Draft version April 17, 2016
Preprint typeset using LaTeX style emulateapj v. 01/23/15

A CRYOGENIC TESTING ENVIRONMENT FOR SPT-3G, THE NEXT GENERATION SOUTH POLE TELESCOPE RECEIVER

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Draft version April 17, 2016

ABSTRACT

The next generation optical system for the South Pole Telescope, SPT-3G, is set to be installed in early 2016. This report outlines the fundamental science goals and operation behind SPT-3G, and covers the continued development of a cryogenic testing environment at the University of Toronto for characterizing the next generation of detectors.

1. INTRODUCTION

The South Pole Telescope (SPT) is a 10 metre microwave telescope, located at the geographic South Pole in Antarctica. Designed to observe temperature and polarization anisotropies in the Cosmic Microwave Background (CMB) (Ruhl et al. 2004), the telescope has been optimized to operate in the millimetre (mm) band spanning from 75 GHz to 240 GHz. The next generation optical system to be installed at the beginning of 2016, SPT-3G, is to contain over 16,000 polarization sensitive detectors in the focal plane array. This order of magnitude increase in the number of detectors over the current receiver will allow for high signal-to-noise mapping of both the E-mode and B-mode CMB polarization anisotropies (Benson et al. 2014). With the increased sensitivity achieved by SPT-3G, significant advances can be made in the fields of large scale structure formation, particle physics, and cosmic inflation.

The SPT-3G detector wafers are currently being fabricated by Argonne National Laboratory, using a range of designs in order to tweak device parameters. Each wafer is tested within the SPT collaboration, providing characteristic feedback for the nanofabrication process. The detectors operate in the superconducting transition for niobium, requiring a sub-kelvin cryogenic environment for detector testing. This report outlines the development of such a system at the University of Toronto (UofT), to assist in the testing and characterization of SPT-3G wafers. In conjunction, this system also features the SPT-3G Digital Frequency Multiplexing (DfMUX) readout system. This enables testing of the entire SPT-3G detector readout chain at UofT. In Section 2, the science goals of SPT-3G are outlined, with the instrumentation required to achieve these goals covered in Section 3. Section 4 details the development of the cryogenic testing at UofT, with current testing results in Section 5. Finally, Section 6 takes a brief look at processing SPTpol detector timestreams into usable scientific data.

2. SPT-3G SCIENCE GOALS

The telescopes location at the Amundsen-Scott South Pole Station provides one of best sites on Earth for observing mm-wavelength anisotropies. This is in part due to the South Pole's elevation of 2.8 kilometres above sea level, resulting in desirably low levels of atmospheric fluctuation power. The near zero air humidity also weakens the strong absorption and emission features of atmospheric water vapour at mm-wavelengths. The current optical design produces a beamwidth of ∼1 arcmin at 150 GHz, allowing for high resolution mapping of small-scale CMB features. Coupled with the high raw sensitivity achievable through the new multi-chroic polarization-sensitive pixel design, SPT-3G will be able to extract a wealth of previously unobtainable cosmological information from the CMB.

Lensing measurements of the CMB are capable of probing matter fluctuations out to the last scattering surface, providing a detailed lensing power spectrum. SPT-3G's precise measurement of the growth of structure on small angular scales places tight constraints on the number of relativistic species at recombination. Combined with measurements from the *Planck* experiment, it is expected that the sum of neutrino masses will be constrained to within $\sigma(\Sigma m_\nu) \sim 0.06$ eV (Benson et al. 2014).

Currently pursued by a number of other experiments is the measurement of the energy scale of inflation, described by the tensor-to-scalar ratio r of primordial perturbations (Samtleben et al. 2007). While instruments such as BICEP2/KECK are optimized for measuring low angular modes, they have little or no sensitivity to small-scale temperature and polarization anisotropies. In order to fully characterize the inflationary and lensing B-mode signals, it is vital to take a high-resolution, multi-frequency approach. SPT-3G will be capable of producing a high signal-to-noise map of the lensed B-modes, achieving a noise level of $\sim 3.5\mu$K-arcmin. When used in conjunction with its exquisite E-mode measurements, the lensing potential can be reconstructed, allowing for the separation of the lensing B-mode signal from the inflationary signal. This process is known as "delensing", improving the shape of the tensor power spectrum and constraining r to within $\sigma(r) \ll 0.01$ (Benson et al. 2014).

The high angular resolution of the telescope also provides a unique way of probing the largest gravitationally bound objects in the universe, clusters of galaxies. CMB photons collide with high energy electrons contained within galaxy clusters, where they inverse Compton scatter to higher energies. This produces a distortion in the CMB signal, known as the Sunyaev-Zel'dovich (SZ) effect. This effect is largely redshift independent, allowing for the identification of almost every massive cluster above a given mass threshold, depending on instrument sensitivity. SPT-3G will be surveying a nearly identical 2500 deg^2 area to SPT-SZ, albeit with noise levels $\sim$12, 7, and 20 times lower at 95, 150, and 220 GHz, respectively. The lowering of the cluster mass threshold and extension of redshift reach will allow SPT-3G to find $\sim$5000 clusters at a signal-to-noise > 4.5, an order of magnitude more clusters than SPT-SZ. Complimenting and calibrating the Dark Energy Survey (DES) cluster survey, the SZ data is predicted to result in a dark energy figure-of-merit of $\sim$100.

3. SPT-3G INSTRUMENTATION

While the SPT third-generation receiver design also features a new optical system and cryostat, this report is to focus on the detectors contained in the focal plane array and its novel readout system.

3.1. *Focal Plane Array*

A significant contribution to SPT-3G's leap forward in sensitivity can be attributed to the newly designed focal plane array, featuring 2710 independent pixels compared to SPT-POL's 768. Each pixel is polarization sensitive across three observing bands at 95, 150, and 220 GHz. Using a sinuous log-periodic antenna, each pixel can absorb a wide band of mm-wave photons at orthogonal polarizations. Once absorbed, microstrip transition line filters route the power from each band to one of six independent transition edge sensor (TES) bolometers (one for each band and polarization). This design results in over 16,000 detectors across the entire focal plane array. The focal plane array itself consist of 10 nanofabricated 6" wafers, each containing 217 of these polarization sensitive tri-chroic pixels in both left and right-handed configurations (to account for polarization wobble induced by the antenna shape).

Each detector is essentially a microstrip termination resistor located on a thermally isolated TES bolometer island. The TES bolometer itself is held in its superconducting phase transition, where a small increase in temperature results in a dramatic increase in resistance. By passing current through the TES, a change in resistance can be measured when an absorbed photon dumps energy onto the island through the microstrip. This configuration allows for a negative feedback loop, where the increase in resistance restricts the bias current. This lowers the power passing through the TES, dropping the detector back into its superconducting phase transition. The bolometer time constant for this process is $\sim$3 ms.

3.2. *Readout System*

Reading out the thermal loading of each bolometer individually introduces an unnecessary number of wires to the sub-Kelvin stage, and as such, SPT-3G utilizes a frequency multiplexing readout system, enabling 64 bolometers to be addressed using a single wire (Dobbs et al. 2012). By placing each resistive bolometer in series with a unique LC filter, an LCR resonator is formed (Henning et al. 2012) that can be interrogated using its characteristic resonant frequency, allowing the warm electronics to perform readout in Fourier space. A digital frequency multiplexing (DfMUX) (Dobbs et al. 2012) system has been developed by McGill University, designed to deliver small amplitude excitations to each resonator with active digital feedback for nulling the subsequent signal. The error in signal cancellation is then sensitively measured using superconducting quantum interference devices (SQUIDs) (Dobbs et al. 2012), inferring changes in the bolometer impedance and hence thermal loading.

4. TESTING ENVIRONMENT

The Long Wavelength Lab (LWlab) at UofT currently houses an Olympus 104 cryostat, designed and fabricated by *High Precision Devices* (HPD) in Colorado. Featuring a helium pulse tube refrigerator in conjunction with an adiabatic demagnetization refrigeration (ADR) system, the cryostat is capable of achieving temperatures as low as 35 mK. These sub-Kelvin temperatures are realized through the ADR, consisting of two paramagnetic salt pills within a superconducting electromagnet, backed by the 3 K base temperature of the pulse tube. By applying a large current to the electromagnet, magnetic domains within the salt pills will begin to align, freezing out a thermal degree of freedom within the salt pills. Once fully magnetized, the current can be removed, allowing magnetic domains to realign themselves and reintroducing the thermal degree of freedom. In accordance with the conservation of energy, the realignment process draws heat from the system, lowering the pills to sub-Kelvin temperatures.

The cryogenic testing environment also features an interactive control system and web interface, facilitating the measurement of system parameters such as temperature, pressure, and electromagnet current, as well as conducting the magnetization process. An image of the current web interface is shown in Figure. Following demagnetization, a proportional-integral-derivative (PID) controller maintains the cold-stage temperature at a predetermined setpoint, capable of regulating temperatures of 100 mK for 100 hours.

4.1. *Cryostat Control System Development*

4.2. *DfMUX Integration*

5. TESTING RESULTS

SQUIDS 4 dayz.

6. DATA PROCESSING

Looking towards the future!

7. CONCLUSION

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