21 cm cosmology.

In terms of the farther term future, extending the redshift range far into the cosmological dark ages (before the epoch of reionization) will eventually require space based antennas. This is because of both the RFI difficulties on Earth and the fact that the ionosphere reflects highly redshifted 21 cm radiation above z~60. A neat solution to both these problems is a proposed 21 cm observing array on the dark side of the moon [http://lunar.colorado.edu/lowfreq/index.php].

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