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Abstract The primordial B-mode polarisation of the Cosmic Microwave Background is the imprints of the gravitational wave background generated by inflation.

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Observing the B-mode is up to now the most direct way to constrain the physics of the primordial Universe, especially inflation. To detect these B-modes, high sensitivity is required as well as an exquisite control of systematics effects. To comply with these requirements, we propose a new instrument called QUBIC (Q and U Bolometric Interferometer for Cosmology) based on bolometric interferometry. The control of systematics is obtained with a close-packed interferometer while bolometers cooled to very low temperature allow for high sensitivity. We present the architecture of this new instrument, the status of the project and the self-calibration technique which allows accurate measurement of the instrumental systematic effects.

Keywords Cosmic microwave background · Polarisation · Interferometer · Bolometer

1 Introduction

The detection and characterisation of the B-mode polarisation of the Cosmic Microwave Background (CMB) is one of the next challenges in observational cosmology. These odd parity polarisation anisotropies are generated by primordial gravitational waves (and by lensing of even parity polarisation at small scales). Detection of these waves would represent a major step towards understanding the inflationary epoch that is believed to have occurred in the early Universe. Tensor modes (primordial gravitational waves) in the metric perturbation are indeed a specific prediction of inflation. The measurement of the corresponding B-mode polarisation anisotropies would therefore provide constraints on inflation. A detection would reveal the inflationary energy scale, which is directly related to the amplitude of this signal. The

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tensor to scalar ratio r is however expected to be small, smaller than 0.2 from today's best indirect measurement. It correspond to B-mode signals lower than about 300 $\mathrm{nK_{CMB}}$ RMS so that the quest for the B-modes is a major experimental challenge.

Such a small signal justifies the new generation of instruments operating from the ground or from balloons (before a potential dedicated satellite mission [1]) with unprecedented sensitivity and control of systematics. From this perspective, we propose the QUBIC experiment, making use of the novel technique of Bolometric Interferometry, bringing together the advantages of bolometric detectors in terms of sensitivity (availability of large arrays of background-limited detectors with wide bandwidth) and of interferometry in terms of control of systematic effects (clean optics with low induced polarisation, low sidelobes and therefore low ground pickup, well defined synthesised beam, small impact of individual primary beam differences) with a large number of detectors which can be replicated quite simply.

2 QUBIC Design

The bolometric interferometer we propose with the QUBIC instrument is the millimetric equivalent of the first interferometer dedicated to astronomy: the Fizeau interferometer. It was obtained by placing a mask with two holes at the entrance pupil of a telescope. Fringes were then observed at the focal plane of the telescope. In our case (see Fig. 1 for a sketch) we use an array of back-to-back horns acting as diffractive pupils just behind the window of a cryostat. The electric field coming from a given sky direction experiences phase differences due to the distance between the input horns. The back horns re-emit the electric field preserving this phase difference inside the cryostat. The interference fringe patterns arising from all pairs of horns are then formed on the focal plane of an optical beam combiner which is actually just a telescope that superimposes the electric fields from all the horns at each point of the focal plane. The polarisation of the incoming field is modulated using a half-wave plate located after the back horns. A polarising grid separates both polarisations towards two different focal planes each measuring a linear combination of I, Q and U Stokes parameters.

The fact that the electric fields from all horns are added and then squared and averaged in time using the bolometers makes our instrument an adding interferometer (Fizeau combination), in contrast to radio-interferometers, where the signals (visibilities) are obtained by multiplying the electric fields from pairs of receivers (Michelson combination) using an analog or digital correlator. We do not need a large number of complex and expensive correlators as the correlation between channels is naturally achieved with the bolometers:

$$\left\langle |E_1 + E_2|^2 \right\rangle = \left\langle |E_1|^2 \right\rangle + \left\langle |E_2|^2 \right\rangle + 2\left\langle \mathrm{Re}\left(E_1 E_2^\star\right)\right\rangle \tag{1}$$

The first sum, $\langle |E_1|^2\rangle + \langle |E_2|^2\rangle$, which is the power in the primary beam, is just a background power. The last term, the interference term, is proportional to the visibility. This simple beam combiner allows the instrument to be scalable to a large number of input horns.

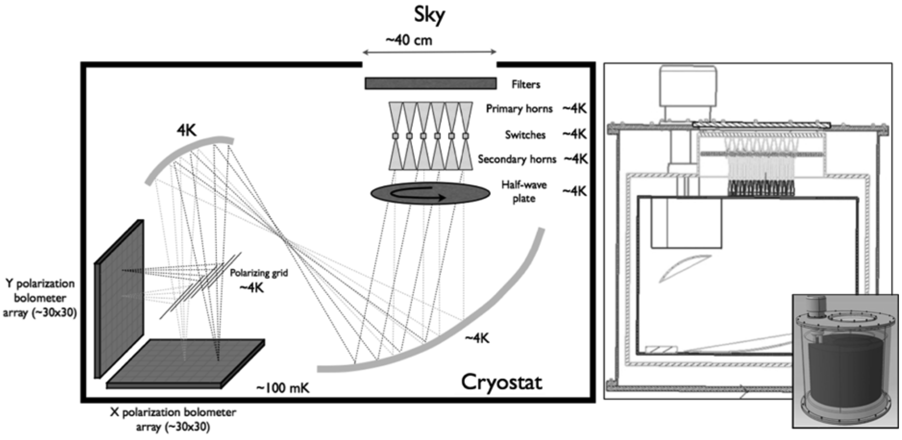

Fig. 1 (Color online) *Left*: Sketch of the QUBIC concept. *Right*: CAD view of the QUBIC cryostat

The image we observe on the focal plane is actually the so-called “synthetic image” making our bolometric interferometer a synthetic imager in contrast to usual interferometers whose observables are the visibilities (Fourier Transform of the synthetic image) [2]. With this synthetic imager the usual imaging techniques can be applied easily, such as scanning the sky (in order to improve the sky coverage uniformity and modulate I, Q and U), map-making and classical power-spectrum estimation. This simplifies the analysis with respect to the visibility-space case that is more difficult to achieve outside the flat-sky approximation. The statistical sensitivity of QUBIC is comparable (within a factor ~ 2) to that of an imager with the same number of horns covering the same sky fraction [3] while we expect the systematic effects to be different from those of an imager [3, 4].

We plan to install a first QUBIC module at the Franco-Italian Concordia station in Dôme C, Antarctica within two years. The first module will consist of an array of 400 horns operating at 150 GHz with 25% bandwidth and 14 degree (FWHM) primary beams. The optical combiner will have a focal length of about 30 cm and each of the two focal planes will be comprised of arrays of 30×30 bare TES bolometers of 3 mm size. The full instrument will include modules at three different frequencies (90, 150, 220 GHz) and will constrain a tensor to scalar ratio of 0.01 in one year of data taking at the 90% confidence level (see Fig. 2).

3 Self-calibration

We present here a brief description of the self-calibration technique and an illustration of what is achieved in simulation. Detailed derivations could be found in separate papers [5, 6].

One of the main reason to think that systematics might be more controllable in a bolometric interferometer than in a traditional imager is self-calibration [2, 5]. Self-calibration allows the determination of most of the systematic effects (as modelled using the Jones matrix formalism for instance) independently for all channels from

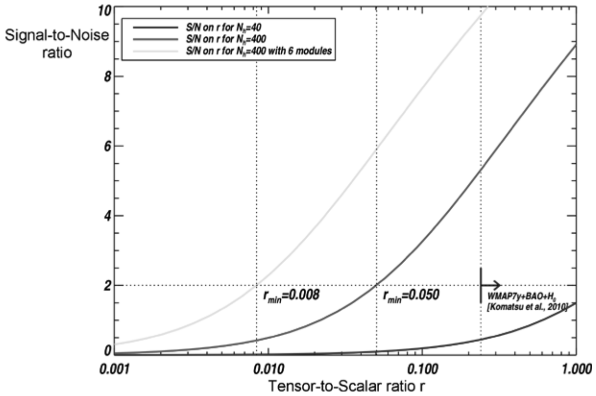

Fig. 2 (Color online) Projected signal-to-noise ratio on *r* (tensor-to-scalar ratio) as a function of its value assuming 1 year observation time, a bolometer $NET = 200\ \mu\text{K} \cdot \text{Hz}^{-1/2}$ and a binning $\Delta\ell = 15$. The *green curve* corresponds to the full QUBIC configuration comprising 6 modules of 400 horns, while the *red one* is for the first module. The *blue curve* corresponds to a smaller module (with 40 horns) for comparison

observations of a polarised source (whose polarisation does not need to be known) using the switches that can be seen in the schematic view of the instrument (Fig. 1) between the back-to-back horns. This self-calibration technique is inspired by traditional interferometry (especially long baseline and optical) where the phase is often lost due to atmospheric turbulence. The more powerful technique to solve this problem is based on the redundancy of the receiver array [7–9]. It is rarely used because most interferometers have low redundancy as they seek high angular resolution and good image reconstruction (dense uv-plane coverage) rather than sensitivity.

The self-calibration technique uses the fact that in the absence of systematic effects, equivalent baselines of the interferometer (see left part of Fig. 3) should measure exactly the same quantity. Using the switches located between the back-to-back horns one can modulate on/off a single pair of horns while leaving all the others open in order to access the visibility measured by this pair of horns alone. By repeating this with a subset of all available baselines (equivalent and different), one can construct a system of equations whose unknowns are the systematic effects parameters for each channel (as modelled using Jones matrices for instance) meaning two polarisations for each primary horn on each of the bolometers of the focal plane. It can be shown that for a large enough array of primary horns (at least 20 horns) the system is over-constrained and can be solved [5]. No information is required on the actual polarisation of the observed source (which can be artificial) except that it needs to be polarised and that the signal-to-noise ratio should be high enough. The self-calibration requires the knowledge of the individual primary beams of each horn that can be obtained through scanning an external unpolarised source. Once all the couplings and gains are known for each channel and for each bolometer in the focal plane, the synthesised beam can be calculated very accurately. It can be compared to a direct measurement obtained by opening all the switches and scanning a source as well as to direct calculations using the positions of the horn and the optical simulation of the beam combiner. All these comparisons will allow for a number of consistency checks and measurements of systematic effects that will allow handling these effects in a very precise way.

We have simulated this self-calibration technique in order to check its behaviour (in the absence of noise) and we obtain excellent results as shown in Fig. 3. We start from a set of visibilities observed with a 144 horn bolometric interferometer

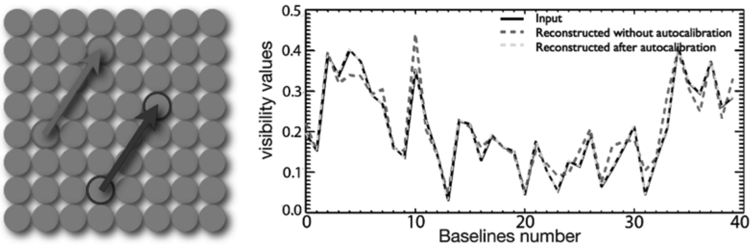

Fig. 3 (Color online) *Left*: illustration of 2 equivalent baselines. *Right*: Simulation of the self-calibration technique on the baselines

and apply randomly drawn systematic effects on each channel (complex gains and coupling using a Jones matrix formalism), the reconstructed visibilities are clearly corrupted (red dashed line) without using the self-calibration technique, but are exactly reconstructed (there is no noise in this simulation) when one includes in the visibility reconstruction the systematics coefficients determined by the self-calibration technique (green dashed line, superimposed to the black one). This shows that the self-calibration techniques actually works well and allows recovery of the systematics in an efficient manner. An over-simplistic back of the envelope calculation shows that with $NET \simeq 300\ \mu\mathrm{K}\cdot\mathrm{s}^{1/2}$ detectors and a $T = 100$ K polarised source, one can reach an accuracy of order $T/NET \simeq 3\cdot 10^{-6}$ on each of the Jones matrix coefficient if one spends one second on each baseline. For the whole array this would imply a self-calibration procedure that would last about 9 hours. It could be done once in a while and on a more regular basis one could perform the self-calibration only with baselines within subarrays of a smaller number of horns allowing to perform the self-calibration in about one hour.

There is no equivalent to this self-calibration technique with an imager that just relies on scanning sources (polarised and unpolarised) with the instrument. We can gather more information than that with our bolometric interferometer and therefore hope that the bolometric interferometer will allow us to handle the systematic effects in a more accurate way than an imager, making the best of its interferometric nature.

4 Conclusions

The QUBIC instrument is a bolometric interferometer combining the signals from an array of wide entry horns using a cold telescope as an optical combiner to form interference fringes of I, Q and U Stokes parameters (modulated with a half-wave plate) on a bolometer array. This instrument can be achieved with technology that is mostly already available. We also propose a self-calibration technique, specific to bolometric interferometry, which allows accurate determination of the systematic effects for each of the channels of the instrument. We anticipate that this will allow QUBIC to achieve good control of systematics and therefore approach its statistical sensitivity. The full QUBIC instrument will comprise three frequencies and targets to constrain at the 90% confidence level a tensor-to-scalar ratio of 0.01 with one year of data from the Concordia Station at Dôme C, Antarctica.

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References

1. The COrE Collaboration, arXiv:1102.2181v1 (2011)
2. The QUBIC Collaboration, Astropart. Phys. **34** (2011)
3. J.-Ch. Hamilton et al., A&A **491**, 923–927 (2008)
4. R. Charlassier et al., Astron. Astrophys. **497**(3), 963–971 (2009)
5. R. Charlassier, PhD, University Paris-Diderot (2010)
6. Bigot-Sazy, et al., in preparation
7. Y.P. Yang, A&A **189**, 361–364 (1988)
8. M. Wieringa, Ast. Soc. of the Pacific Conf. series **19**, 192–196 (1991)
9. J.E. Noordam, A.G. de Bryn, Nature **299**, 597 (1982)