Test Small Aperture Telescope

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1 Abstract

Measurements of the Cosmic Microwave Background (CMB) radiation have been used to further the understanding of the early development of the Universe. Data about the anisotropies in temperature and polarization of CMB provides information about the cosmological model, that defines the content and evolution of the Universe. The Test Small Aperture Telescope being built in Princeton is one of the four detectors working with Simons Observatory aimed at measuring the anisotropies in the polarization of CMB, that contains imprints of gravitational waves permeating the universe during the decoupling period, to more accurately determine the value that defines the density variations of the early Universe.

2 Introduction

Cosmic Microwave Background radiation is a remnant of the early Universe, known to have been released 300,000 years after the birth of the Universe during the decoupling epoch, when the electrons and protons from the primordial plasma cooled down enough to form neutral Hydrogen and decoupled from photons [6]. The data obtained from this radiation can, therefore, be used to support

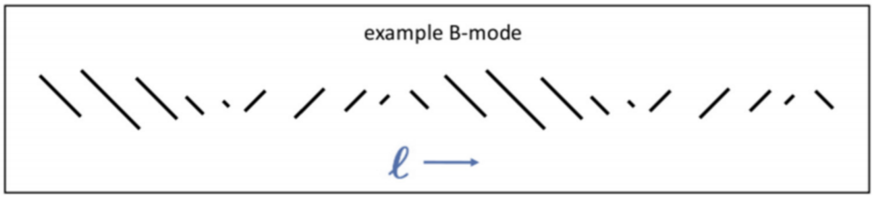


Figure 1: B-modes are polarized such that they are anti symmetric with respect to rotations about the wave-vector [6]

the ΛCDM model of cosmology, and ascertain whether theories that explain the early expansion and development of the Universe are truly applicable.

According to the cosmic inflation theory, in the primordial stages of the Universe, space-time expanded exponentially increasing its size by a factor of about 10^{26}. This theory compliments the thermal isotropy of CMB, that is known to have a temperature average of 2.7 K across the night sky. These simple inflationary models of the Universe predict the existence of tensor perturbations, generally attributed to gravitational waves. The ratio of the power of these tensor fluctuations to the power of scalar fluctuations is denoted by the constant r, and is used to define densities of primordial fluctuations [4].

The primordial fluctuations bring about two different types of polarization called E-modes and B-modes, which are both coordinate independent quantities. The former carries the parity symmetric component whereas the latter, carries the curl component which is anti symmetric [4]. Anti-symmetric polarization is known to be caused by quadrupole intensity variations in the radiation. These quadrupole moments are expected to have been generated by primordial gravitational waves causing tensor fluctuations [6]. Therefore, the CMB B modes are expected to be polarized at an anti-symmetric angle of 45 degrees appearing as shown in Figure 1.

Previous attempts at measuring B-modes or determining the value of the tensor to scalar ratio r has only resulted in the setting of an upper limit, r

< 0.07, with 95% confidence (BICEP2/Keck and Planck Collaborations 2015; Planck Collaboration 2018)[1]. Detectors like the TSAT at Princeton aim to detect signal with r as low at 0.01. A detection of any B mode signals indicating a value of r equal to or higher than 0.01 would be evidence against any early inflation theories that do not predict the existence of tensor fluctuations [1] as well as other non inflationary cosmologies such as ones where the big bang singularity is replaced by a smooth transition 'bounce'.

Even though the average temperature of CMB across the sky is 2.7 K [6], the polarized B-modes of the radiation have a much lower temperature associated with their amplitude. Therefore, the detector must have a very high sensitivity to distinguish anisotrpies in the B-modes which occur in the mili Kelvin range. The device generally used to measure the intensity of radiation, by detecting the radiative heat deposited on an absorber is called a bolometer. The Small Aperture Telescopes, including the one at Princeton, uses a Transition Edge Sensor (TES) bolometer. These sensors are made with a film of superconducting material, whose resistance sharply drops to zero after as the material cools through is transition temperature; this property of the material allows it to be used as a high sensitivity thermometer [5]. Within the detector, the superconducting film is maintained in the narrow band of temperature between the normal and super conducting state; as the detector scans the sky for radiation, the fluctuations in resistance are logged and used to measure the anisotropy in radiation.

High sensitivity Transition Edge Sensors are usually made of superconducting material; these materials exist at their normal state until they are cooled down to their transition temperatures, beyond which their resistance drops to zero. Most superconductive materials have transition temperatures extremely close to absolute zero, with low transiton temperature sensors having higher sensitivity [5]. The sensor is maintained at its transition temperature, and the

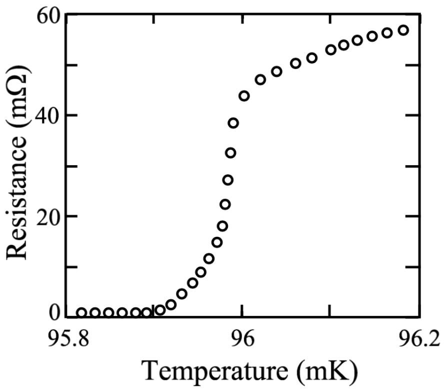


Figure 2: When temperatures fall beyond the transition temperature the resistance of the material drops to zero [5]

fluctuations in resistance caused by the B-Mode signals are measured Therefore, the detector must me maintained at extremely low temperatures to effectively detect CMB B-modes.The Sensor itself is temperature regulated using a thermal bath mechanism, aloing with maintaining a voltage bias, so that fluctuations in resistance of the sensor caused by B- Modes do not increase the power, and therefore the temperature, of the sensor.[4]

The cold temperature needs to be gen erated within the detector and is maintained across three stages in the TSAT, with a 40K outer shell, followed by a 4K shell which encompasses a shell cooled to below 1K by strong cryo-refrigerators [4]. This stage based cool down acts as a radiative shield, decreasing the temperature lost from the coolest shell through radiation and the power required to cool the 1K shell. To further decrease the radiative factor, the 'blankets' made of sheets of mylar must be made to cover the entire detector. Finally, to remove the convective factor, a near vacuum is created within the detector. To ensure this vacuum is created the pressure within the detector would ideally need to be tracked.

Finally, the signal outputted by the TES is amplified using a Superconduct-

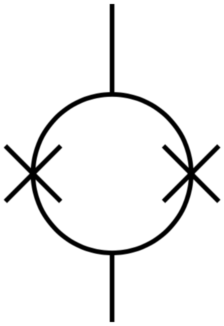
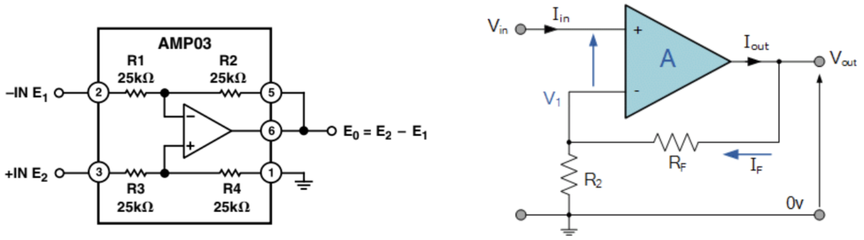


Figure 3: Circuit diagram of a SQUID, where the Josephson junctions are denoted by an 'x' symbol [4]

ing Quantum Interference Device (SQUID). This device is made of two halves of a superconducting ruing, separated by a non conducting material, creating what us called a Josephson Junction[4] (see figure 3). This device created a large AC voltage when the current running through the device exceeds a certain current limit. The input to this device takes the form of a fluctuating current, that created a changing magnetic flux across the area of the SQUID loop. To counter the changing magnetic field the an added current runs through the SQUID loop when the current crosses the limit, a high frequency voltage is created and the signal is therefore amplified. Since this device is very sensitive to any changes in magnetic fields, it needs to be shielded and the magnetic field within and right outside the detector need to be tracked to ensure smooth functioning.

3 Methodology

Multiple pressure sensors are placed at each cool down shell, to track data and determine when the pressure reaches near 0 and the magnetic field within the detector remains low. The most important instrumentation required to do the test cool-down to 4K and test shielding effects of the detector are the pressure sensors and magnetometer.



(a) Figure a

(b) Figure b

Figure 4: Figure a: An AMPO3 Circuit, with built in feedback, usually used as a differential amplifier [2] Figure b: How an OP77 can be used with feedback in an amplifying circuit [3]

The goal was to understand the instrumentation, how they work and the form of output they produce, to feed the output into circuit boards that effectively amplified and stabilized their signal and fed it to a computer to be live plotted. The devices facilitating communication, like an analog to digital converter, along with the circuitry that leads the output of the instrumentation through the converter to the computer were to be assembled in a metallic box. Since this was a practice followed by many previous detection experiments, such as the Atacama B-Mode Search, we used previously created boxes to understand the pin outs of the instrumentation, understand the circuitry required to stabilize and amplify signals, and to have a basic map upon which we would add our more advanced or newly designed circuit boards and conversion devices.

We read data-sheets and probed previous circuits to understand the output of the instruments. Each instrument outputs a reference or ground voltage along with the true signal. The circuits need to therefore, not only stabilize and amplify the signal but also find the absolute difference between the reference output and signal, to ensure that the reference voltage of all the instrumentation can be set to the same voltage value of 0. To do so, our circuits used two electronic components: OP77 and an AMPO3. Both have different circuitry within them but work on the basic principals of amplifiers.

Amplifiers are generally built with a large gain, such that the output voltage, denoted as V_{out} in Figure 4b and $E_o$in Figure 4a, equals the gain times the difference between the voltages entering the amplifier at the positive and negative terminals in open loop circuits [3]. With gain represented as 'A' the relation between the output voltage and the voltages supplied to the positive and negative terminals can be denoted as:

$$V_o = A(V_+ - V_-)$$

However, in closed loop circuits, with resistors and feedback [1] the gain is controlled and decreased. Both the OP77 and AMPO3 in our circuit boards, use negative feedback loops, either supplied by our circuitry or provided within the piece itself. In these closed loop circuits Operational Amplifiers work on two basic laws - they have infinite input impedance, which means that there is no current running through the input terminals, and they have zero offset voltage i.e.; the difference across the voltage of each input terminal is zero [3].

$$V_+ = V_-$$

The signal from the instrument goes through the OP77 to be amplified in some cases, and stabilized by the feedback loop. In the circuit diagram depicted in Figure 4b, using the voltage divider formula for the region between V_- and V_{out} we get:

$$V_- = \frac{R_2}{(R_2 + R_F)} \cdot V_o$$

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[1] V_o is fed back to V_- such that changes in gain are countered by the anti phase relation across output and negative input, creating a stabilizing effect.

And then, using the law followed by amplifiers in closed loop circuits we get:

$$\frac{V_O}{V_{in}} = 1 + \frac{R_F}{R_2}$$

Therefore, if R_F is set to zero, the circuit creates no amplification and the closed loop gain is stabilized to a value we can control with the resistors we choose to use in the circuit.

Unlike the OP77, the AMPO3 comes with built in feedback as well as a resistor circuit that makes it perfect for difference amplification i.e.; to output the difference across the voltage values of the two inputs [2]. Most instrumentation has two outputs, one labelled as ground and the other labelled as the positive output signal. We use AMPO3s in out circuits to find the absolute difference between the ground of the instrument and its signal, against the ground we set up for all instrumentation within the box. Therefore, AMPO3s are used to create a common ground across all the instrumentation to get an accurate, absolute value of signal.

A simple analysis depicts how the AMPO3 outputs the difference between the input voltages. If the current flowing from E_1 is I_1 and the current flowing through R_2 is I_2 and current flowing through $R3$ is I_3 then these currents can be expressed as:

$$I_1 = \frac{E_1 - V_-}{R1} \qquad I_3 = \frac{E_2 - V_+}{R_3} \qquad I_2 = \frac{V_- - E_o}{R_2}$$

Also, using the voltage divider equation we have:

$$V_+ = \frac{R_4}{R_3 + R_4} \cdot E_2$$

Now if we set $R_1 = R_3$ and $R_2 = R_4$ and use the previously mentioned laws followed by amplifiers in closed loop circuits we get the difference amplifier equation:

$$E_o = \frac{R_2}{R_1} \cdot (E_2 - E_1)$$

Since these resistors are all exactly equal to each other in the AMPO3 built-in circuit the device outputs the exact difference across the two input voltages.

4 Results

In many cases, the amplifiers were just used to find the difference across the two input voltages and stabilize the signal, without any amplification; any amplification would require changing the calibration curve data, that gives us the conversion function between the voltage output and the actual value of pressure or magnetic field strength the signal refers to.

We were successfully able to trace connections in older versions of the box we created, to understand instruments, their outputs and how power supply for the instruments and each of the circuit boards work. We also were able to use a more compact analog to digital converter, with a Mux80 multiplexer extension that allowed us to create a single container that would read in signal from a variety of instruments, such as heaters, pressure sensors, magnetometers, inclinometer, temperature sensors etc. while also feeding the signal into the converter within the same space, making the entire process much more compact.

After ordering a metal box, and machining it to add connectors, power buses, a fan and a vent, we connected the input points of input to the circuit board and drew up a pin out of all the circuit boards involved, so that in the future the input and output circuits can be easily interpreted. In most cases, we created multiple outputs for the same signal, one going to the converter and another that could directly be read from the box through a BNC connector making testing of circuitry and instrumentation easy. The magnetometer inclinometer were mounted, and wires running from the instrumentation to the box itself have been made. Though the converter that tracks temperature by taking signals from diodes does not run through our box, it is installed in same rack that hold the box. Test cool-downs were run to track the temperature outputs of the diodes using the converter and match them to their respective calibration curves.

5 Conclusion and Further Direction

Though the instrumentation an circuitry can be tested easily, using magnets or vacuum pumps to change the environment and obtain a test read-out, the detector can only be cooled down once all the blankets are prepared, instrumentation is mounted and all parts of the detector are appropriately assembled. The estimated time at which the test cool-down to 4K will be run is the end of September. This test cool-down will provide insight into effectiveness of blankets and the ability of all the elements of the detector to cool down to their appropriate temperatures.

if this detector gets deployed, the time of completion and installation in Chile is estimated to be three to four years from now. Measuring B-modes would greatly increase confidence in the inflation theory and cosmological model that is most widely accepted today. However, a lack of strong B-mode signals would also offer great direction, forcing cosmologists to look at alternative expansion theories that do not predict the existence of anti-symmetrically polarized B-mode signals.

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