The Polarimeter for Observing Inflationary Cosmology at the Reionization Epoch (POINCARE)

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Abstract. We describe the Polarimeter for Observing Inflationary Cosmology at the Reionization Epoch or POINCARE, a novel ground-based instrument for measuring the polarization of the cosmic microwave background with sensitivity to detect the B-mode signal induced by inflationary gravitational waves. POINCARE's 3 frequency bands span the polarized Galactic foreground minimum. POINCARE covers $\sim$ 65% of the sky at these 3 frequency bands to provide sensitivity to the large scale reionization bump of the polarized spectrum at sensitivities down to $r \sim 0.01$.

1. Introduction

The polarization of the cosmic microwave background (CMB) provides a tool with which to probe the earliest epoch of the universe. Specifically, if the universe underwent a brief period of inflation, an exponential expansion that has been posited as a solution to the flatness, structure, and horizon problems of the Big Bang paradigm, it would have produced gravitational waves that leave a polarized signature on the CMB. Detection of this signal would provide direct evidence for inflation, and its measurement may provide insight into physics at or near that of grand unification.

The Polarimeter for Observing Inflationary Cosmology at the Reionization Epoch (POINCARE) complements the current fleet of ground- and balloon-based CMB polarimeters by providing large sky coverage at frequencies that span the polarized Galactic foreground minimum. POINCARE utilizes detectors in which HE_{11} feedhorns are coulpled to Transition Edge Sensors via superconducting microstrip circuits. At the front end of the optics, a variable-delay polarization modulator (VPM) provides rapid (∼2 Hz) modulation. This rapid front-end modulation reduces $T \rightarrow B$ contamination because the modulation is encoded before the focusing optics can induce instrumental polarization from the unpolarized CMB. POINCARE's primary modulation will be done in polarization rather than in scanning. Because of this, each pointing provides an independent polarization measurement. This enables POINCARE to cover a large fraction of the sky and thus attain sensitivity to the reionization bump at large angular scales where the contamination due to gravitational lensing is lowest. In this work, we briefly describe the POINCARE instrument, focusing specifically on the plan for mitigating systematic effects.

2. Instrument Overview

POINCARE will consist of three separate telescopes mounted to the existing Viper telescope frame. Each measures the linear polarization that is oriented at a 120° angle with respect to that of the other two optical paths. This arrangement simultaneously characterizes the polarization state of the sky at a given pointing, while providing a cross-check on the relative calibration of the three focal planes. Polarization is modulated in each telescope using a VPM. The VPM is the closest optical element to the sky. The plan for the telescope is shown in Figure 1.

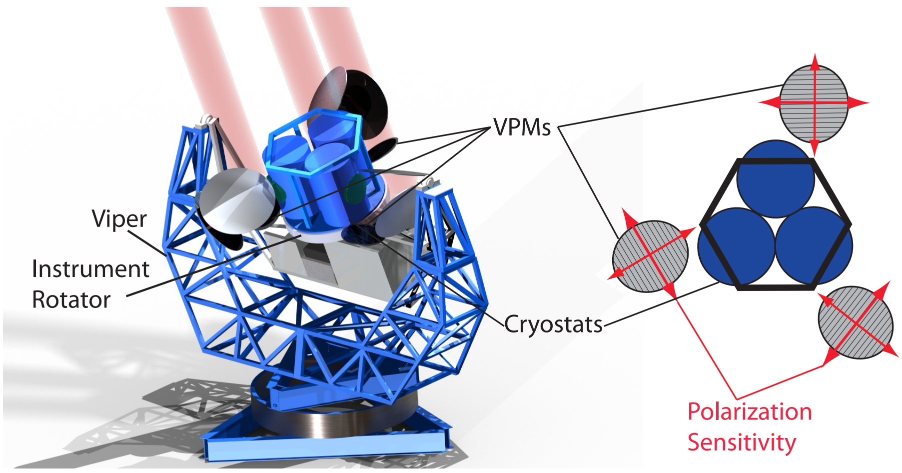

Figure 1. POINCARE uses the existing Viper telescope mount and contains 3 focal planes, each measuring a component of linear polarization oriented at 120° with respect to the other two. This allows simultaneous detection of Stokes Q and U with sufficient redundancy for cross-checks.

Instrument specifications are given in Table 1. These assume a 50% observing efficiency for 2 years and a 30% optical efficiency. Figure 2 shows the expected sensitivity to B-modes at a gravitational wave amplitude of $r \sim 0.01$. Observing from Atacama, approximately 65% of the sky is observable over the course of the year, and thus POINCARE will be sensitive to B-modes at large angular scales.

Frequency bands have been chosen to simultaneously span the Galactic foreground minimum and to maximize atmospheric transmission (See Fig. 3). The 40 GHz channel is particularly

Channel	40 GHz	90 GHz	150 GHz
Number of Detector Pairs	36	300	60
Angular Resolution (FWHM; °)	1.4	0.6	0.4
Detector NEQ ($\mu K\, s^{1/2}$)	176	151	204
Band NEQ ($\mu K\, s^{1/2}$)	29.3	6.2	26.3
Noise Limit (nK)	5.2	1.5	4.7

Table 1. POINCARE specifications and sensitivities assuming 2 years of observing with 50% efficiency and 30% optical efficiency

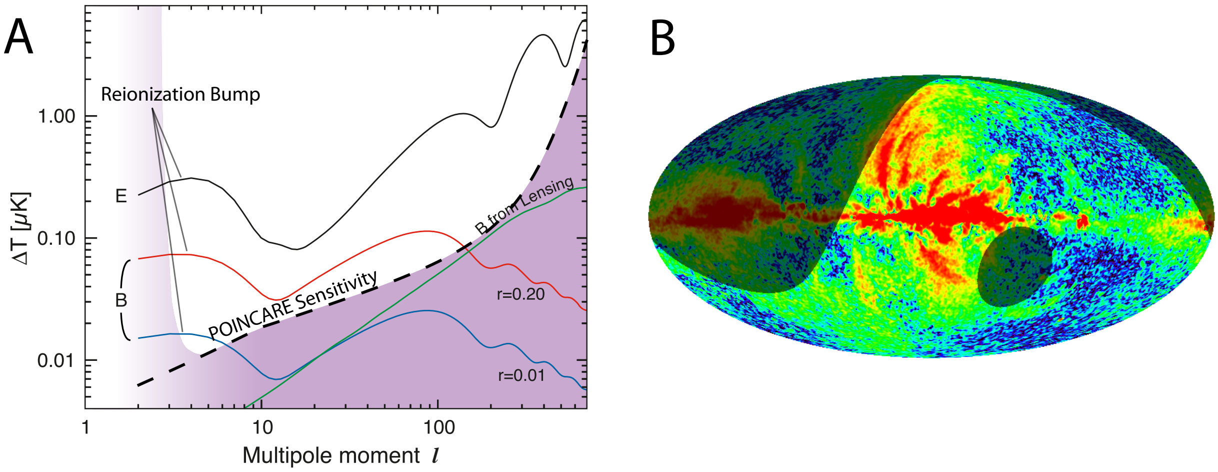

Figure 2. (A) POINCARE has sensitivity to detect B-modes at a gravitational wave amplitude of $r \sim 0.01$. Sensitivity (white region) is calculated assuming ∼400 detectors for 2 years of integration with a 50% duty cycle and 30% optical efficiency. (B) From Atacama, POINCARE will cover ∼65% of the sky above a 45° elevation angle.

important, since it provides a synchrotron guard channel, thereby greatly reducing the noise penalty associated with foreground removal.

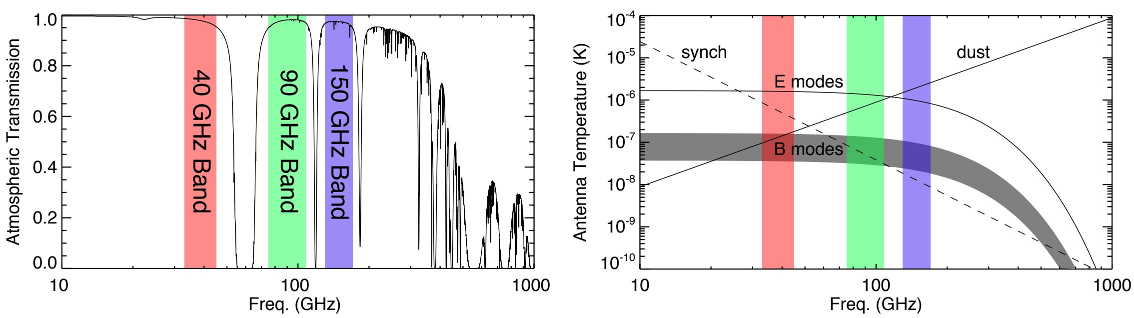

Figure 3. The frequency bands in which POINCARE will observe are chosen to straddle the Galactic foreground spectral minimum and to minimize atmospheric effects. The atmosphere represents that from Atacama with 1 mm precipitable water vapor. Synchrotron and dust spectra are based on WMAP5 data [?].

POINCARE will use scans across the Galactic plane to calibrate. During a calibration, the modulator will be held fixed. Between calibrations, the temperature of the detector will be monitored to test the stability of the calibration.

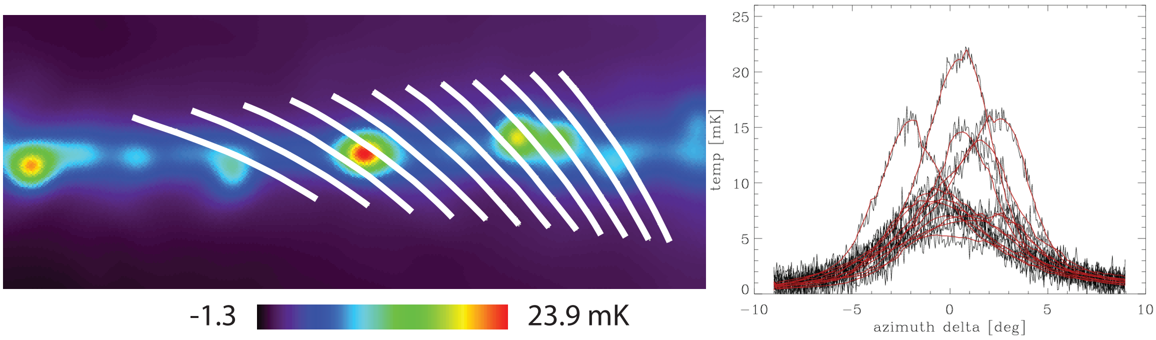

Figure 4. (left) Candidate azimuth scans of the Galactic plane from Atacama are shown. Such scans will be used to calibrate POINCARE. (right) Azimuth plots of the scans are shown with anticipated noise.

Behind the VPM, POINCARE utilizes a crossed-Dragone architecture, allowing for a large field of view and minimal geometric cross-polarization. Figure 5 shows the general layout.

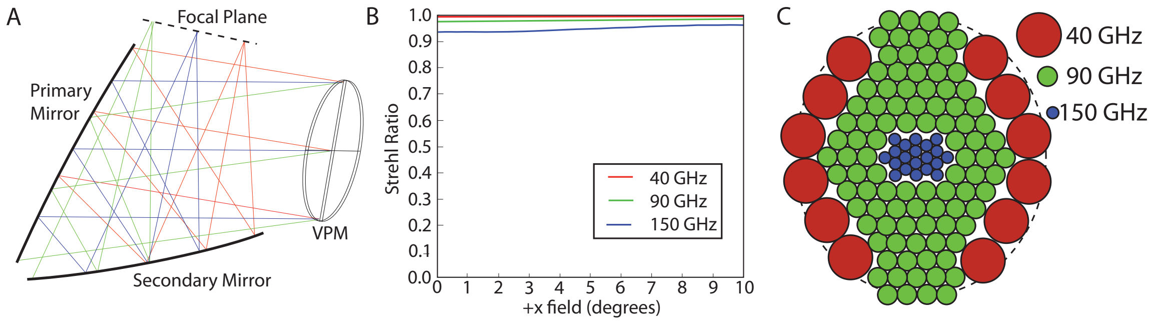

Figure 5. (A) POINCARE uses a crossed-Dragone telescope with the VPM out front. (B) This designed provides a large field of view with good Strehl ratios. (C) Each of the three focal planes in the POINCARE instrument contains dual-polarization detectors at three frequences: 12 beams at 40 GHz, 100 beams at 90 GHz, and 20 beams at 150 GHz.

3. Polarization Modulators

The Variable-delay Polarization Modulator (VPM) modulates polarization by physically separating two orthogonal linear polarizations and adding a controlled variable path difference [?]. It achieves this separation by using a polarizing grid that is positioned parallel to and in front of a mirror. The component of linear polarization having its electric field parallel to the grid wires reflects off of the grid surface. The orthogonal component passes through the grid and reflects off of the mirror. The mirror-grid spacing is directly proportional to the phase separation of the two polarized components (see Fig. 6).

In POINCAREs optical design, the detector basis for separating two orthogonal linear polarizations (defined by the OMT) is oriented at an angle of 45° with respect to the orientation of the wires of the polarizing grid in the VPM. In this configuration, Stokes Q at the detector

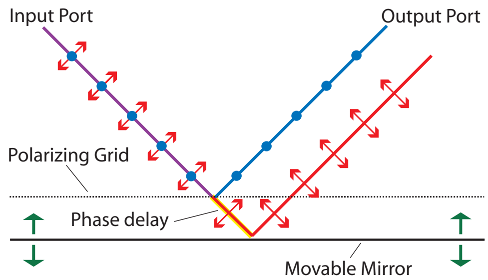

Figure 6. The VPM modulates polarization by introducing a variable phase delay between orthogonal linear polarizations.

(measured by differencing the signals of the two polarizations) is related to Stokes Q and V of the source by:

$$Q_{detector} = Q_{sky}\cos\Delta + V_{sky}\sin\Delta \tag{1}$$

Here, $\Delta = 2\pi d/\lambda$, where d is the path difference between the two polarizations and λ is the wavelength.

Over a broad passband, the measured Q modulation produced is an interferogram that is a function of the mirror-grid separation. The Fourier transform of this interferogram is a spectrum of Stokes Q of the source. In Figure 7, a two spectral component fit is shown to VPM data.

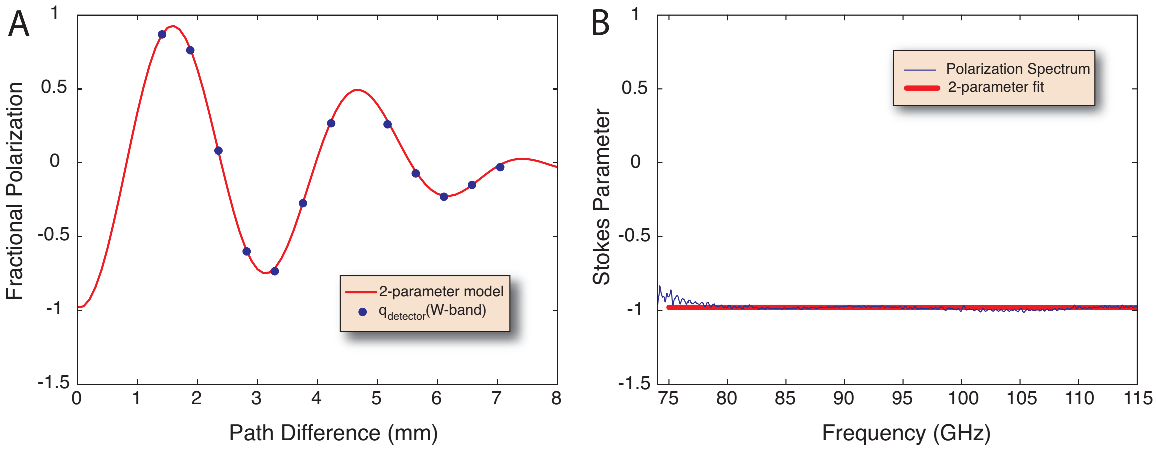

Figure 7. (A) At W band (75-115 GHz), the polarization transfer function has been measured for a 100% polarized source. The data are fit using a polarization spectrum with two frequency components. (B) The resulting broadband measurement of Q for a linearly-polarized source is superposed on the polarization signal measured in each of the individual channels of the VNA.

The symmetry of the VPM can be contrasted with that of a half-wave plate. Figure 8 illustrates the difference between these two modulations on the Poincaré sphere. The half-wave plate employs a fixed phase delay between two orthogonal polarization. The basis of this phase delay is then rotated mixing Q and U throughout the modulation. Finite bandwidth effects cause a dispersion in a direction perpendicular to the modulation on the Poincaré sphere. In contrast, the VPM modulates a single linear Stokes parameter (in this case, Q) by mixing it with circular polarization. The lack of Q, U mixing means that the basis for the modulation is constant and Q, U (and consequently E, B) mixing is minimized. Another way of stating this is that residuals for the VPM are mapped into circular polarization states that are cosmologically negligible.

A second difference that is notable in Figure 8 is that the dispersion for the VPM is parallel to the direction of modulation. It also increases with phase delay. This is the manifestation of the interferometric property of the VPM. It is capable of measuring the polarization spectrum within the band, thereby avoiding systematics that are dependent upon the shape of the input polarization spectrum.

The advantages of the VPM can be summarized as follows:

- The modulation symmetry allows for spectropolarimetry. This allows avoidance of systematic effects associated with the input polarization spectrum.
- The VPM is used in reflection, eliminating the use of dielectrics.
- The VPM employs small, linear motions rather than large circular ones. This is a potential advantage for space applications.
- The VPM has more flexibility in size than HWPs. This allows larger apertures that enable lower frequency systems with front-end modulators.
- The modulation of a single linear Stokes parameter at a time allows good separation between Q and U. Systematic effects are generally introduced in the basis of the unmeasured Stokes parameter. Thus effects that mix Q and U (such as instrument cross-polar response) are manifest in the VPM system as a gain rather than a false polarization.

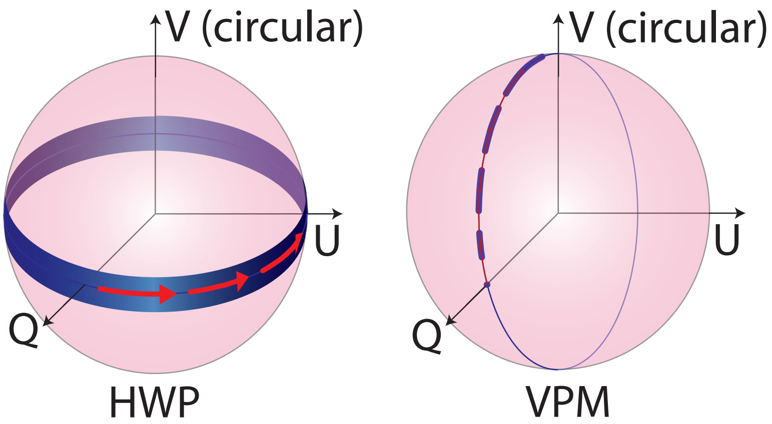

Figure 8. The VPM does not mix Stokes Q and U, as opposed to a HWP. Residuals due to spectral effects are shown qualitatively in blue. In the case of the VPM, these are a function of the modulation parameter and can be measured.

There are several potential systematics that are inherent in the VPM architecture. Each of the systematics in this class is greatly mitigated by the fact that each of them produces a signal that has the characteristics of a polarization that is either parallel or perpendicular to the grid wires. That is, any false polarization will appear *correlated* in the Horizontal (H) and Vertical (V) detectors (which are oriented at 45° with respect to the grid wires). True polarization signals from the sky are *anticorrelated* in the H and V detectors. In other words, if the instrument is sensitive to $Q = H - V$, the systematics are U-like, and thus do not contaminate the measurement. The fact that intrinsic systematic effects appear in the unmeasured linear Stokes parameter is a key advantage of the VPM aproach. These effects can weakly couple to the measured polarization signal if there is a rotational misalignment between the detectors and the VPM wires. Assuming a pessimistic misalignment of 1°, the coupling is $\sin[2(1°)] = 3\%$.

The following is a list describing three such potential systematics along with estimates of their effects. These are considered before taking into account the few per cent coupling to the signal.

- *Variable illumination*: The illumination of the mirror (rear optic) is variably vignetted by the grid (front optic) during a variation in grid-mirror separation. Thus, the power in one polarization is variable. By underilluminating the VPM to keep the power at its edge to 1% of the power at the center (-20 dB edge taper), it is possible to keep the modulated signal to 4×10^{-5} of the total power. This reduces the problem of measuring the B-modes to $r \sim 0.01$ from that of measuring 1 part in 10^9 to measuring the polarization to 0.01%. This effect is further mitigated because this signal is expected to increase linearly with grid-mirror separation. As such it enters the data stream differently than a true polarization signal and can be rejected on this criterion.
- *Resonances*: The grid-mirror pair could produce resonances due to standing waves between the two surfaces similar to those measured by [**?**]. It is possible to mitigate the effects of such resonances. 1. POINCARE's broad passband dilutes such resonances, 2. The wire pitch and spacing are chosen to maximize grid efficiency to prevent the leakage that causes such resonances, 3. POINCARE's beam waist at the modulator is electrically 10 times larger than that used by [**?**] such that the collimation within the device is better and resonances are reduced, 4. We have located the VPMs at a pupil to ensure that the adjacent rays are parallel.
- *Grid emission and absorption*: Because the wires have a finite conductivity and the grid is not perfectly efficient, the emission and absorption of the VPM varies with the grid-mirror separation. At 300 K, emission dominates over absorption. Using a transmission line model that includes the loss of the wires, we estimate that the emission is 4.5-30 mK for the range of POINCARE frequencies. This translates into background polarizations of 0.2-1%. In taking account the weak coupling to Stokes Q, the background polarization from this effect is reduced to 0.006-0.03%. This can be removed by the relative rotation of the sky with respect to the instrument.

4. Detectors

Detectors for POINCARE consist of feedhorn-coupled detectors under development at NASA Goddard and NIST Boulder. HE_{11} feedhorns couple the signal from the optics into superconducting microwave circuits via a planar orthomode transducer (OMT). The 40 and 150 GHz detectors are currently being developed by NASA Goddard and NIST, respectively. For the 40 GHz design [**?**], the signals from the opposite antennas of a given polarization are combined electrically using a "Magic Tee" hybrid coupler [**?**]. The signal in each polarization is then filtered and then terminated in a resistor that is thermally connected to a TES. In the 150 GHz design, the signals from each antenna in a single polarization are combined thermally by connecting them to the same termination. This termination is coupled to the TES for each polarization. The concept for the detector is shown in Figure 9.

5. Systematics Summary

POINCARE addresses the control of systematics in the following ways:

- $T \rightarrow B$: The front end modulation is the primary control over instrumental polarization. The modulation is encoded before the optics can contaminate the polarization signal. It is important, however, to have sufficient edge taper on the VPM so as to not modulate the flux with variable edge vignetting.
- $\Delta T \rightarrow B$: The front end modulation ensures that the beam shape is not changed by the modulation. The primary modulation is done in polarization rather than by scanning. This

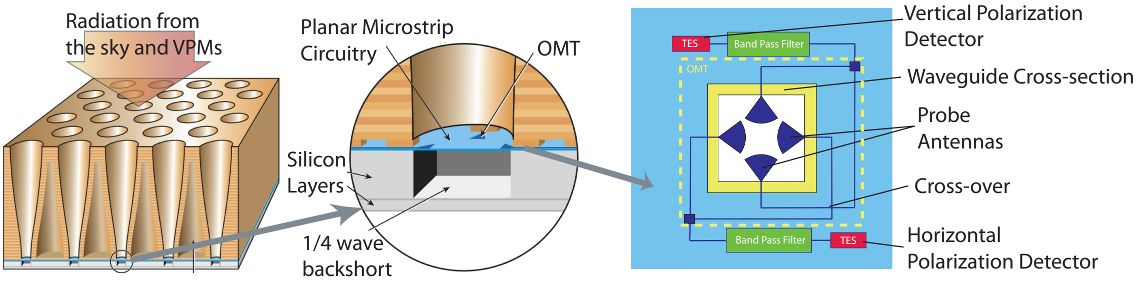

Figure 9. POINCARE's detectors combine the symmetric beam properties of feedhorns with the sensitivity of transition-edge sensors. On the right is a schematic circuit layout for the 40 GHz detectors. The 150 GHz detectors differ slightly in that the signals from opposite waveguide probes are combined thermally rather than electrically.

breaks the degeneracy between signals resulting from variations in unpolarized flux and those from polarized sky signal.

- $E \to B$: Because the basis of linear polarization modulation is never changed, good isolation between Q and U (and consequently E and B) is maintained. This symmetry prevents cross-polarization from mixing Q and U. The three telescopes oriented at 3 separate polarization angles provide instantaneous Q and U measurements as well as cross-calibration between them.
- $\Delta T_{Optics} \to B$: The rapid front-end modulation is used to remove the effects of drifts in the temperature of the optics. The 2 Hz modulation is faster than anticipated temporal drifts.
- $\Delta T_{Cold\,Stage} \to B$: The detectors will be calibrated frequently using scans across the Galactic plane. Between these scans, the temperature and bias of the TESs will be monitored.
- *Foregrounds*: The effect of polarized Galactic foregrounds is minimized by straddling the foreground minimum. The gravitational lensing foreground is avoided by providing the sky coverage to measure the B-modes on large angular scales (where the lensing contamination is expected to be at its weakest).

References