CLOVER- A Novel Instrument for Measuring the CMB Polarization

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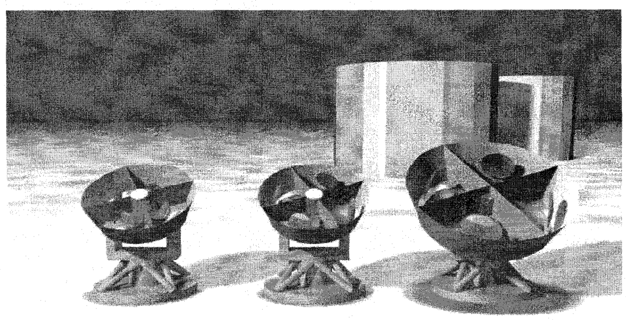

We describe the design and performance of a new fully-funded instrument, CLOVER, to measure the B-mode polarization of the cosmic microwave background. The instrument comprises three independent telescopes operating at 90, 150 and 220 GHz and is planned to be sited at Dome C, Antartica. Each telescope will fed by a focal plane array of 256 horns with background-limited detectors and will measure the polarization signal over angular multipoles $20< l<1000$. The unique design of the telescope and extremely low systematics should enable the B-mode signature from gravitational waves to be measured, or constrained to a lensing confusing limited tensor-to-scalar ratio $r \sim 0.005$.

1. Introduction

The Cosmic Microwave Background (CMB) provides direct information about the origin of the universe, and our current understanding of the cosmological evolution of the Universe is heavily based on measurements of the CMB radiation. Over the past 15 years a vast amount of information has been accumulated about the angular power spectrum of the CMB anisotropies. Ground-based, balloon-borne and satellite instruments such as COBE, CAT, DASI, VSA, Boomerang and WMAP have measured the CMB anisotropies at various angular

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scales and frequencies. The power spectrum obtained from these measurements agrees remarkably well with that predicted by the present cosmological models. The main cosmological parameters have been determined with impressive accuracy.

Despite these discoveries, it is now becoming clear that measurement of the temperature anisotropy alone will not provide the complete picture of the early universe. The anisotropy must be combined with additional information in order to break some degeneracies between cosmological models. This can only be done with the CMB alone by measuring its other defining characteristic, namely its polarization. Polarization of the CMB is caused by Thompson scattering of CMB photons at the last scattering surface (Hu and White, 1997). The signal can be decomposed into a curl and a curl-free component, known as the *B*- and *E*-mode respectively. The *E*-mode component is generated mainly as a result of density perturbations and has amplitude of approximately 10% of the temperature anisotropy. The *B*-mode signal however is generated entirely by primordial gravitational waves. It provides unique information about the early universe and would greatly increase our ability to place constraints on inflationary models. Unfortunately, the *B*-mode signal is at best an order of magnitude weaker than the *E*-mode component and its detection constitutes a major technological challenge. Recent advances in detector technology however, combined with better understanding of systematics have made this exciting prospect quite feasible.

In this paper we describe a novel instrument design with extremely low systematics that will be able to reach the sensitivity required for detecting the *B*-mode component to the limit set by contamination from gravitational lensing of the *E*-mode signal. The instrument comprises three completely independent telescopes, operating at 90, 150, and 220 GHz. Each telescope consists of four separate optical assemblies, fed by 265 background-limited detectors. The telescope beamwidth is 15' and will cover the range of angular multipoles $20 < l < 1000$. The division into four arrays, symmetrically distributed with respect to the cryostat axis, reduces aberrations substantially, and also helps to reduce cross polarization. A key feature of the instrument design is the employment of large-format arrays of antenna-coupled Transition Edge Sensors (TES). Power is fed to the TES via an antipodal finline taper that transforms the waveguide into a microstrip. The array symmetry allows us to feed groups of four channels, corresponding to horns pointing to the same direction in the sky and the same polarisation, to a single TES.

2. Science requirements

The polarization signal on the sky is a second-rank tensor that can be decomposed into a curl and a curl-free component, known as the *B*- and *E*-mode respectively (Kamionkowski, et al, 1997). The component generated as a result of density (scalar) perturbations has a characteristic zero-curl, i.e. *E*-mode, pattern. Polarization due to the metric perturbations of gravity waves has pure curl, i.e. *B*-mode, pattern. In addition, gravitational lensing by the intervening large-scale structure distorts the polarization field and converts power from one mode to the other. Since the *E*-mode has much higher amplitude, the important effect is to introduce a new *B*-mode component due to the lensing of the intrinsic *E*-mode.

The main science goal of CLOVER (Taylor *et al*, 2004) is to measure the power spectrum of B-mode polarization in the multipole range l=20–1000. We aim to make the measurement down to sensitivity limited by the contamination due to foreground lensing of the E-mode signal for multipoles $l \leq 200$. From a two-year experiment, observing a near-circular survey region of radius 15 degrees we expect a thermal thermal noise level after subtraction of foregrounds of ~ 0.3 μK 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 2.1μK at 15-arcmin resolution; 0.1μK 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 power B-mode spectrum for three different values of the tensor-to-scalar ratio is shown in Fig. 1. We find that the one-sigma error on r, computed from the errors on C_l^B in the null hypothesis $r = 0$, is Δr = 0.004, and is limited by the sample variance of the lensing signal. This sets the detection limit of gravitational waves from a measurement of B-mode polarization with CLOVER. A summary of the instrument specification is given in table 1.

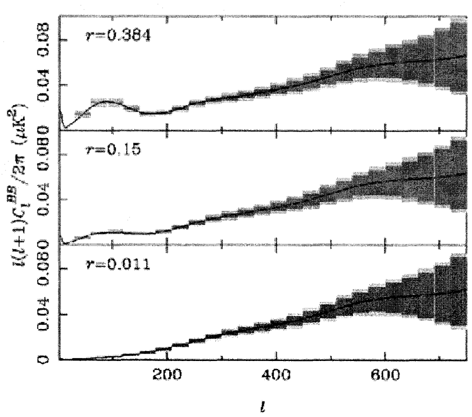

Figure 1: *Expected errors from CLOVER on the B-mode power spectrum for flat, ΛCDM inflation models. The upper panel has tensor-to-scalar ratio r=0.384 corresponding to the 68-per cent upper limit from CMB and large-scale structure data of (Leach & Liddle 2003). The middle panel is for ϕ^2 inflation, with r=0.15. The lower panel is for small-field, parabolic inflation with r=0.011. The inner error boxes are the contribution from instrument noise; the outer boxes also include sample variance (from gravitational waves and weak lensing).*

Table 1: Key specifications of CLOVER

Telescope frequency	**90 GHz**	**150 GHz**	**220 GHz**
Δf (GHz)	30	45	60
Photon NEP $\mathrm{W}/\sqrt{\mathrm{Hz}}$	2.7×10^{-17}	3.7×10^{-17}	5.8×10^{-17}
Detector NEP $\mathrm{W}/\sqrt{\mathrm{Hz}}$	$< 2\times10^{-17}$		
NET μs s$^{1/2}$	170	215	455
Array NET μs s$^{1/2}$	10.5	13.4	28.5
Number of horns	256	256	256
Number of modes	512	512	512

3. Instrument description

3.1 General layout

We have already indicated that CLOVER consists of three completely independent telescopes. The design of the array, optical assemblies and pseudo-correlator are shown in Fig. 2. Each telescope consists of four separate, co-pointed optical assemblies, each fed by an 8 *x* 8 array of feed horns. The signal from each horn is separated into the two independent linear polarization states, converted to circular polarization, phase modulated and then correlated. The two correlator outputs encode the Stokes parameters *I*, *Q* and *U*. The outputs from each corresponding pixel in the four telescopes 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. The four optical assemblies are built around a single cryostat which houses all four horn/polarimeter arrays and the detector array, and are mounted on a common mount which allows altitude-azimuth tracking as well as rotation of the entire optical assembly.

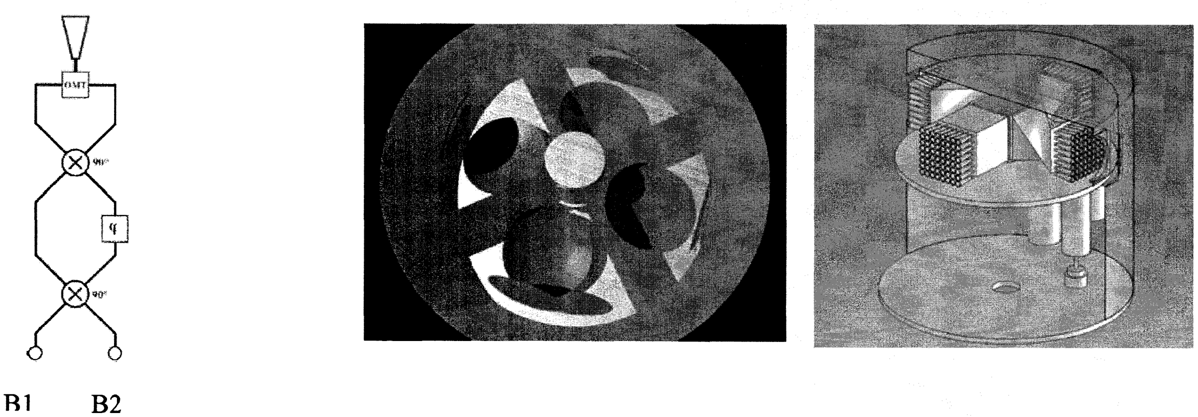

Figure 2: **Left:** Schematic view of the pseudo correlation receiver. **Middle**: A schematic view of a CLOVER telescope with four co-pointing Compact Range Antennas (CRA). Each CRA is fed by 64 horns. **Right**: The central cryostat containing four 64-feed arrays and the sections behind containing the hybrids and phase switches.

The division into four arrays distributed symmetrically with respect to the Cryostat axis reduces aberrations substantially, helps to minimise cross polarization and reduces the number of required TES devices by a factor of 4.

3.2 The pseudo correlation polarimeter

There are several advantages in utilizing a correlation receiver scheme for the imager. In particular, it allows determining the Stokes parameters Q and U simultaneously at the sky pixel, by taking the difference of the detector outputs, without moving the optics. To calculate the polarimeter outputs, the electromagnetic radiation incident on each antenna is written in terms of its Jones vector. Each component of the polarimeter shown in Fig. 3 is then expressed in terms of its Jones polarisation matrix and the total polarisation matrix is found by multiplying the individual matrices. It can be shown that the outputs of the two polarimeter detectors is given by:

$$B1 = I - Q \cdot \cos\varphi - U \cdot \sin\varphi$$
$$B2 = I + Q \cdot \cos\varphi + U \cdot \sin\varphi$$

The above equation tells us that our polarimeter is sensitive to I, U and Q Stokes parameters. By varying the phase difference from 0 to 90 degrees we can cycle the outputs between Q ($-Q$) and U ($-U$). If we chop the phase difference between 0 and 180 degrees, the U term is always zero and we can measure just Q.

3.2 Telescope optics

We have already indicated that each CLOVER telescope employs four optical assemblies, each is a Compact Range Antennas (CRA) which is an offset-fed design consisting of a hyperbolic secondary and an offset parabolic primary. This design exhibits low beam distortion and cross polarisation, hence is ideal for a large imaging array, since beams generated by feeds at the edges of the array suffer much less distortion than those obtained in offset Cassegrain or Gregorian systems. An important advantage of this design is that it allowed the choice of the reflectors dimensions to be entirely based on the required resolution (l-range) rather than to be artificially large in order to reduce aberrations. The l-range chosen for CLOVER was $20<l<1000$ corresponding to a 15-arcmin FWHM main beam. This could be obtained at 150 GHz with a main reflector diameter 800 mm, sub-reflector dimensions 735 mm *x* 700 mm and ideal hybrid feeds with flare angle 10 degrees and aperture diameter 15 mm.

Calculation of the radiation patterns of the antenna was made using the software package GRASP which employs the rigorous Physical Optics method. In Fig. 3 we show co-polar contour plots, both for the feed located at the centre of the array and also when the feed is offset by 50 mm in the focal plane. The cross polarization component for the central pixel is less than –60 db and for the outer pixel –35 db. The very low levels of cross-polarization and aberration of this optical system are a key advantage of the CLOVER design.

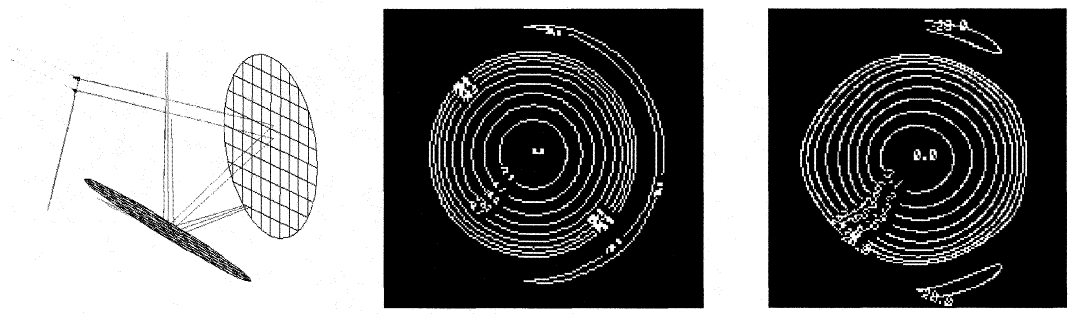

Figure 3. *Radiation patterns obtained when the feed is placed in the centre of the array (centre) and with the feed is moved 50mm in the positive x-direction (right). The Physical Optics simulated geometry of the CRA (left) is also shown.The rays are shown for clarity but are not used in the calculations.*

3.3 **Detector array**

3.3.1 *The single pixel*

A detector may be considered suitable for CMB polarization measurements if it satisfies the following requirements: (i) background limited sensitivity (ii) high dynamic range (iii) large bandwidth and (iv) easy to fabricate. The need for large bandwidth to enhance sensitivity makes bolometric detection appealing for CMB polarisation measurements. We aim to achieve a bandwidth of 30%, which is possible through careful design of all components. The single-pixel sensitivity required for detecting CMB polarization is high, and therefore it is essential to ensure that the sensitivity is limited by the sky background rather than the detectors themselves. Assuming that the background level at Dome C limits the sensitivity at 150 GHz to $s \approx 200\,\mu\mathrm{K}\,\mathrm{s}^{1/2}$ and assuming an RF bandwidth of 50 GHz, the required NEP $\approx 4\times10^{-17}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ which is within the capability of modern TES bolometers operating at 300 mK.

Voltage-biased Transition Edges Sensors have recently been thoroughly investigated in view of using them in CMB instruments. A TES consists of a thin superconducting film deposited on a silicon nitride membrane. The device is biased at the middle of the transition region between the normal and superconducting states. Absorbed photons heat the quasiparticle gas, causing a sharp increase in the electrical resistance, and therefore a decrease in bias current. This electro-thermal feedback keeps the TES on the transition point and, as a by-product, decreases the effective time constant, making the devices very fast. The change in electrical current is read out by a SQUID. An important advantage of the TES over other widely-used detectors (eg NTD bolometers) is that it can be fabricated using lithography. This means that the detector itself and the feeding RF circuits can be fabricated at the same time using miniature superconducting planar circuits. Moreover, the detector lends itself to frequency or time domain multiplexing which reduces the required readout components substantially. These properties become crucial for large format arrays such as for CLOVER. Finally the TES can be shown to have large dynamic range, hence it has all the properties that are required for high performance CMB instruments.

3.3.2 *The TES chip*

The design of the individual TES and the detector chip architecture is clearly chosen to suit the array configuration. In CLOVER, groups of four horns (one from each sub-array) are pointing at the same direction in the sky. Consequently, each TES is fed by four microstrip lines corresponding to the same polarimeter output, as shown in Fig. 4. Transition from waveguide to microstrip is made using an antipodal finline taper consisting of two superconducting fins of 300 nm Niobium separated by 400-nm SiO with the whole structure fabricated on a 200 μm silicon substrate (Yassin and Withington, 1995) . The width of the resulting microstrip is 3 μm, corresponding to a characteristic impedance of 20 Ω which is both electrically convenient and allows the fabrication of a large number of microstrip networks on a single substrate. Efficient coupling of power from the microstrip to the TES is achieved by terminating the microstrip with a resistor that heats the device. Details of the electric and thermal design of the antenna coupled TES have already been reported (Dunlop *et al*, 2004)

The detector operates from a bath temperature of 300 mK, and is modelled as a $50\times 50\ \mu\text{m}^2$ Mo/Cu TES each of 50 nm thickness with 300 nm thick Cu edges - to ensure fully normal edges of the TES, with a total Nb volume of $200\times 200\times 0.5\ \mu\text{m}^3$ representing the microstrip and TES bias lines. The total heat capacity for $T_c = 400\ \text{mK}$ is estimated as $84\ \text{fJ/K}$. Thermal isolation is provided by patterning the $0.5\ \mu$m thick Si_3N_4 into 8 bridges each of $20\ \mu$m width giving a total thermal conductance of $G = 58\ \text{pW/K}$, an intrinsic time constant of 1.4 ms and a limiting NEP of $1.7\times 10^{-17}\ \text{W}/\sqrt{\text{Hz}}$ determined by the thermal conductance.

The detector array configuration is illustrated in Fig. 4. One possible layout is a rectangular wafer loaded with finline substrate transitions from 4 sides, each side fed by one of the four horn arrays. Each side of the wafer will therefore have 16 finline channels corresponding to 8 horns with two polarisations. In total, the wafer will have 64 microstrip channels and 16 TES detectors. Sixteen of the chips shown in Fig 4. are needed to populate the array, two for each horn array vertical layer. Alternatively the finline channels can be re-directed to two sides of the rectangular substrate thus avoiding microstrip crossings as shown in Fig. 4. Each group of 8 TESs is frequency multiplexed and read by a single wideband, low-noise SQUID.

3.3.3 *Readout and multiplexing*

Frequency multiplexing is obtained by AC biasing the TES devices with a comb generator, ΣV, which is a sum of bias voltages at the resonant frequencies. Each TES is modelled as an RLC circuit with a resonant frequency $f_i = 1/(2\pi\sqrt{LC_i})$ which is equal to the frequency of the voltage bias of the individual TES.

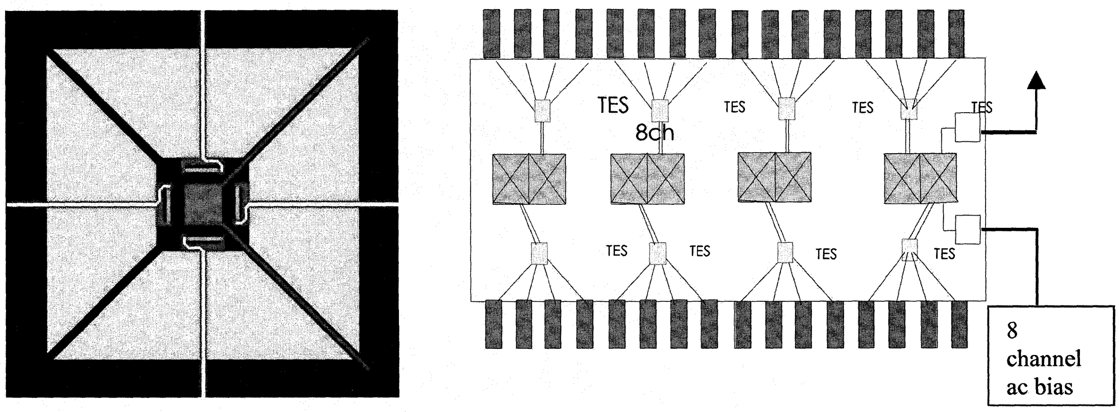

Figure 4: (a) *Scale layout of a single pixel with TES (red), Nb bias lines (blue), microstrip line (white on blue) and termination resistors (green). The nitride membrane is removed in the regions shaded yellow.* (b) *Schematic of a detector module. 32 fin-lines are coupled to 8 TES and a single 8 channel multiplexer. Read-out is by a single wideband, low noise SQUID.*

The half-width of the resonance $\Delta f_i = f_i/2Q_i$ needs to be chosen to exceed both the detector thermal bandwidth $f_{thermal} = 1/2\pi\tau$, where the time constant includes the effect of electro-thermal feedback, and the signal bandwidth Δf_{sig}.

We assume a frequency spacing of 20 kHz and a minimum resonant frequency of 100 kHz. With a signal bandwidth of 1 kHz, the maximum required $Q_{\max} = f_{\max}/2\Delta f_{sig} = 120$. Assuming $R_{TES} = 0.5\,\Omega$ at the operating point, we require capacitor values in the range 11 to 64 nF. These can be achieved by anodization of thin film Nb with dimensions in the range $1.9\text{ to }4.6\,\text{mm}^2$. Estimated power cross-talk is about -25 dB in this example. The resonant bias AC sources for the TESs also provide reference signals for the demodulation, cancelling phase noise to first order. Demodulated signals are low-pass filtered so that the sampling rate for each individual A to D needs to be $f_{sample} = 2f_{bw}$ of order 2 kHz.

4. Observation 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. 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.

5. Conclusion

We have presented the design of a high performance imaging instrument, CLOVER, for measurement of the *B*-mode polarization component of the Cosmic Microwave Background. The focal plane array of CLOVER combines both the low systematics of corrugated feed and the simplicity and reliability of planar circuit technology. The novel design of the telescope optics allows 512 pixels (for two polarizations) to be used without substantial degradation in the radiation pattern. The large number of background-limited detectors combined with the well-known advantages of Dome C should allow CLOVER to reach the required sensitivity to detect gravity waves down to a tensor-to-scalar ratio $r \sim 0.005$, after two years of integration. The instrument will be fully operational by 2008. However, first light will be seen by a subset of the instrument at one frequency by the end of 2006.

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