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QUBIC, A BOLOMETRIC INTERFEROMETER TO MEASURE THE B-MODES OF THE CMB

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Abstract. The quest for the B-modes in the CMB polarization is one of the main challenges of modern cosmology as it would allow to give sharp constraints on the inflationary period. One of the main challenges of B modes detection is the treatment of systematic errors. Comparison of observations subject to different systematics is crucial. Interferometers offer such an alternative to imagers. However, to obtain the required sensitivity, a very large number of baselines is needed, which is extremely difficult to achieve with heterodyne interferometry. Bolometric interferometry copes with this problem using a new technique: the interference pattern produced by a few hundred horns is imaged on a bolometer array, and a time modulation of phase shifts insures the separation of visibilities while coherently adding redundant ones. The QUBIC collaboration proposes to build such an instrument.

1 Introduction - The B-mode Quest

The idea of an epoch of inflation at early times during which the universe experienced accelerated expansion can solve simultaneously several questions in cosmology. Quantum fluctuations during this period lead to the creation of the density perturbations that are observed today as the large-scale structure of the universe and as Cosmic Microwave Background anisotropies. The same mechanism should also generate primordial gravitational waves of cosmological size. Their observation would give clear evidence for inflation and provide a direct measurement of the relevant energy scale (most likely associated with Grand Unification at $10^{15} - 10^{16}$ GeV, just 10^{-38} seconds after the Big Bang). The CMB offers a unique way to observe these primordial gravitational waves by their unmistakable imprint in the polarization anisotropies. The CMB polarization map can indeed

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be decomposed into a non-local base of two components, a scalar one denoted E and a pseudoscalar denoted B. On large angular scale (spherical harmonics multipoles included between 50 and 200), only tensor modes originating from primordial gravitational waves should have induced B-modes. The amplitude of the B-modes signal is however expected to be much lower than the E-mode one -the present constraint [Dunkley et al., 2008] on the tensor to scalar ratio modes is $r < 0.43$ (95% CL); thus, their detection -sometimes presented as the Holy Grail Quest of nowadays cosmology- is at least a tremendous experimental challenge.

In addition to an exquisite statistical sensitivity (huge number of feedhorns and bolometers required), future experiments will need an excellent quality of foreground removal (multiwavelength detectors required) and an unprecedented control of systematics. Systematic effects are an important field of study in itself [Hu et al., 2002]. Instrument-induced effects include for instance beam errors (mismatching and cross-polarization), gain errors (pointing and detector miscalibration), coupling (due to instrumental polarization, misalignment of polarization angles), as well as polarized sidelobes due to front optics or atmospheric polarization for ground-based experiments (this is not an exhaustive list).

2 A bolometric interferometry primer

2.1 Imagers versus interferometers for the B-mode Quest

An important remark is that most future experiments expecting to detect B-mode (EBEX [Oxley et al., 2005], QUIET [Samtleben et al., 2008], PLANCK [Planck Collaboration, 2006], CLOVER [Taylor et al., 2006], etc.) will be imaging ones where all the same instrumental error sources will lead to the same systematic effects. An alternative approach to the imaging systems is interferometry. Two interferometers, DASI [Leitch et al., 2004] and CBI [Contaldi et al., 2002], have been the first experiments to detect E-mode polarization of the CMB. While imagers measure maps of the CMB (power spectra are then computed from them), interferometers directly measure Fourier components of the Stokes parameters. Difficult systematic problems that are inherent to total power and differential measurements are absent in a well-designed interferometer. The absence of optics in front of primary feedhorns reinforces this advantage by allowing one to model the sidelobes more accurately with an interferometer. At least one can say that same instrumental error sources than the imaging ones lead to different systematic effects [Bunn, 2006].

Unfortunately, the sensitivity of current "classical" interferometers is intrinsically limited because they are pairwise interferometers constituted by coherent receivers: the electromagnetic signals collected by two feedhorns are amplified (HEMT amplifiers in the case of DASI and CBI) and mixed to lower frequencies before being correlated by pair. Even if the amplifiers technology is in constant evolution [Samtleben et al., 2008], amplifiers are intrinsically less sensitive than cooled bolometers (at least for the 90 to 300 GHz range). Above all, the hardware complexity of such interferometers grows as the square of their number of feedhorns (for N feedhorns they need, $N(N-1)$ correlators) and thus, it is very

difficult [Bock et al., 2006] to build a coherent radio-interferometer for a number of receivers larger than a dozen (13 for DASI and CBI), knowing that typically, hundreds and even maybe thousands of receivers will be required for the B-mode detection. The goal of bolometric interferometry is therefore to combine the advantages of interferometry with the sensitivity advantages of large bolometers arrays. As we will see, it is based on additive interferometry as opposed to multiplicative interferometry used for coherent systems.

2.2 Bolometric Interferometry : basic concepts and sensitivity

The basic observables in CMB interferometry are the visibilities : the Fourier transform through the beams of the observed sky field (the power spectrum is the square modulus of these visibilities in the flat sky approximation). The basic idea of bolometric additive interferometry is that the correlation between two microwave signals can be done by the cooled bolometers themselves : the bolometers act as "square-law" devices, squaring the sum of the collected electromagnetic signals, the cross terms being the visibilities. Hence, a bolometric interferometer is composed of a 2-D array of feedhorns directly observing the sky (without front telescope). Each couple of feedhorns defines a baseline matching a multipole l. Each feedhorn is coupled to an ortho-mode transducer (OMT) in order to separate the two polarization. The collected signals are added together by a beam combiner that can be made optically as we will see (Quasi-Optical combiner). The outputs of the combiner are then coupled to bolometers, which square the sum of all the feedhorns signals. Each bolometer signal is then a linear combination of the pursued visibilities. Hence, phase-modulation is required to recover the visibility from each baseline. Controlled phase-shifters, located between the antennas and the beam combiner allow this: phase-shift sequences are realized, and the problem of visibilities recovery can be solved [Charlassier et al., 2008, Hyland et al., 2008].

The second issue is a sensitivity one. As explained in [Charlassier et al., 2008] and [Hyland et al., 2008], the sensitivity of a bolometric interferometer critically depends on the way sequences of phase-shifts are performed in order to multiplex all the measured visibilities. The main conclusion of our study is that, with well chosen phase-shifts sequences, a bolometric interferometer can reach a sensitivity roughly equivalent to that of an imaging experiment built with the same number of horns and bolometers [Hamilton et al., 2009]. This is shown in Figure 1. The vertical axis shows the ratio of the noise only error bars on the CMB power spectrum with respect to the classical imager case (with a one degree resolution) corresponding to the dotted black horizontahl line at 1. The horizonthal axis is the multipole ℓ considered. The thick line and the points corresponds respectively to analyscal and simulated noise only error bars for the bolometric interferomter and the thin line corresponds to including the sample variance for $r = 0.1$. This plot is and updated version of the one shown in [Hamilton et al., 2009] including a realistic 25% bandwidth [Charlassier at al. 2009], realistic horn geometry (characterized by $\kappa = 1.334 = \sqrt{A\Omega/\lambda^2}$) and the fact that the NET for a bolometric interferomter will be smaller than that of an imager because of the larger dilution

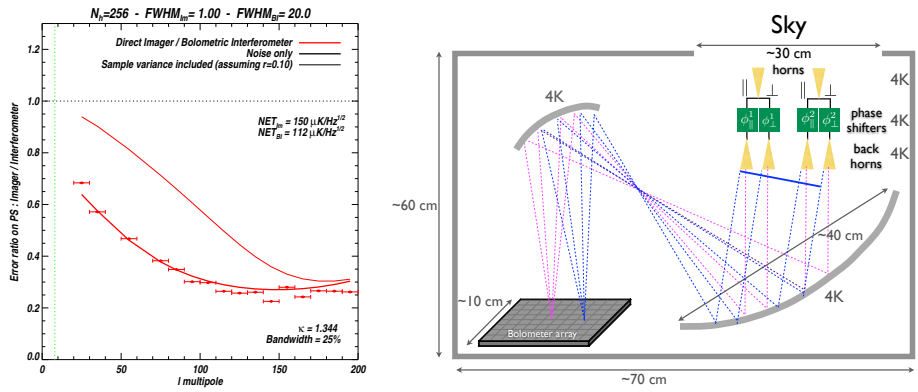

Fig. 1. (left) Sensitivity comparison between imager and bolometric interferometer (see text). **(right)** Sketch of the Quasi-Optical Interferometer for QUBIC.

of the signal among bolometers. An imager has 2 bolometers (PSB) for each entry horn while a bolometric interferomter has more bolometers per horn. This results in a smaller effect of the *bunching* term in the expression of the NET and therefore a smaller background NEP. As a result the bolometric interferomter needs to be cooled down to a lower temperature than an imager to be photon-noise limited. We have used here a 100 mK stage for the bolometric interferometer resulting in a $\mathrm{NET_{BI}} = 112\ \mu\mathrm{K.Hz}^{-1/2}$ and a 300 mK for the imager resulting in $\mathrm{NET_{Im}} = 112\ \mu\mathrm{K.Hz}^{-1/2}$ (note that the absolute values of these NET can be subject to discussion, what matters here however is their ratio).

3 The QUBIC experiment

3.1 The QOI design

The right panel of figure 1 shows a sketch of the QUBIC instrument based on the Quasi-Optical Interferometer concept which has been introduced by the MBI collaboration [1]. The sky is directly observed (without front optics) by primary feedhorns. The two polarizations are separated by Ortho-Mode Transducers, and then phase-shifted by controlled phase-shifters. Secondary back horns then reemit the signals towards an off-axis telescope. All the system is installed in a cryostat cooled to 4 K. An array of bolometers, cooled to 100 mK by the second stage of the cryostat, is located in the focal plane of the telescope. Assuming back to back horns are acting as secondary sources, two signals coming from the same point on

[1] MBI [Timbie et al. 2006] is a bolometric interferometric project which already has a prototype (QOI design) with 4 horns named MBI-4 that has been succesfully tested at the Pine Bluff Observatory in Wisconsin and allowed to observed fringe patterns similar to those shown in figure 2.

the sky but from different horns form interference patterns on the bolometer array (see figure 2). The Quasi-Optical beam combiner is thus equivalent to a Butler

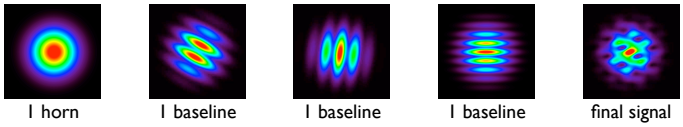

Fig. 2. Fringes obtained at the focal plane of a bolometric interferometer (simulation). The left one is obtained with only one entry horn and shows to the beam of the secondary horn. The other images are obtained with different pairs of entry horns corresponding to different baselines. When all entry horns are active, one obtains the superposition of fringes shown on the right that needs to be phase-modulated to recover the visibilities.

combiner : each pixel in the bolometer plane measures a linear combination of all the visibilities, whose coefficients depend on the pixel position : this is a kind of spatial multiplexing. Controlled phase-shifters also allow time-domain multiplexing. As we have already said, recovering the visibilities is not straightforward : we will not discuss it here, but the sensitivity of the detector critically depends on the multiplexing scheme [Charlassier et al., 2008].

3.2 The Dôme C site

Our goal is to install the QUBIC instrument in Antarctica, in the French/Italian Concordia Station located at the Dôme C site (3233 m altitude). This site has many advantages for millimetric astronomy : a very low brightness temperature of its atmosphere (around 14 K) and an excellent transmission both due to its very low precipitable water vapor level, an exceptional atmospheric stability within the polar vortex, and a low sun set on the horizon. Furthermore, these favorable experimental conditions are available most of the year. A series of CMB experiments operated from the American station at the South Pole have already shown the exquisite quality of the sky in Antarctica for the purpose of CMB observation, and its polarization in particular.

3.3 The QUBIC Program & Schedule

The QUBIC Experiment is a collaboration between France (APC Paris, CESR Toulouse, CSNSM Orsay, IAS Orsay), Ireland (NUI Maynooth) Italy (Università di Roma La Sapienza, Università di Milano Bicocca), United Kingdom (University of Manchester) and USA (University of Wisconsin and Brown University). The QUBIC program is currently twofold.

First, the Pathfinder program is in charge of site testing, logistics and team preparation. We already had two campaigns (January 2006, January 2007) at the Dôme C with the pathfinder instrument, giving us one month of observations [Polenta et al., 2007]. Preliminary results indicate that the quality of the site is as good as expected.

Simultaneously, we are developing the QUBIC prototype. The idea is to build a first module that will be one of the six of the final instrument. This final instrument will operate at 90, 150 and 220 GHz (two modules per frequency channel). Each modules will be composed of 144 feedhorns with a beam size of 20°. The number of bolometers per module will be typically about one hundred. Recall that for an interferometer, the angular resolution is not given by the beam size of feedhorns but by the baselines size. Typically, the arrays of feedhorns will be designed in such a way that most of the baselines will observe multipoles included between 50 and 200. Note that all these specifications can evolve. The first module is planned to be installed in 2010-2011 and the full size instrument in 2012. Our studies (paper in preparation) show that, with these characteristics, the QUBIC Experiment can constrain with a 4σ accuracy the existence of primordial gravitational waves for a tensor to scalar ratio of r=0.01 in one effective year of data.

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