CLOVER – A NEW INSTRUMENT FOR MEASURING THE $B$-MODE POLARIZATION OF THE CMB

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We describe the design and expected performance of Clover, a new instrument designed to measure the $B$-mode polarization of the cosmic microwave background. The proposed instrument will comprise three independent telescopes operating at 90, 150 and 220 GHz and is planned to be sited at Dome C, Antarctica. Each telescope will feed a focal plane array of 128 background-limited detectors and will measure polarized signals over angular multipoles $20 < \ell < 1000$. The unique design of the telescope and careful control of systematics should enable the $B$-mode signature of gravitational waves to be measured to a lensing-confusion-limited tensor-to-scalar ratio $r \sim 0.005$.

1 Introduction

In recent years the power spectrum of temperature anisotropies in the CMB has been measured with ever increasing precision and resolution allowing tighter constraints to be placed on cosmological models and parameters. However, yet more information can be obtained via measurements of the polarization of the CMB. Thomson scattering of the CMB at recombination and reionization gives rise to linear polarization which can be decomposed into a curl-free part ($E$-mode polarization) and a divergence-free part ($B$-mode polarization). The primordial scalar perturbations that are responsible for the observed temperature anisotropies can produce only $E$-mode polarization in linear theory but a cosmological background of gravitational waves (tensor modes), such as that generated in most models of inflation, produces both $E$- and $B$-mode polarization. Detection of either of the $E$- or $B$-mode polarization provides a wealth of information complementary to that contained in the temperature anisotropies, and a detection of the
Tensor contribution will provide a uniquely powerful test of inflationary models. The predicted amplitudes of the $E$- and $B$-mode polarization fluctuations are extremely small ($\sim 5 \mu K$ and $<0.1 \mu K$ respectively) and hence measurement of either requires both superb sensitivity and an unprecedented control of systematics. A detection of the $E$-mode polarization was first reported by the DASI$^1$ team and a measurement of the temperature-polarization cross-correlation on larger angular scales ($\ell < 200$) has been published by the WMAP$^2$ team. However, as yet there has been no detection of the $B$-mode polarization of the CMB. Here we describe a new experiment, Clover, which has been designed with the sensitivity and control of systematics required to allow a detection of the gravitational wave contribution to $B$-mode polarization.

## 2 Instrument overview

The main science goal of Clover is to measure the power spectrum of the $B$-mode polarization in the multipole range $\ell = 20$–1000, with the aim of making measurements down to a sensitivity limited by the contamination due to foreground lensing of the $E$-mode signal for multipoles $\ell < 200$. Clover consists of three completely independent telescopes, operating at 90, 150 and 220 GHz and hence will allow spectral subtraction of foreground components. Each telescope consists of four separate, co-pointed optical assemblies (Fig. 1, left), each fed by an 8×8 array of feed horns and scaled in size such that each has a beam on the sky of 15 arcmin. The signal from each horn is separated into the two independent polarization states, converted to circular polarization, phase modulated and then correlated (Fig. 1, right). The two correlator outputs encode the Stokes parameters $I$, $Q$ and $U$. The outputs from each corresponding pixel in the four optical assemblies are then summed incoherently before being detected by a TES bolometer. There are thus 256 horns per telescope but only 64 simultaneously observed pixels, since the optical assemblies are co-pointed. The sensitivity, however, is equivalent to 256 individually-detected pixels. Stokes parameters $Q$ and $U$ are measured instantaneously by the phase modulation in the polarimeter, while $I$ is measured by scanning the telescope. Table 1 summarises the current specification for Clover.

### 2.1 Telescope and mount

The optical assembly of Clover comprises a Compact Range Antenna (CRA) which is an offset-fed design exhibiting low off-axis beam distortion and cross-polarization ($<-35$dB for an edge pixel). The four optical assemblies on each telescope are built around a single cryostat which houses all four horn/polarimeter arrays and the detector array (Fig. 1, middle), and are mounted on a common mount which allows altitude-azimuth tracking as well as rotation of the entire optical structure around the pointing axis. This arrangement allows the total optical throughput to be increased relative to a single telescope design with the same size of focal plane array, while the rotational symmetry allows physically different arrays to be rotated into the same orientation thus providing cross-checks on telescope-dependent systematics.

| Telescope frequency | 90 GHz | 150 GHz | 220 GHz |
|---------------------|--------|---------|---------|
| Bandwidth           | 30 GHz | 45 GHz  | 60 GHz  |
| Pixel NET           | 170 $\mu$Ks$^{1/2}$ | 215 $\mu$Ks$^{1/2}$ | 455 $\mu$Ks$^{1/2}$ |
| Array NET           | 10.5 $\mu$Ks$^{1/2}$ | 13.4 $\mu$Ks$^{1/2}$ | 28.5 $\mu$Ks$^{1/2}$ |
| Beam FWHM           | 15 arcmin | 15 arcmin | 15 arcmin |
Figure 1: **Left:** Schematic view of a single observing platform with four co-aligned telescopes each feeding an array of 64 feed-horns. **Middle:** The central cryostat containing four 64-element feed arrays and the sections behind containing the hybrids and phase switches. Note the twisted waveguide sections mating the horn arrays to the detector array (central cube), allowing the same sky pixels to be brought to the same detector. **Right:** Schematic of the pseudo-correlation receiver for a single feed.

2.2 Array and polarimeter

The signals from each optical assembly are fed into an 8×8 array of corrugated feed-horns and then in waveguide to a pseudo-correlation polarimeter (Fig. 1, right). Each polarimeter has two outputs, $D_1$ and $D_2$, given by

\[
D_1 = I + Q \cos \phi + U \sin \phi \\
D_2 = I - Q \cos \phi - U \sin \phi
\]

where $\phi$ is the phase introduced by a phase modulator. The detector outputs can thus clearly be used to determine both $Q$ and $U$ at the sky pixel by taking the difference of the detector outputs and phase-sensitively detecting. The effect is similar to that of a rotating wave plate, but is achieved without any moving optics. The intensity $I$ of the pixel is also obtainable from the sum of the detector outputs but is not modulated. Modulation of the intensity is achieved by scanning of the array across the sky.

2.3 Detector array

The outputs from the pseudo-correlation receivers are detected using an array of voltage-biased Transition Edge Sensors (TESs) operating at 300 mK. Since the four optical assemblies feeding the horn-arrays are co-pointed, the signals from common pixels in the four arrays can be detected by the same TES. Each telescope has four arrays, containing 64 horns and 128 outputs (for the two polarizations), and so a total of 128 TES detectors is required for each of the three Clover telescopes. Readout of the TES detectors is achieved by frequency multiplexing of eight TES detectors onto one SQUID.

3 Site and observing strategy

It is intended that Clover will be installed at Dome C on the Antarctic Plateau at an altitude of 3200 m. This site is one of the premier locations for mm and sub-mm observations, providing dry and atmospherically stable conditions which are comparable to, if not slightly better than, the South Pole. In the first two years of operation we aim to observe a connected region of sky of a few hundred square degrees. We plan to implement a multi-cross scanning strategy consisting of observing a given patch of sky scanning over a fixed azimuth range while keeping the elevation constant for a 2-3-hour period. Once this time has elapsed, the centre azimuth and elevation are changed to follow the sky patch and constant elevation scans are repeated.
Figure 2: Expected errors from Clover on the $B$-mode power spectrum for flat, $\Lambda$CDM inflation models. The upper panel has tensor-to-scalar ratio $r=0.384$ corresponding to the current 68-per cent upper limit from CMB and large-scale structure data$^3$. The middle panel is for $\phi^2$ inflation, with $r=0.15$. The lower panel is for small-field, parabolic inflation $[V \propto 1 - (\phi/\phi^\ast)^2]$ with $r=0.011$. The inner error boxes are the contribution from instrument noise after foreground removal; the outer boxes also include sample variance from the gravitational wave signal and weak lensing.

This strategy results in a well cross-linked coverage of a single sky area. The telescopes will also be periodically rotated about the pointing axis to calibrate out instrumental effects and improve the density and cross-linking of the sky coverage.

4 Science predictions

Modelling of foreground removal with reasonable assumptions about the level of Galactic contaminants suggests that the effective sensitivity of the full instrument will be similar to that obtained by a single frequency channel in the absence of foregrounds. From a two-year experiment observing a near-circular survey region of radius 15 degrees we expect a thermal noise level after subtraction of foregrounds of approximately 0.24 $\mu$K per resolution element (15-arcmin by 15-arcmin) to the Stokes parameters $Q$ and $U$. For comparison, the expected r.m.s. of $Q$ and $U$ is 2.1 $\mu$K at 15-arcmin resolution; 0.1 $\mu$K of this arises from the $B$-mode polarization generated by lensing, and $0.3\sqrt{r} \mu$K from gravitational waves. The performance of Clover in measuring the total $B$-mode power spectrum for three different values of the tensor-to-scalar ratio is shown in Figure 2. We find that the one-sigma error on $r$, computed from the errors on $C_B^\ell$ in the null hypothesis $r = 0$, is $\delta r = 0.0037$, and is limited by sample variance of the lensing signal. This sets the detection limit of gravitational waves from a measurement of $B$-mode polarization with Clover.

5 Conclusions

We have briefly described the scientific aims and design of a new instrument, Clover, which is designed to measure the $B$-mode polarization of the CMB. It is intended that deployment of the experiment to the site will be phased over three years and the full instrument consisting of three 256-horn arrays operating at 90, 150 and 220 GHz is planned to be operational by 2008. It is expected that with a two-year observing schedule, Clover will allow measurements of the $B$-mode polarization over the $\ell$-range 20–1000, with a detection limit of $r \sim 0.005$.

References

1. J. Kovac et al, Nature 420, 763 (2002).
2. A. Kogut et al, ApJ Suppl. 148, 161 (2003).
3. S.M. Leach and A.R. Liddle, Phys. Rev. D 68, 123508 (2003).
4. L. Dunlop et al, in proceedings of SPIE Vol. 5498, Glasgow, UK, 2004.
5. G. Yassin et al, to appear in proceedings of the 15th International Symposium on Space THz Technology, UMASS, USA, 2004.