Dome C Astronomy and Astrophysics Meeting
M. Giard, F. Casoli and F. Paletou (eds)
EAS Publications Series, **14** *(2005) 251–256*

CLOVER: THE CMB POLARIZATION OBSERVER

B. Maffei[1], P.A.R. Ade[1], C. Calderon[1], A.D. Challinor[2], P. De Bernardis[3], L. Dunlop[2], W.K. Gear[1], Y. Giraud-Héraud[4], D.J. Goldie[2], K.J.B. Grainge[2], K.G. Isaak[1], B. Johnson[1], M.E. Jones[2], A.N. Lasenby[2], P.D. Mauskopf[1], S.J. Melhuish[1], A. Orlando[1], L. Piccirillo[1], G. Pisano[1], A.C. Taylor[2], S. Withington[2] and G. Yassin[2]

Abstract. We present a new, fully-funded ground-based instrument designed to measure the B-mode polarization of the Cosmic Microwave Background (CMB). The concept is based on three independent subsystems operating at 90, 150 and 220 GHz, each comprising a telescope and a focal plane of horn-coupled background-limited bolometers. This highly-sensitive experiment, planned to be based at Dome C station in Antarctica, is optimised to produce very low systematic effects. It will allow the detection of the CMB polarization over angular multipoles $20 < l < 1000$ accurately enough to measure the B-mode signature from gravitational waves to a lensing-confusion-limited tensor-to-scalar ratio $r \sim 0.005$.

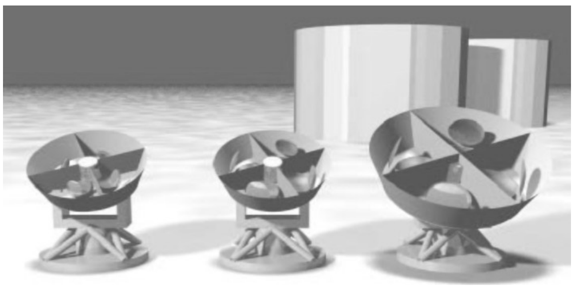

Fig. 1. The C_lOVER instrument.

[1] Department of Physics and Astronomy University of Cardiff, UK
[2] Cavendish Astrophysics, University of Cambridge, UK
[3] Università La Sapienza, Roma, Italy
[4] Collège de France, Paris, France

DOI: 10.1051/eas:2005039

1 Introduction

The Cosmic Microwave Background (CMB) provides direct information about the origin and the evolution of the Universe. In the last 15 years a number of experiments provided us with a vast amount of information, first about the spectral characteristics of the CMB (COBE), then about the power spectrum of its temperature anisotropies (BOOMERanG, WMAP). However, it is now becoming clear that the temperature anisotropies alone will not provide the complete picture of the early Universe. Indeed, the anisotropy must be combined with additional information in order to break the degeneracy in the cosmological models. This can be done by measuring the CMB polarization caused by Thompson scattering of CMB photons at the last scattering surface. The signal can be decomposed into a curl and a curl-free component, known as the B- and E-modes respectively. The amplitude of the E-mode component is about 10% of the temperature anisotropy signal while the contribution from the B-mode signal is at best an order of magnitude lower than this. The measurement of B-mode polarization is of critical importance for constraining models of the early Universe, since, in standard models, the B-mode signal arises in linear theory only from gravitational waves generated during inflation. On smaller scales, secondary effects, most notably weak gravitational lensing, generate additional B-modes that act as a confusing foreground for gravity wave searches *via* this route.

While several experiments have been designed to measure the E-modes – first detected by DASI (Kovac *et al.* 2002) – the detection of the B-mode signal constitutes a major technological challenge. CMB experiments, because of their scientific objectives, require not only the very highest sensitivity, but also a high level of sidelobe and spectral rejections to be able to detect the weak CMB signal emission, minimising the measurement contamination due to strong sources. Previous missions have shown how critical are the instrumental systematic effects in order to get an accurate reconstruction of the CMB anisotropy power spectrum. It is then in this context that C$_l$OVER (Taylor *et al.* 2004) is being developed. This novel instrument design, with extremely low systematics, will be able to reach the sensitivity required for detecting the B-mode component to the limit set by confusion from gravitational lensing of the E-mode signal. The targeted resolution of 15 arcmin will allow the measurement of the polarization power spectrum across an angular multipole range of $20 < l < 1000$.

2 Instrument Description

The concept of this instrument relies on three independent sub-systems (Figs. 1 and 2), each dedicated to a specific spectral range coverage centered at 90, 150 and 220 GHz to allow foreground component separation. The bandwidth is set to about 30% in order to maximise the signal-to-noise ratio. All three are based on the same design, scaled with frequency. A sub-system comprises a telescope made of four co-pointed optical assemblies, each focusing its beam onto an 8×8 feed horn array located inside a Dewar housing the whole focal plane. The signal from each horn goes through a pseudo-correlator with two outputs encoding 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. Stokes parameters Q and U are measured instantaneously by modulating the phase in the two arms of the correlation receiver. The intensity I of the pixel can be obtained 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.

2.1 Optical Scheme

The optical assembly design follows a Compact Antenna Test Range (CATR) configuration using two off-axis mirrors, a parabolic primary and a hyperbolic secondary, resulting in very low beam distortion and cross-polarization across the focal plane. In order to be able to reach the desired l coverage ($20 < l < 1000$), the target resolution has been set to 15 arcmin for all three spectral bands. At 150 GHz, this is obtained by using a 800 mm primary and a 735 mm × 700 mm secondary mirror. The optical coupling between the mirrors and the receivers is achieved through single-moded corrugated horns. These are designed to fully illuminate the telescope, thus taking advantage of the full resolution while reaching a sidelobe rejection of at least –25 dB to reduce the straylight contamination. Several designs have been investigated: a Winston cone profile has been selected due its low cross-polarization, beam Gaussianity and low sidelobe level characteristics (Maffei *et al.* 2004), giving a 10° FWHM beam pattern. GRASP modelling of the antenna beam using such feed horns (Yassin *et al.* 2004) suggests that the cross-polarization should be no higher than –35 dB for the most extreme pixel position in the focal plane, leading to very low optical systematic effects.

2.2 Focal Plane

For reasons explained later, the whole focal plane is housed in a cryostat. The four optical assemblies are then built around this cryostat which has four optical inputs, separated by 90° from one another. Each horn receiving the radiation from the telescope, is followed by a pseudo-correlator unit (Pisano *et al.* 2004). In this scheme, the signal from each horn is separated into two independent linear polarizations through an Orthomode Transducer (OMT), converted to circular polarization, phase modulated and correlated using hybrid converters and a phase shifter. The pseudo-correlator has then two outputs D_1 and D_2 given by:

$$D_1 = \frac{1}{2}(I - Q\cos\Phi - U\sin\Phi) \quad \text{and} \quad D_2 = \frac{1}{2}(I + Q\cos\Phi + U\sin\Phi)$$

where Φ is the differential phase shift between the two branches of the pseudo-correlator.

The outputs from the corresponding pixels in the four optical assemblies are summed incoherently before being detected by a background-limited antenna-coupled TES (Transition Edge Superconductor) bolometer. Such detectors consist

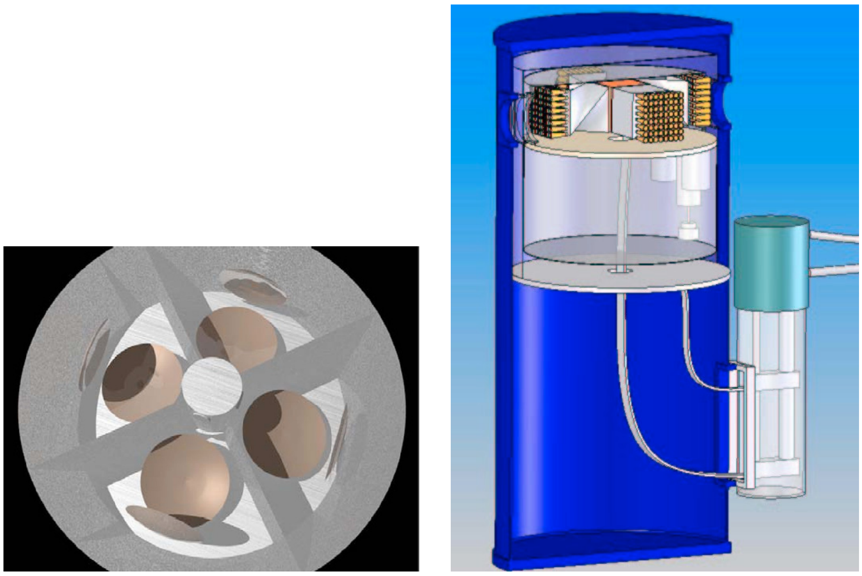

Fig. 2. *Left*: telescope made of 4 sets of mirrors and the cryostat located at the centre. *Right*: horn arrays and focal plane cooled by a pulse-tube cooler attached on the side of the cryostat and a ^{3}He/^{4}He sorption cooler (shown below cold plate).

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. TES detectors are then read out by a SQUID after multiplexing.

Most astronomical experiments require the detection of faint sources in the presence of large background, this being especially true in observational cosmology. We therefore have to optimise the efficiency of all the components in order to increase the signal-to-noise ratio. This can be achieved using multimoded optics, where each mode increases the signal reaching the detector. However, this technique is generally avoided in CMB experiments due to the resulting increase in cross-polarization and sidelobe levels. Moreover, the antenna beam prediction and definition of such systems are not as accurate as single-moded systems and could lead to difficulties during data analysis when reconstructing the CMB power spectrum. In the adopted design, instead of using proper multimoded optics, the detectors are collecting four times the same fundamental HE_{11} hybrid mode selected by the corrugated horn waveguide. This is achieved through the co-addition of the four beams coming from the four separate single-moded co-pointed optical assemblies. Such a mode has a very low associated cross-polarization and the resulting beam can be accurately predicted. Thus, there are 256 horns (four 8×8 arrays) per sub-system, yet only 64 simultaneously observed pixels using 128 TES detectors (two pseudo-correlator outputs per pixel). Taking into account the background level at Dome C, such a system requires a detector NEP of 4×10^{-17} W/$\sqrt{\text{Hz}}$ achievable with TES bolometers operated at 300 mK. The resulting expected sensitivity is given in Table 1.

Table 1. C_lOVER sensitivity.

Spectral Band	90 GHz	150 GHz	220 GHz
Pixel NET (μK$\sqrt{\text{s}}$)	170	215	455
Array NET (μK$\sqrt{\text{s}}$)	10.5	13.4	28.5

2.3 Thermal Architecture

At infrared, sub/mm and millimetre wavelengths, the thermal background due to the surroundings and the instrument itself can be comparable and often larger than the observable signal. For this reason, the whole focal plane needs to be cooled down to typically 4 K, and the detectors need to be cooled to an even lower temperature to meet the required performances.

The three cryostats have been designed to be cryogen free for logistical reasons. Cooling to 2.5 K will be achieved using a pulse-tube cooler, while a ^{3}He/^{4}He sorption refrigerator will cool the detector block to around 330 mK (Fig. 2). The four optical inputs in each dewar will produce a large radiative background. Blockers and bandpass filters relying on interference filter technology will be used to maximise the in-band transmission, while the unwanted radiation will be rejected in order to decrease the background load that would otherwise impact the operation of the cryogenic systems and the detectors.

3 Site and Observations

We propose to install C_lOVER at one of the best mm and sub-mm observing sites in the world: the French-Italian Dome Concordia station (Dome C) on the Antarctic Plateau at an altitude of 3200 m. This choice was driven by the needs of high atmospheric stability and low opacity at high frequency that this site can offer. During operations we anticipate very little maintenance, and it is intended that the experiment will run over the Antarctic winter. The design and development of the instrument has already started. The deployment of the experiment to the site will be phased over three years, with a fully operational instrument planned for 2008.

In the first two years of operation we aim to observe a connected region of sky of a few hundred square degrees. The telescope mount is designed to allow altitude-azimuth tracking as well as rotation of the entire optical structure around the pointing axis, so we can adopt a multi-cross scan strategy. This consists of observing a patch of the sky at a given right ascension and declination range, scanning over a fixed azimuth range while keeping the elevation constant for a 2-hour period. After this interval, the pointing centre will be changed to one at the same RA but at a slightly higher declination and the procedure repeated. This scanning strategy should result in a high degree of cross-linked coverage. In addition, the whole telescope structure 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 Conclusion

The main science goal of C_lOVER is to measure the power spectrum of B-mode polarization on large and intermediate scales, in the multipole range $20 < l < 1000$. We aim to make the measurement down to a thermal sensitivity below the sample variance of the lens-induced B-modes for multipoles $l \leq 200$. For a two-year experiment, observing a near-circular survey region of radius 15°, we expect a thermal noise level after subtraction of foregrounds of $0.24\,\mu$K to the Stokes parameters Q and U per resolution element (15 arcmin by 15 arcmin). For comparison, the expected rms 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, and is limited by the sample variance of the lensing signal.

We find that the one-sigma error on the tensor-to-scalar ratio r, computed from the errors on C_l^B in the null hypothesis of $r = 0$, is $\Delta r = 0.0037$. This sets the detection limit of gravitational waves from a measurement of B-mode polarization with C_lOVER.

The authors would like to acknowledge the support of the Particle Physics and Astronomy Research Council for funding this experiment.

References

Kovac, J., *et al.* 2002, Nature, 420, Issue, 6917, 772

Maffei, B., *et al.* 2004, to appear in the proceedings of SPIE conference Astronomical Telescopes and Instrumentation, Glasgow

Pisano, G., *et al.* 2004, this volume

Taylor, A., *et al.* 2004, proceedings of the XXXIXth Rencontres de Moriond, Exploring the Universe (La Thuile, Italy)

Yassin, G., *et al.* 2004, proceedings of the 15th International Symposium on Space THz Technology, Amherst, MA, USA