QUBIC: a Fizeau interferometer targeting primordial B-modes

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QUBIC (Q and U Bolometric Interferometer for Cosmology) is a Fizeau interferometer sensitive to linear polarisation, to be deployed at the Antarctic Station of Dome C. This experiment in its final configuration will be operated at 97, 150 and 220 GHz, and is intended to target CMB primordial B-modes in a multipole window $20 \leq \ell \leq 150$, to achieve a final sensitivity of r=0.01 (90%CL) after 1 year of operation. Here we review in particular its working principles and we show how QUBIC interferometric configuration can be considered equivalent to a pupil-plane filtered imaging system. In this context, we show how our instrument can be self-calibrated. Finally, we conclude by showing an overall view on the 150 GHz unit, which will play the role of a demonstrator for the subsequent modules, and review the technological choices we did for each subsystem.

1 Introduction

The importance of primordial B-mode detection can hardly be overestimated [1]. We know that from primordial B-mode amplitude measurement, knowing the amplitude of the stronger E-mode signal, we can infer the energy scale at which Inflation occurred. In fact, the ratio of B-mode and E-mode angular power spectra at $\ell = 2$ gives directly the tensor to scalar ratio r, while Inflation energy scale is related to r through the relation $V^{1/4} = 1.06 \times 10^{16}$ GeV $(r/0.01)^{1/4}$. Nowadays, a first claim of B-mode detection by the BICEP2 collaboration [2] is having a large echo within the scientific community and on the media. If BICEP2 $r = 0.2$ detection will be confirmed, this will be the further demonstration that ground-based experiments can still play the role of pathfinders. In passing, we remind that also E-modes have been detected first from the ground by DASI [3] (precisely from the South Pole, exactly where BICEP2 is installed). In general, *suborbital* experiments provide also the way to test and validate experimental techniques and state-of-the-art devices. This is a critical point for current CMB experimental research, since to target extremely faint signals, once our devices are photon noise-limited the only way to increase the sensitivity is to go towards kilo pixel arrays, or hundred pixel arrays provided they are illuminated through a multi-moded optics. Nonetheless, precision is not the only issue. Accuracy is critical as well, and must follow closely precision requirements. Systematics control is therefore a key point to address, and the landscape of running, scheduled and proposed experiments is particularly rich with this respect. If we concentrate on the experiments explicitly designed to target primordial B-modes, we find imagers modulated with warm or cryogenic temperature Half Wave Plates (ABS [4], at room temperature; EBEX [5], at 4K), or with Variable Polarization Modulators (CLASS [6], PIPER [7]) on top of small telescopes. Correlation polarimeters are known to be robust against systematics, and they will fly on the STRIP [8] module of LSPE. The option of large throughput optics will be demonstrated by the SWIPE [9] instrument on LSPE, and is proposed also for MuSE [10]. In this landscape, QUBIC [11] is the only interferometer, endowed with kilo pixel arrays of Transition Edge Sensors.

2 QUBIC: the concept

The most common technique to make mm-wave interferometers is certainly multiplicative (heterodyne) interferometry. In this case, long baselines (up to 10 km, or more) can be achieved, and IF bandwidth $\sim$ some GHz wide allow sensitive operation when observing *continuum* sources. The drawback is that pairwise correlation of antennas is achieved through fast digital correlators, whose complexity and costs make it practically unfeasible for systems with hundreds of antennas. In adding interferometry, on the contrary, correlation is achieved *through* direct bolometric detection, so that in principle hundreds of signals can be correlated at a time. In the particular case of an adding all-to-one interferometer, all the signals are combined on each detector (see Fig.1), so that each detector's output is a linear combination of total intensities collected by each antenna, plus interference terms that are proportional to the visibilities corresponding to the Fourier modes selected by the antenna array. In the case of QUBIC, the linear combination of the antenna signals is achieved by means of an optical beam combiner (which is essentially a very fast telelescope). As shown in [11], 400 closely packed back-to-horns observe the sky and re-emit towards the beam combiner located within the cryostat. In turn, the families of parallel rays re-emitted from the back horns are summed in phase on each detector by the combiner. This is the implementation of a Fizeau interferometer scheme.

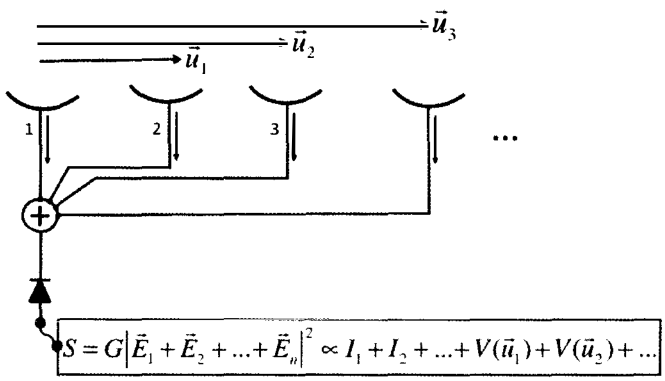

Figure 1 – A generic adding all-to-one interferometer. Antennas collect signals that are sent towards an adding unit. After linear superposition, a detector responding to the intensity of the incoming signals correlates the incoming fields, in such a way that its output is a combination of single antenna intensities, plus visibility terms (in blue in the formula). The Fourier spatial frequency $\vec{u}$ correspond to the multipole $\ell = 2\pi|\vec{u}|$.

Now, if we imagine to remove the back-to-back horn array, we are left with an imager (by construction, our combiner is a telescope). If we put the horns back again, what we obtain is again an imager, but with a pupil plane filtering structure (our horn array). Therefore, our instrument makes images using only a subset of those modes that would be otherwise accepted by the bare telescope. The Fourier mode bandpass is fixed by horn aperture and arrangement. The far-field pattern of the instrument is represented in a qualitative way in Fig.2: (1) for a uniformly illuminated pupil (that mimic our bare combiner), to obtain an Airy diffraction pattern and (2) in the case of an illumination profile formed by a set of gaussian apertures, producing a beam with higher order maxima. The synthetic beam of QUBIC central pixel will be qualitatively close to the case (2), even though we have to stress that each pixel will observe the sky through slightly different synthetic beams. For what we have just said, QUBIC is essentially an imager, and as such it must be used, from the scanning strategy to the map-making procedure [12].This is a very nice fact in itself, but doesn't explain why Fizeau architecture is powerful for our experiment. The key point is that each back-to-back horn of QUBIC is endowed with a shutter that allows us to switch-on, or switch-off, all the baselines we like. This fact, as demonstrated by [13], allows the self-calibration of our interferometer. Especially the Fourier modes corresponding to the short baselines can be realised (one by one!) by hundreds of horn pairs (380 realisations for the shortest baseline, corresponding to $\ell \sim 50$). Especially the shortest baselines, so relevant for Cosmology, will be those that will be better self-calibrated by virtue of their large redundance, with suppression of systematic effects adequate to reach a final sensitivity equivalent to $r \simeq 0.01$ (90%).

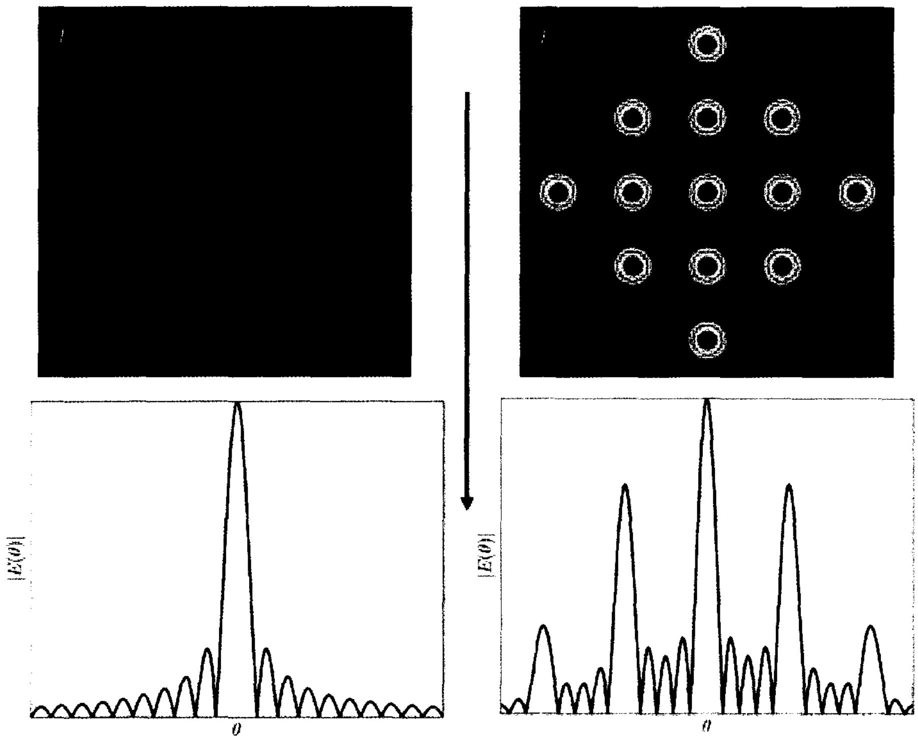

Figure 2 – A qualitative view of far-field patterns discussed in the text. Top Left panel: uniformly illuminated aperture with, in the Bottom Left panel, its far-field pattern. Top Right panel: series of apertures with gaussian illumination, and the corresponding far-field pattern (Bottom Right Panel).

3 First module and perspectives

QUBIC, in its final configuration will be operated at 97, 150 and 220 GHz, with 2 modules per frequency (each one endowed with 2000 TES), and is intended to target CMB primordial B-modes in a multipole window $20 \leq \ell \leq 150$, to achieve a final sensitivity of r=0.01 (90%CL) after 1 year of on-sky operation. The first module to be deployed at the Antarctic station of Dome C is the one at 150 GHz. Dome C has been demonstrated as one of the most transparent and most stable places on Earth for mm-wave astronomy: a relevant fact for an efficient use of observation time. The first 150 GHz module will observe the sky through a field of view of $\sim 14°$, with a resolution of $\sim 0.54°$. It is nowadays completely dimensioned, and the different subsystems are being realised. Subsystem assembly is scheduled in 2015. The primordial B-mode signal peaks slightly below $\ell \sim 100$ ($\sim 2°$), where QUBIC has its maximum sensitivity, and its best systematic rejection capabilities. QUBIC, with its novel way of controlling systematics, together with a deployment of kilo-pixel focal planes, can play an important role to confirm the BICEP2 claim, which is opening a new era in our understanding of Inflation.

Acknowledgments

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