Draft version April 18, 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

Matthew Young
Astronomy & Astrophysics Department, University of Toronto, ON

Supervised by: Keith Vanderlinde and Tyler Natoli
50 St. George Street
Toronto, Ontario, Canada
M5S 3H4

Draft version April 18, 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 region for titanium, 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 the processing of 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 $\sim$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*

If each bolometer within the focal plane array were read out using independent wire pairs, the resulting thermal load would make it near impossible to maintain the array below the TES superconducting transition temperature. As such, a Digital Frequency Multiplexing (DfMUX) readout system is utilised, allowing 64 bolometers to be read out using a single pair of wires. Developed by McGill University, the DfMUX system relies on each resistive bolometer being placed in series with a unique inductance L and capacitance C. This configuration forms an LCR_{bolo} resonator, allowing the bolometer to be interrogated using a unique resonant frequency. Recent improvements in the DfMUX bandwidth now allows 64 of these LCR_{bolo} resonators to be placed in parallel, up from 16, with resonances spaced from 1.6 to 4.6 GHz. A sinusoidal voltage bias can then be fed in on a single pair of wires, consisting of every bolometer's resonant frequency summed together into a single waveform (referred to as a *comb of carriers*) (Bender et al. 2014). Changes in bolometer resistance from absorbed photons modulates each carrier, appearing as sidebands in the current. This resulting signal is then amplified using Superconducting Quantum Interference Device (SQUID) amplifiers.

SQUIDs are used as the first amplification stage due to their high gain, low input-impedance, and low noise performance. The amplifiers consist of a superconducting loop containing two Josephson junctions that allow the current to be measured. Any applied magnetic flux to the SQUID will cause produce a screening current, requiring that the flux within the loop remains at an integer number of magnetic flux quanta. This results in a periodic voltage output as a function of the magnetic flux in the input coil. The DfMUX SQUID operation requires them to first be tuned to the region of maximum gain and linearity, by applying known current flux biases to the input coil (Bender et al. 2014). The dynamic range of the SQUIDs is capable of limiting the multiplexing factor, and so an inverted copy of the carrier comb in injected prior to the SQUID input coil (referred to as the *nuller*). The improved DfMUX multiplexing factor of 64 is realised through the use of Digital Active Nulling (DAN), an active feedback loop that nulls both the carriers and sidebands for each bolometer. Following the DAN stage, the signal is demodulated back to baseband allowing the current from each bolometer to be measured.

4. TESTING ENVIRONMENT

The operation of SPT-3G wafers and readout demands sub-Kelvin temperatures, requiring a cryogenic testbed. The Long Wavelength Lab (LWlab) at UofT currently houses an Olympus 104 cryostat, designed and fabricated by *High Precision Devices* (HPD) in Colorado. The cryostat consists of several stages, with successively colder and smaller stages located within one another. The largest of these, a 50 K stage and 3 K stage, are driven by a PT415 helium pulse tube refrigerator developed by *Cryomech*. This refrigerator relies on the acoustic resonance of sharply pulsed highly-pressurised helium gas. Pulses travelling through the tube, tuned to a particular resonance, produce heating on one end and cooling temperatures as low as 2 K at the other. The sub-Kelvin temperatures required for testing SPT-3G wafers are then realised using an Adiabatic Demagnetization Refrigerator (ADR) based on the 3 K stage.

The ADR itself consists of two paramagnetic salt pills, situated within a powerful superconducting electromagnet ($L \sim 10$ H). When a large current is applied to the electromagnet, the produced magnetic field aligns the magnetic domains within the paramagnetic salt pills. This freezes out a thermal degree of freedom within the salt pills. Once soaked, removing the current from the coil allows the magnetic domains to realign, reintroducing the thermal degree of freedom. In accordance with the conservation of energy, this adiabatic realignment process lowers the temperature of the paramagnetic salt pills. The ADR system installed in the Olympus 104 cryostat features two salt pills, one of Ammonium Iron(III) Sulfate (FAA) and one of Gadolonium Gallium Garnet (GGG), with base temperatures 35 mK and 500 mK respectively. The FAA pill drives what is referred to as the *ultra-cold stage*, while the GGG pill drives the *itermediate stage*. The inclusion of an intermediate stage allows the ultra-cold stage to be buffered by the GGG pill's greater cooling power. This configuration ensures most of the thermal loading from the cold wiring is absorbed at the GGG pill, rather than the FAA.

The ADR's superconducting electromagnet contains $\sim$5 km of Niobium-Titanium (NbTi) wire looped around the magnet bore. This NbTi wire is superconducting below $T_c = 9.2$ K, resulting in a series resistance of $\sim$0.1 Ω below this temperature. While superconducting, the NbTi wire has a critical current density of $J_c = 10^3$ A$\cdot$mm^{-2} beyond which the superconducting state will break down. This sets an magnet current upper limit of 19.0 A for this given implementation. By exceeding this current or the critical temperature T_c, the superconductivity of the wire will cease, resulting in the dumping of magnet's field energy to the 3 K stage. This scenario is called a magnet "quench", and can cause significant damage to the system. As such, multiple safeguards have been implemented in both hardware and software to avoid such a scenario.

Following demagnetization, the ADR's ultra-cold temperature is regulated at a chosen setpoint using a Proportional-Integral-Derivative (PID) loop control system. Thermometry feeds in the stage temperature to the PID controller, which if below the chosen setpoint, will apply current to the coil heating up the stage. If above the chosen setpoint, the current is decreased, cooling the stage through the aforementioned adiabatic process. While regulating at 250 mK, this control loop can maintain the FAA temperature to within 0.05 mK. Once the regulation current supplying the cooling power has been depleted, a full magnetization cycle must be repeated.

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

REFERENCES

Addison, G. E., Huang, Y., Watts, D. J., et al. 2015, arXiv:1511.00055 [astro-ph]

Samtleben, D., Staggs, S., Winstein, B. 2007, in Annual Review of Nuclear and Particle Science, 245-283

Bender, A. N., Cliche, J. F., Haan, T., et al. 2014, arXiv:1407.3161 [astro-ph]

Henning, J. W., Ade, P., Aird, K. A., et al. 2012, arXiv:1210.4969 [astro-ph]

Dobbs, M. A., Lueker, M., Aird., K. A., et al. 2012, Review of Scientific Instruments, 83, 7

Benson, B. A., Ade, P. A. R., Ahmed, Z., et al. 2014, arXiv:1407.2973 [astro-ph]

Ruhl, J. E., Ade, P. A. R., Carlstrom, J. E., et al. 2004, arXiv:astro-ph/0411122