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QUBIC I: Overview and Science Program

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Abstract.

The Q & U Bolometric Interferometer for Cosmology (QUBIC) is a novel kind of polarimeter optimized for the measurement of the B-mode polarization of the Cosmic Microwave Background (CMB), which is one of the major challenges of observational cosmology. The signal is expected to be of the order of a few tens of nK, prone to instrumental systematic effects and polluted by various astrophysical foregrounds which can only be controlled through multichroic observations. QUBIC is designed to address these observational issues

with its unique capability to combine the advantages of interferometry in terms of control of instrumental systematic effects with those of bolometric detectors in terms of wide-band, background-limited sensitivity. The QUBIC synthesized beam has a frequency-dependent shape that results in the ability to produce maps of the CMB polarization in multiple sub-bands within the two physical bands of the instrument (150 and 220 GHz). This unique capability distinguishes QUBIC from other instruments and makes it particularly well suited to characterize and remove Galactic foreground contamination. In this article, first of a series of eight, we give an overview of the QUBIC instrument design, the main results of the calibration campaign, and present the scientific program of QUBIC including not only the measurement of primordial B-modes, but also the measurement of Galactic foregrounds. We give forecasts for typical observations and measurements: with three years of integration and assuming perfect foreground removal as well as stable atmospheric conditions from our site in Argentina, our simulations show that we can achieve a statistical sensitivity to the effective tensor-to-scalar ratio (including primordial and foreground B-modes) $\sigma(r) = 0.015$. Assuming the 220 GHz is used to subtract foreground contamination together with data from other surveys such as Planck 353 GHz channel, our sensitivity to primordial tensors is given by that of the 150 GHz channel alone and is $\sigma(r) = 0.021$.

Keywords: CMBR polarisation – Gravitational waves and CMBR polarization – Inflation – Interferometry – Imaging Spectroscopy

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1 Introduction

A phase of exponential expansion called “Inflation” in the early Universe was proposed as a solution to two major problems with the standard Big-Bang model [1, 2]. The horizon problem relates to the observed homogeneity of the Universe as evidenced by the smoothness of the Cosmic Microwave Background (CMB). The flatness problem is the fact that the observed curvature of space-time is so close to flat in present times, that it must have been flat to enormous precision in the early universe. The inflationary paradigm has been so successful in resolving the flatness and horizon problems, that it soon became a keystone component to the standard model of Cosmology. However, there continues to be a lack of direct observational evidence of Inflation despite the 40 years that have passed since it was first proposed.

One observable effect of Inflation is the generation of polarization B-modes in the CMB. This happens because during the exponential expansion of the Universe intense gravitational waves are generated. The gravitational waves induce re-orientation of the primordial plasma such that B-modes are visible in the radiation released at the surface of last scattering, which is the CMB. This weak signal has not been detected so far and many projects are operating, or are proposed, to measure the polarization B-modes in the CMB. These project include SPTPol [3], POLARBEAR [4], ACTPol [5], and BICEP2 [6]. Planned experiments include CLASS [7], POLARBEAR 2 + Simons Array [8], Simons Observatory [9], advanced

ACT [10], PIPER [11], upgrade of the BICEP3/Keck array [12], LSPE [13], CMB-S4 [14] and LiteBird [15, 16].

The use of bolometric interferometry to measure polarization B-modes in the CMB was proposed for a series of projects leading up to QUBIC. These are the Millimeter-wave Bolometric Interferometry [MBI, 17, 18], the Einstein Polarization Interferometer for Cosmology [EPIC, 19], the Background RADIation INterferometer [BRAIN, 20], and CMBPol[21]. Members of all these collaborations joined together to develop the Q & U Bolometric Interferometer for Cosmology [QUBIC, 22–26].

This paper is part of a special issue on QUBIC which includes details on all design aspects of QUBIC, as well as on the performance of an advanced prototype, the Technological Demonstrator (TD). The scientific overview and expected performance of the instrument are addressed here. The other papers in the special issue address the following topics: the ability of bolometric interferometry to do spectral imaging [27], the calibration and performance in the laboratory of the Technological Demonstrator [28], the performance of the detector array and readout electronics [29], the cryogenic system performance [30], the Half Wave Plate rotator system [31], the back-to-back feedhorn-switch system [32], and the optical design and performance [33].

This paper is organized as follows. A description of bolometric interferometry is provided in Section 2. This is followed in Section 3 with an overview of the scientific objectives, the current state-of-the-art of CMB polarization experiments, and the expected performance of QUBIC. Finally, conclusions are presented in Section 4.

2 Bolometric Interferometry and QUBIC

2.1 Bolometric Interferometry

The idea of bolometric interferometry dates back to the 19th century when Fizeau proposed an adding interferometer to measure the expected difference in the velocity of light traveling in moving media [34]. The setup split the signal from the Sun into two pipes, each filled with water flowing in opposite directions. The beams were then recombined and the interference fringes measured to determine the phase difference between them. In QUBIC, the pipes are replaced by an array of back-to-back feedhorns, and the beams are recombined by an arrangement of two mirrors [see 33, for details].

An important advantage of the Fizeau arrangement is its inherent wide band performance. There is no wavelength selectivity which results in an ideal performance at any particular wavelength. This can be compared to the case for example of the Martin-Puplett interferometer [35] which introduces a quarter wavelength optical path difference by moving one of the corner mirrors, making it tuned to a particular wavelength.

Imaging radio interferometers generally work with electronic signals where multiplicative correlation is a natural operation with electronic components, both analog and digital. The correlations between signals from different antennas build up a sampling of the “ u - v plane”. The Fourier transform of the u - v plane is an image of the sky, usually called the “dirty image” because no compensation has been done for the under-sampling of the u - v plane, and no calibration has been done [see for example 36]. In a bolometric interferometer, this “dirty image” is formed directly by the optical combiner, and is recorded by the detector array. QUBIC treats the entire band “in one go”, whereas a traditional radio interferometer using narrow band electronic processors must channelize the band into many sub-bands, making large bandwidths impossible to realize in terms of processing and power requirements.

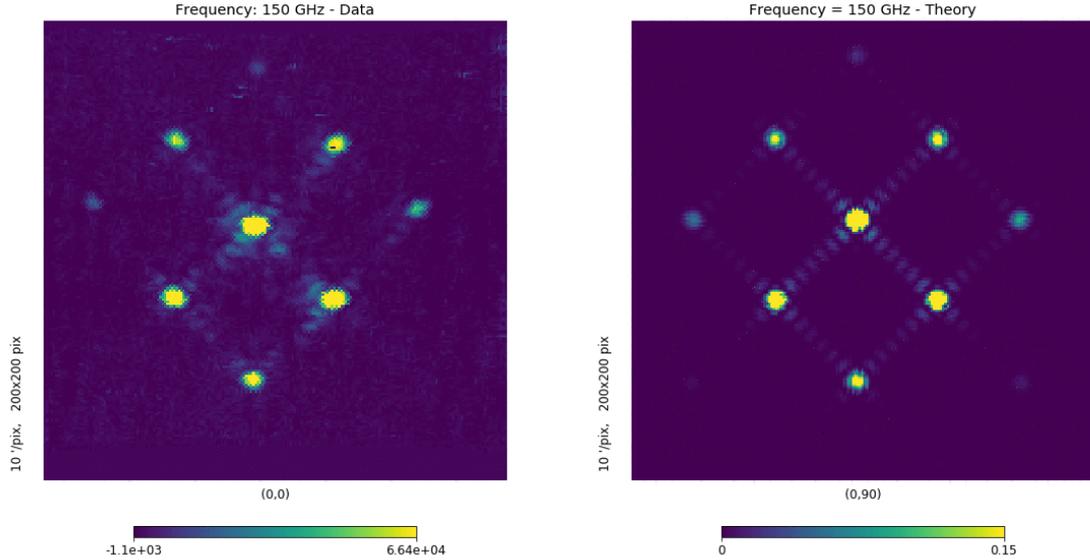


Figure 1. QUBIC synthesized beam on the sky (left: laboratory measurement with the TD, right: simulations without optical aberrations) at 150 GHz. Note that the color scales are arbitrary units, different for both images. Details on this measurement can be found in [28] from this series of articles. The synthesized beam shrinks with increasing frequency as can be seen with the animated version of this image that can be found online at <https://box.in2p3.fr/index.php/s/bzPYfmtjQW4wCGj>.

This method is equivalent to imaging the sky with an imager whose beam is the synthesized beam of the bolometric interferometer (the “dirty beam” of the interferometer), formed by the combination of all interference patterns of all possible pairs of horns in the aperture array [24]. In the case of the QUBIC final instrument, 400 horns form the synthesized beam shown in figure 1 for one specific detector. This is the beam the detector located in this position in the focal plane scans the sky with. Note that the synthesized beam differs for different detectors in the focal plane (see [27, 33] from this series of articles for details). The synthesized beam is very different from a classical imager beam as it exhibits multiple peaks (because the horn array has a finite extension), the angular distance between two peaks is driven by the ratio between the wavelength and the distance between two nearby horns while the angular resolution of each peak is driven by the ratio between the wavelength and the maximal distance between horns. This is detailed in O’Sullivan et. al [33] from this series of articles. In the case of QUBIC, with 400 horns, the angular resolution achieved is 23.5 arcminutes at 150 GHz. Being the result of the summation of interference fringes, this synthesized beam significantly evolves with electromagnetic frequency, which is the basis of the spectro-imaging capabilities of QUBIC (described briefly in section 2.3 and in detail in [27] in this series of articles).

2.2 Self-Calibration

Self calibration in aperture synthesis evolved from the idea of “phase-closure” [37–39] in a phased-array radiotelescope. Signals from the individual antenna elements of a phased-array are combined together and phase differences between the signals are corrected such that the combination of all the signals is equivalent to the signal captured by a large single-dish antenna pointing to the desired direction. With the advent of digital correlators, the corre-

lation coefficients could be saved and a more sophisticated processing resulted in improved calibration. This came to be known as “self-calibration” [40, 41].

Bolometric interferometry can also take advantage of the self-calibration used in traditional aperture synthesis in radio astronomy. However, as a bolometric interferometer directly observes the dirty image, one needs to ‘go backwards’ from the dirty image and reconstruct the u - v plane. The detailed procedure and analysis technique are described in Bigot-Sazy et al. [42]. The general idea is to observe a polarized artificial point source with the bolometric interferometer with only one pair of horns open at a time while the others are closed¹, which can be achieved using the mechanical shutters (also called RF switches) developed for QUBIC that can open or close each horn (see Cavaliere et al. [32] in this series of articles for details on the QUBIC horns and RF switches). In the absence of instrumental systematic effects, two “redundant” pairs of horns (same distance and orientation) would correspond to the exact same visibility (Fourier mode on the sky) and the bolometric interferometer would therefore measure the same quantity. A difference between the two can only come from instrumental effects. By measuring in this manner all possible visibilities, one can fit parameters of a very general instrument model comprising hundreds of parameters (a few for each horn, bolometer) as well as for different electromagnetic frequencies if the source can be tuned in frequency. The number of constraints scales as the number of horns squared while the number of unknowns is proportional to the number of horns. As a result the problem is heavily over constrained for an instrument like QUBIC. This self-calibration is unique to bolometric interferometry for measuring instrumental systematic effects and subsequently accounting for them in the data analysis process through a more accurate modeling of the synthesized beam than the purely theoretical one.

2.3 Spectro-Imaging

As mentioned in section 2.1 and shown in figure 1, the multiply peaked shape of the synthesized beams evolves with frequency. A cut of the QUBIC synthesized beam is shown in figure 2 for two different frequencies. As the respective distance between peaks changes with frequency, the signal detected with a given bolometer will combine (through convolution with the synthesized beam) different directions on the sky for different incoming frequencies within the physical wide band. These signals from different frequencies will only be significantly different from each other if the corresponding side-peaks are more separated than their intrinsic width.

This shows how one can simultaneously recover spatial and frequency information within a wide physical band for a bolometric interferometer. This spectro-imaging reconstruction is done at the map-making stage in the data-analysis pipeline with data collected within a wide bandwidth. It can be done by reconstructing maps in as many different sub-frequencies as allowed by the ratio between frequency shift and intrinsic peak width in the synthesized beam. Spectro-imaging is described in detail in Mousset et al. [27] from this series of articles.

In the current context of search for primordial B-modes in the CMB originating from tensor perturbations from inflation, spectro-imaging appears as a unique opportunity to constrain foregrounds in a powerful fashion. Previous analyses have indeed shown that B-modes measurements are largely dominated by foregrounds [43–46] which can only be removed

¹In practice, in order to keep a roughly constant loading on the detector array, we achieve this observation through measuring successively the point source with one horn closed, all the others being open, then only the second horn closed, then both closed and finally all horns open. We eventually combine these observations to achieve the same measurement as with a single pair of horns open.

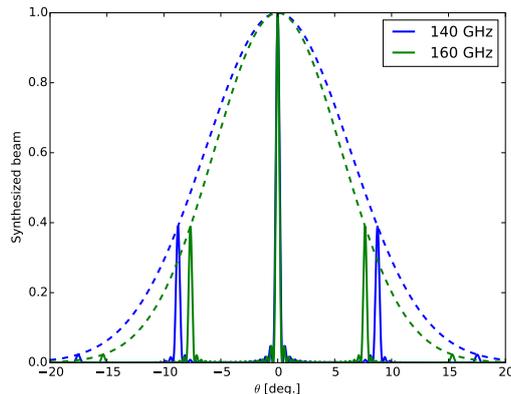


Figure 2. A cut of the QUBIC synthesized beam at two different frequencies showing how the location of the multiple peaks significantly changes for a small frequency change. This behaviour is at the basis of the spectro-imaging capabilities offered by bolometric interferometry. This figure can also be found in [27] from this series, dedicated to spectro-imaging.

through their frequency behaviour which is distinct from that of the CMB. Classical imagers usually approach this issue by multiplying the number of frequencies at which they observe the CMB. Galactic dust is currently the most worrying foreground. It can be constrained from the ground through wide atmospheric windows around 150 and 220 GHz. The noise severely increases at higher frequencies because of atmospheric emissivity. As a result, constraints on foregrounds can only be achieved through comparisons between these few, largely separated frequency bands. While their large separation in frequency may appear as an advantage as it increases lever arm, it is also a limitation as it prevents data analyses to consider realistic electromagnetic spectra for dust emission that could exhibit changes of slope or dust decorrelation between frequencies [46, 47]. With spectro-imaging, one can measure the spectrum of the foreground components **locally** (i.e., within the bandwidth) and avoid large extrapolations between distant frequencies. This may turn out to be a key feature for obtaining convincing evidence for primordial B-modes instead of dust contaminated results. This is studied in section 3.3 of this article.

2.4 The QUBIC Instrument

In order to achieve bolometric interferometry, QUBIC relies on an optical system consisting of back-to-back horns that select the relevant baselines and an optical combiner focusing on a bolometric focal plane. The optical combiner forms interference fringes while the bolometers average their powers over timescales much larger than the period of the electromagnetic light. This is therefore the optical equivalent of a (wide-band) correlator in classical interferometry. Being a bolometric device, the whole instrument operates at cryogenic temperatures thanks to a large cryostat described in Masi et al. [30] from this series of articles.

A schematic of the design of QUBIC is shown in figure 3 and the main instrument parameters are listed in table 1. The sky signal first goes through a 56 cm diameter window made of Ultra-High-Molecular-Weight Polyethylene followed by a series of filters cutting off frequencies higher than the desired ones. The next optical component is a stepped rotating Half-Wave-Plate which modulates incoming polarization. This sub-system is described in D’Alessandro et al. [31] from this series of articles. A single polarization is then selected

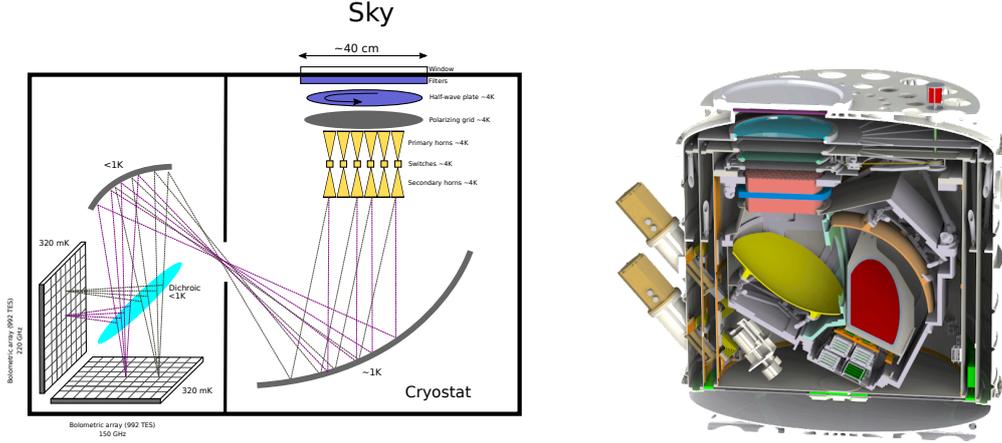


Figure 3. Schematic of the QUBIC instrument (left) and sectional cut of the cryostat (right) showing the same sub-systems in their real configuration.

Table 1. QUBIC main parameters

Parameter	TD	FI
Frequency channels	150 GHz	150 GHz & 220 GHz
Frequency range 150 GHz ...	[131-169] GHz	[131-169] GHz
Frequency range 220 GHz ...	-	[192.5-247.5] GHz
Window Aperture [m]	0.56	0.56
Number of horns	64	400
Number of detectors	248	992×2
Detector noise [$W/\sqrt{\text{Hz}}$]	2.05×10^{-16}	4.7×10^{-17}
Focal plane temp. [mK]	300	300
Sky Coverage	1.5%	1.5%
FWHM [degrees]	1.0	0.39 (150 GHz), 0.27 (220 GHz)

thanks to a polarizing grid. Although reflecting half of the incoming photons may appear as a regrettable loss, it is in fact one of the key features of QUBIC for handling instrumental systematics, especially polarization-related ones, down to an unprecedented level: a single polarization is selected just after polarization modulation by a wire-grid, while our bolometers are not polarization sensitive. As a result, any cross-polarization occurring after the polarizing grid (horns, uncontrolled reflections inside the optical combiner) are completely irrelevant to us. The next optical device is an array of 400 back-to-back corrugated horns made of an assembly of two 400-horns arrays, composed of 175 aluminium platelets (0.3 mm thick) chemically etched to reproduce the corrugations required for the horns to achieve the required performance. An array of mechanical shutters (RF switches) separates the two back-to-back horn arrays in order to be able to close or open horns for self-calibration (see section 2.2). Both front and back horns are identical with a field of view of 13 degrees FWHM with secondary lobes below -25 dB. The horns and switches are described in detail in Cavaliere et. al [32] from this series of articles. The back-horns directly illuminate the two-mirrors off-axis Gregorian optical combiner (described in detail in O’Sullivan et al. [33]) that focuses the signal onto the two perpendicular focal planes, separated by a dichroic filter

that splits the incoming waves into two wide bands centered at 150 GHz for the on-axis focal plane and 220 GHz for the off-axis one. The focal planes are each equipped with 992 NbSi Transition-Edge-Sensors (the detection chain is described in detail in [29] from this series of articles) cooled down to 300 mK using a sorption fridge. A realistic view of the cryostat can be seen in the right panel of figure 3. The cryostat weights roughly 800 kg and is around 1.6 meter high for a 1.4 meter diameter.

2.4.1 The QUBIC Technological Demonstrator

The QUBIC Technological Demonstrator (hereafter QUBIC TD) uses the same cryostat, cooling system, filters and general sub-system architecture as described above but with only 64 back-to-back horns and mirrors reduced according to the illumination of the 64 horns. It also uses a single 248 TES bolometer array operating at 150 GHz. The QUBIC TD has been used as an intermediate step before the Full Instrument (FI) in order to characterize and demonstrate bolometric interferometry in the laboratory. We have fully demonstrated the expected behaviour of the instrument and all the anticipated specific features of bolometric interferometry during this calibration campaign which is detailed in Torchinsky et al. [28]. A selection of the most relevant results from the calibration includes:

- the measurement of the bolometric interferometer synthesized beams multiple peaked shape in perfect agreement with the theoretical prediction we made in [24], shown in figure 2;
- the evolution as a function of frequency of the inter-peak separation in the synthesized beam (available online at <https://box.in2p3.fr/index.php/s/bzPYfmtjQW4wCGj>) which is at the basis of Spectro-Imaging described briefly in section 2.3 and in detail in [27]. This possibility, only offered by a bolometric interferometer is studied in detail in section 3.3 of this article;
- the measurement of individual fringe patterns using the mechanical shutters [32] shown in the left panel of figure 4 in this article and a more detailed description in figure 13 of [28]. As discussed in section 2.2, this measurement is at the basis of the self-calibration allowing QUBIC to achieve a unique control of instrumental systematic effects, as shown in Bigot-Sazy et al. [42];
- a measurement of the QUBIC TD cross-polarization as low as $0.16\% \pm 0.18\%$ for the best signal-to-noise ratio TES as shown in the right panel of figure 4 from this article and detailed in section 4 (and specifically figure 9) of [28]. This extremely low cross-polarization is clearly a major asset for detecting a signal as small as the primordial B-modes and results from the specific polarization design of QUBIC with a single polarization selected before the interferometer apertures and full-power detectors as discussed above in this section.
- The intrinsic detector noise has been measured to be $4.7 \times 10^{-17} \text{ W}/\sqrt{\text{Hz}}$ but due to noise aliasing with the TD readout chain, the effective detector+readout noise is $2.05 \times 10^{-16} \text{ W}/\sqrt{\text{Hz}}$. This noise aliasing will be resolved for the FI (see [29]).

The QUBIC TD will be shipped to Argentina at the end of 2020 and subsequently deployed in its observing site (see section 2.4.3 for a description). The objective is to conduct a full characterization of bolometric interferometry on the sky throughout 2021. The performance expected from observation with the QUBIC TD is discussed in section 3.3.2.

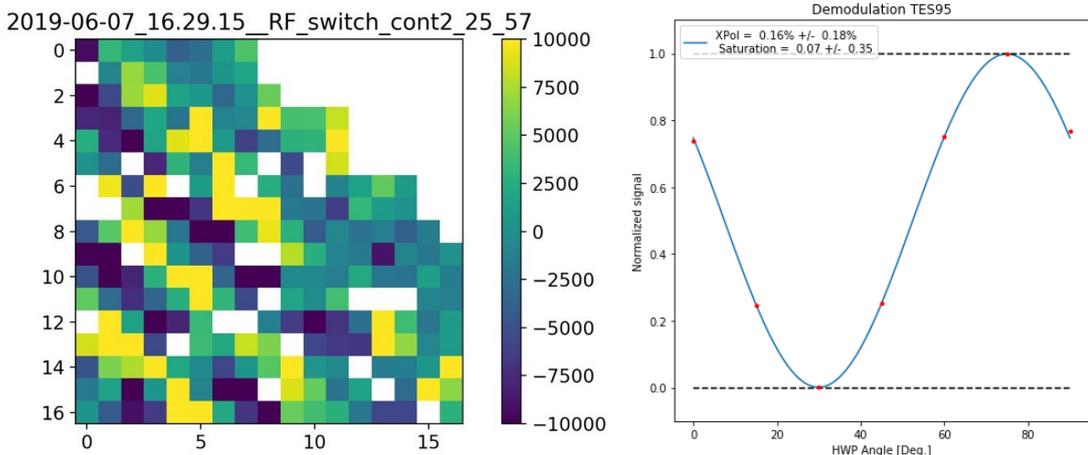


Figure 4. (left) Fringe pattern obtained with the QUBIC TD using the mechanical shutters [32] in order to achieve a measurement equivalent to that of a single baseline (two horns open, all others closed). Units are arbitrary. This is compared with the expected fringe in figure 13 from [28] in this series of articles. (right) Cross-Polarization measured by rotating the Half-Wave-Plate and observing our polarized calibration source. This result is obtained with the TES bolometer showing the best signal-to-noise ratio for this measurement. We do not expect however the cross-polarization to change from one TES to another.

2.4.2 The QUBIC Full Instrument

The upgrade to the FI will consist in:

- replacing the 64 back-to-back horn array by one with 400 horns which is already manufactured and being characterized at the sub-system level (see Cavaliere et al. [32] from this series of articles);
- replacing the current mirrors by larger mirrors that are already manufactured and characterized (see O’Sullivan et al. [33]);
- upgrading the single 248 TES array by eight of these (four at 150 GHz and four at 220 GHz) achieving two focal planes of 992 TES each. Note that detailed quasi-optical simulations have shown that the 150 GHz optimization of the back-short of the TES is also nearly optimal at 220 GHz allowing us to use identical detector designs for both frequencies [48, 49]. A new readout electronics will avoid the TD noise aliasing through the addition of Nyquist inductors [29]. The additional focal plane also requires the installation of a dichroic filter at 45 degrees in between the two focal planes (light-blue in figure 3-left, and in red in figure 3-right).

The back-to-back horns are common to both frequencies in the QUBIC design. They have been optimized to be single-moded at 150 GHz but are multi-moded in the 220 GHz band (see [33] section 2.3) resulting in a significantly higher throughput at 220 GHz.

Despite stronger emission from the atmosphere, simulations have shown (see figure 8 in section 3.2.2) that this will result in an similar sensitivity to primordial B-modes at 220 GHz and at 150 GHz. Several effects contribute to this result. First, considering the intrinsic detector noise (see paper [29]), our noise budget is dominated by the detectors at 150 GHz

and has almost equal contributions from photon-noise and detectors at 220 GHz (see table 2). Because of this, the net sensitivity loss at 220 GHz due to higher emissivity from the atmosphere is not as large as expected from pure photon-noise. We also collect more CMB photons at 220 GHz due to the horns higher throughput.

As a result, the signal to noise ratio in the TOD at 220 GHz is higher than for a single-modulated channel. Finally, multimoded horns at 220 GHz also result in a flatter primary beam (see [33] figure 5) than at 150 GHz where the primary beam is Gaussian. This strongly impacts the spatial noise correlation in our maps (see section 3.1) resulting in a reduction of our power spectra error-bars at the lowest multipoles. This effect occurs for both bands but is stronger at 220 GHz due to the higher amplitude of the synthesized beam secondary peaks.

2.4.3 The QUBIC site

QUBIC will be installed in its final observing site in Argentina at the end of 2020². The site is located at the Alto Chorillos (24°11'11.7" S; 66°28'40.8" W, altitude of 4869 m a.s.l.) about 45 minutes drive from the city of San Antonio de los Cobres in the Salta Province [50]. This site has been studied for mm-wave astronomy for many years as it will also host the LLAMA 12 m antenna (<https://www.llamaobservatory.org/en/>), 800 m away from QUBIC. The synergy between QUBIC and LLAMA at the site simplifies the site preparatory works, logistics and deployment operations.

This site exhibits excellent quality sky for CMB studies: zenith optical depth at 210 GHz $\tau_{210} < 0.1$ for 50% of the time and < 0.2 for 85% of the time as well as relatively quiet atmosphere (winds < 6 m/s for 50% of the time). From the LLAMA site-testing data, we have determined an average atmospheric temperature of 270 K with an average emissivity 0.081 and 0.138 at 150 and 220 GHz respectively. These values are assumed for the atmospheric background in the simulations presented in this article.

The whole instrument is oriented to any sky direction with elevation between 30 and 70 degrees (limitations due to Pulse-Tubes-Coolers) and any azimuth by an alt-azimuthal mount on the top of a well-adapted container. A fore-baffle will be placed at the window entrance with an absorptive inner surface in order to increase side lobes rejection for angles larger than 20 degrees from bore-sight direction. Finally, the instrument will be surrounded by a ground-shield in order to minimize brightness contrast between the sky and the ground. Figure 5 shows an artist view of the mounted instrument. The calibration source used for self-calibration (see [28] for details) will be installed on a 50 m-high tower (telecommunication-like) placed 50 m North from the instrument. It will directly be seen at normal elevations (without the use of a mirror) in the far field of the instrument and in the direction opposite to the main CMB observations.

3 Science Objectives of QUBIC

QUBIC, being a bolometric interferometer, has unique features with respect to traditional imagers designed for observing the CMB and optimized for measuring primordial B-mode polarization. QUBIC is a clean spectro-polarimeter well adapted to the purpose of detecting primordial B-modes because of the following main features:

²It was anticipated to ship the instrument mid-2020 but the global shutdown caused by the COVID19 pandemic induced uncontrolled delays. As a consequence, the date mentioned here is subject to changes depending on the resolution of the COVID19 pandemic crisis.

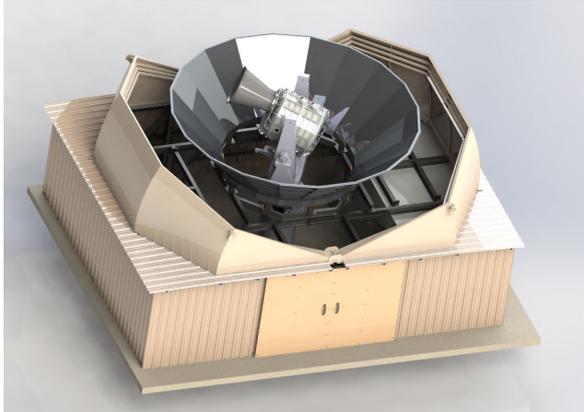


Figure 5. Sketch of the instrument, the cryostat on the alt-azimuthal mount as will be installed on the observing site.

- it scans the sky with a synthesized beam formed by the feedhorn array, that exhibits multiple almost Gaussian peaks (above -20dB) with a resolution of 23.5 arcminutes at 150 GHz;
- the angular separation on the sky between the synthesized beam peaks is given by the smallest distance between two peaks and is 8.8 degrees at 150 GHz. This distance scales as a function of frequency within the physical bandwidth of 25% in such a way that sub-frequency maps can be reconstructed using spectro-imaging;
- a specific optical design with a polarizing grid before any optical component (except for the Half-Wave-Plate, filters and window) combined with full-power detectors on the focal plane make QUBIC largely immune to cross-polarization.

All of these specific features were studied in detail and are incorporated in the forecasts shown in this section.

3.1 Data Analysis and Simulations for QUBIC performance forecasts

The non-trivial shape of the synthesized beam (figures 1 and 2) requires a specific map-making method which was developed for QUBIC. It is based on forward modeling to solve the inverse problem of map-making (see [27] for details). We start from a guess map of the sky and a detailed model of the instrument³. The instrument model uses a detailed description of the synthesized beam. At first we can use an idealized instrument model inspired by an ideal synthesized beam as shown in figure 2, or a more realistic one as simulated including optical aberrations (see figures 11 and 12 in [33]). Then, such a description is expected to be gradually refined during the observation campaigns using information from self-calibration [42]. We observe the guess map at iteration i with the same scanning strategy used with the real data, obtaining simulated Time-Ordered-Data (TOD) that are compared to the real TOD with a χ^2 . Using a preconditioned conjugate gradient we modify the guess map in an iterative manner until convergence. The final guess map is the solution of the map-making linear problem.

³The software makes heavy use of the massively parallel libraries developed by P. Chianial pyoperators [51] (<https://pchanial.github.io/pyoperators/>) and pysimulators (<https://pchanial.github.io/pysimulators/>).

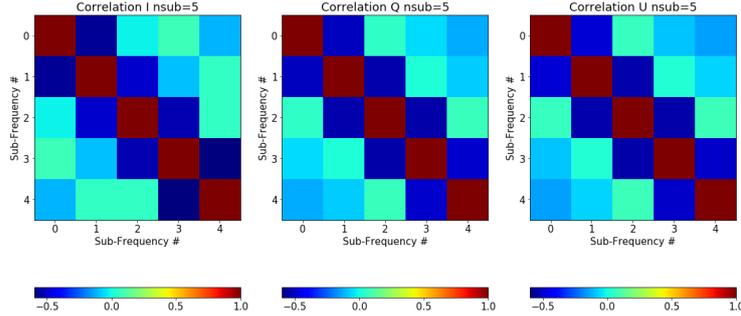


Figure 6. QUBIC sub-bands correlation matrices for I, Q and U Stokes parameters maps obtained from end-to-end simulations at 150 GHz reconstructing the TOD onto 5 sub-bands (equally spaced in log within the physical 150 GHz bandwidth of QUBIC that ranges from 131 to 169 GHz) using spectro-imaging and averaged over pixels in the maps.

The synthesized beam used for the instrument model during map-making is actually just a set of Dirac functions with the relevant amplitude at the location of the peaks of the synthesized beam (ideal, including optical aberrations or resulting from self-calibration). In such a way, and similarly as with an imager, the map-making does not attempt to deconvolve from the resolution of the peaks, but only from the multiple peaks.

If the synthesized beam model accounts for the realistic frequency dependence, one can use multiple maps at multiple frequencies within the physical bandwidth of the instrument and therefore reconstruct such sub-frequency maps. This is spectro-imaging [27]. Another specificity of this map-making is that the presence of multiple peaks separated by 8.8 degrees on the sky at 150 GHz (6 degrees at 220 GHz) makes QUBIC insensitive to modes on the sky larger than this separation. This occurs because the deconvolution from the multiple peaks relies on the measured signal difference between observations pointing to different directions where the peaks capture different amounts of power. For sky signals at angular scales larger than the angular distance between the peaks, such a difference vanishes. This naturally filters-out large-scale information be it from the sky itself, or from atmospheric gradients which produce most of the atmospheric noise.

A careful study of the noise structure in end-to-end simulated maps shows two significant features that merit further explanation. The first is sub-band correlations. When performing spectro-imaging, we show that nearby sub-bands exhibit a significant level of noise anti-correlation [27], as displayed in figure 6 for the three Stokes parameters at 150 GHz and 5 sub-bands. The anti-correlation is strong with the nearest sub-bands but reduces significantly beyond. Similar correlation matrices are found at 220 GHz.

The second feature worth noticing is spatial correlations. Map-making with a multiply-peaked synthesized beam involves partial deconvolution because a given time sample in a detector’s TOD receives power from distant pixels in the sky with weights given by the shape of the synthesized beam. As a result, we expect significant spatial noise correlations in our maps. This is confirmed by end-to-end simulations as shown in the left panel of figure 7. Anti-correlation peaks, as expected, at an angle corresponding to the angular separation between the peaks in the synthesized beam ($\theta_{\text{peaks}}=8.8$ degrees at 150 GHz and 6 degrees at 220 GHz). A similar 2pt-correlation function is found at 220 GHz, but with even higher correlation amplitude because the secondary peaks are higher due to the top-hat shape of the primary beam resulting from multimode optics at 220 GHz (see figure 4 in [33]).

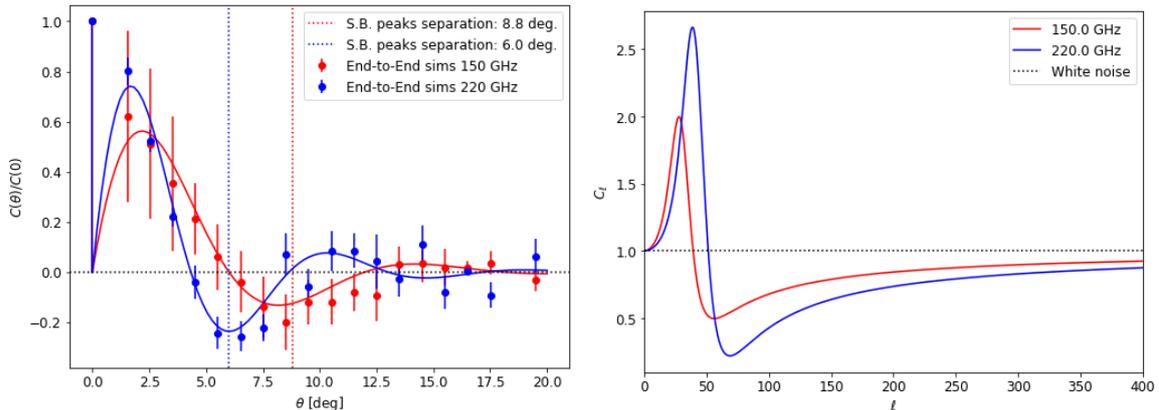


Figure 7. (left) QUBIC spatial noise 2pt-correlation function obtained from end-to-end simulations normalized by the variance in the maps $C(\theta = 0)$. The solid lines show an adjustment by a sine-wave modulated by an exponential with a Dirac function at $\theta = 0$ (the noise variance in the maps). The maximum anti-correlation is found as expected at the scale of the angular distance between two peaks of the synthesized beam (S.B.). The amplitude of the correlation is higher at 220 GHz than at 150 GHz because of the top-hat shape of the primary beam at 220 GHz. (right) Spatial noise correlation converted to multipole space. The straight-line at $C_\ell = 1$ shows the expected shape for white noise. The noise correlation results in a reduction of the noise for multipoles larger than $\sim 40 - 50$, that is for angular scales $\lesssim \theta_{\text{peaks}}$ (angular separation between the synthesized beam peaks). At lower multipoles (larger angular scales), we observe an increase of the noise. This is an advantage for measuring the recombination peak around $\ell = 100$.

In the right panel of figure 7 we display the spherical harmonics transform of the 2pt-correlation function:

$$C_\ell = 2\pi \int_{-1}^1 C(x) P_\ell(x) dx \quad (3.1)$$

where $x = \cos\theta$ and P_ℓ are the Legendre polynomials. This is our noise angular power spectrum: This which corresponds to the equivalent for QUBIC of typical white noise for a classical imager. The shape of this noise in Harmonic Space exhibits an excess with respect to white noise at very large scales (small multipoles, below $\ell = 40$ at 150 GHz and $\ell = 50$ at 220 GHz) and a significant reduction at smaller angular scales (larger multipoles). The scale of this transition is determined by the angular distance between peaks in the synthesized beam⁴. Angular scales $\gtrsim \theta_{\text{peaks}}$ are not well constrained due to the presence of the multiple peaks that are effectively deconvolved during the map-making. On the contrary, angular scales smaller than this angular separation see their noise significantly reduced thanks to the positive correlation of the noise at these angles. Because these angular scales correspond to those of the recombination peak in the B-mode spectrum, this specific noise feature for Bolometric Interferometry turns out to be a significant advantage for detecting primordial B-modes. Also, because our noise is not white, the RMS in the maps does not have direct significance. In our case, it is more meaningful to measure the noise level in the angular power-spectrum as we will detail in section 3.2.

This peculiar noise structure has been studied in detail using a number of end-to-end simulations ran on supercomputers because of large memory requirements. They are done

⁴It is however not strictly equal to $\pi/\theta_{\text{peaks}}$ because of the shape of the 2pt-correlation function and the non-trivial correspondence between angles and multipoles.

in such a way that the effects are directly modelled into a “Fast Simulator” that is used for forecasts with high statistics and can be ran on usual desktop computers.

The anticipated scanning strategy for QUBIC is back and forth azimuth scans at constant elevation, following the azimuth of the center of the field as a function of sidereal time and updating elevation regularly in order to have scans with as many angles as possible in sky coordinates. The latitude of the QUBIC site allows us to cover a wide range of angles. The fast simulations we performed for this study mimic the sky coverage obtained with the scanning strategy using random pointings on the sky from one time sample to another. While this allows obtaining a fast and efficient coverage of the QUBIC observed sky, it prevents one from simulating actual $1/f$ noise from atmospheric or instrumental fluctuations as successive time samples do not correspond to nearby pointings as in a more realistic scanning strategy. As a consequence, the simulations presented in this article implicitly assume a stable atmosphere with $1/f$ noise, but account for the average loading from the atmosphere. We will include realistic atmospheric fluctuations in our simulations when more detailed information than the average emissivity and temperature will be available from the TD data on the sky. In addition, as discussed in the second paragraph of this subsection, the shape of the QUBIC synthesized beam implies a low sensitivity on scales much larger than the angular distance between our multiple peaks, which will significantly reduce the impact of the (mostly large scales) atmospheric fluctuations.

No instrumental systematics are considered in this article, they will be included in future studies as well as how they can be mitigated through self-calibration.

3.2 The quest for CMB B-modes

3.2.1 Overview

We have performed simulations for a three-year observation using the QUBIC FI on a sky without any foregrounds, but with realistic instrumental noise (see [28] and [29]) and with atmospheric background noise (assumed to be stable). The latter has been obtained from measurements performed over 3 years at the QUBIC site in Argentina from a tipper at 210 GHz used for the LLAMA radiotelescope⁵ to be installed near QUBIC. Atmospheric background is averaged over the 9 best months of the year and corresponds to an atmospheric temperature of 270 K and emissivities 0.081 and 0.138 at 150 and 220 GHz respectively.

We have used the “Fast Simulator” described above to produce a large number of realizations of the noise in the maps incorporating the peculiar noise structure (spatial variations of the noise as a function of coverage as well as spatial and sub-band correlations). The parameters of our simulation are summarized in table 2.

For each realization, we have used NaMaster⁶ [52] to compute pure TT, EE, TE and BB power spectra on the residual maps (therefore noise-only maps) in order to compute the expected noise on the power spectra. Exploring various values for the minimum multipole ℓ_{min} , the size of the multipole bins Δ_ℓ and minimum value of the relative coverage (normalized to 1 at maximum) of the sky that defines the region of the sky we keep for analysis, Cov_c , we have found the best configuration to be $\ell_{min} = 40$, $\Delta_\ell = 30$ and $Cov_c = 0.1$ at 150 GHz. We have kept the same configuration for the 220 GHz for the sake of simplicity.

⁵<https://www.llamaobservatory.org/>

⁶<https://github.com/LSSTDESC/NaMaster>

Table 2. Main instrumental and simulation parameters used in our computations. The noise value for TD is measured from the TES calibration data [28] while that for the FI is the intrinsic TES noise and assumes reduction of the noise aliasing in the readout chain found in the TD.

Parameter	Value TD	Value FI
Detector noise [W/ $\sqrt{\text{Hz}}$]	2.05×10^{-16}	4.7×10^{-17}
Atmosphere ¹ temperature [K]	270	270
Atmosphere emissivity at 150 GHz.	0.081	0.81
Photon noise [W/ $\sqrt{\text{Hz}}$]	2.6×10^{-17} (150 GHz)	3.1×10^{-17} (150 GHz), 1.17×10^{-16} (220 GHz)
Total noise [W/ $\sqrt{\text{Hz}}$]	2.06×10^{-16} (150 GHz)	5.7×10^{-17} (150 GHz), 1.26×10^{-16} (220 GHz)
Cumulated observation time [years]	1	3
r upper-limit (68% C.L., No FG)	-	0.021 (150 GHz), 0.023 (220 GHz), 0.015 (Combined)

¹The atmosphere is considered perfectly stable.

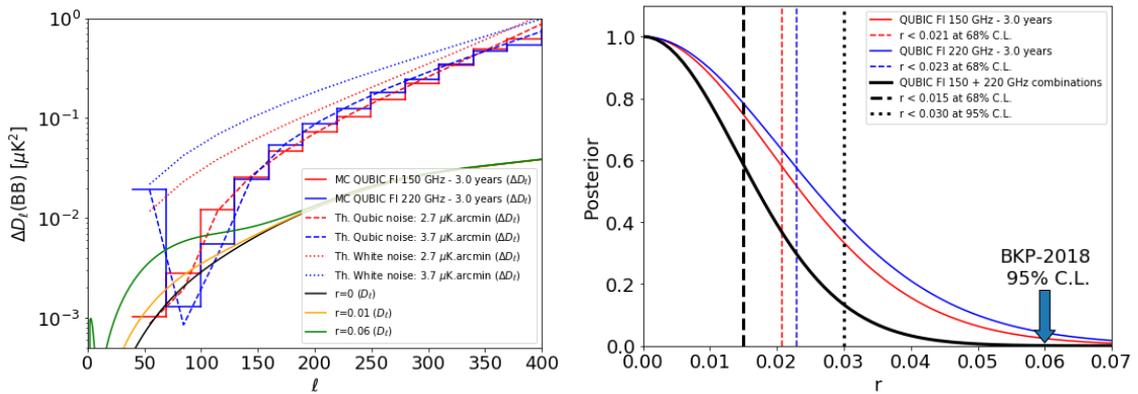


Figure 8. (left) BB power spectrum error-bars ΔD_ℓ on $D_\ell = \frac{\ell(\ell+1)}{2\pi}C_\ell$ on residual maps from the Fast-Simulator Monte-Carlo in the absence of foregrounds, atmospheric fluctuations and instrument systematic effects for an integration time of three years from the site in San Antonio de los Cobres, Argentina. As these are calculated on residual maps, they do not incorporate sample variance and only refer to the instrumental noise. The reduction at low- ℓ of our error-bars with respect to theoretical white-noise (dotted lines) is clearly visible and in agreement with the expected shape from the 2pt correlation function in figure 7 (dashed lines). The difference in the first bin is discussed in the text. (right) Posterior likelihood on the tensor-to-scalar ratio r using QUBIC FI (two bands) with three years of data (including both noise and sample variance). The Bicep-Keck-Planck latest constraint is shown with the blue arrow [46].

3.2.2 QUBIC Full Instrument expected performance

As remarked before, measuring the RMS of a map in the case of non-white noise is meaningless, and the actual measurement of the effective depth of our maps is done in ℓ -space. The resulting uncertainties from the Monte-Carlo on the BB polarization power spectrum (ΔD_ℓ) are shown in the left panel of figure 8. We have also displayed theoretical B-mode power spectra D_ℓ (including lensing) for $r=0$, 0.01, and 0.06 (the current best upper-limit [46]).

Besides the QUBIC error bars, we also plot the expected shape for white noise (dotted lines) and for the QUBIC noise (dashed lines) from figure 7. In both cases the theoretical error-bars are obtained through the well known formula:

$$\Delta D_\ell^{\text{th}} = \frac{\ell(\ell+1)}{2\pi} \times \sqrt{\frac{2}{(2\ell+1)f_{\text{sky}}\Delta\ell}} \times \frac{1}{B_\ell^2} \times \frac{1}{W_\ell^2} \times C_\ell^{\text{noise}} \quad (3.2)$$

where f_{sky} is the fraction of the sky used for analysis ($f_{\text{sky}} = 0.015$ in our case), $\Delta\ell$ is the width of the ℓ -space binning ($\Delta\ell = 30$ in our case). B_ℓ is the beam transfer function and W_ℓ is that of the Healpix pixellisation ($N_{\text{side}} = 256$). C_ℓ^{noise} is the expected shape for the noise power spectrum that can be either a constant in the case of white noise or a constant multiplying the shape from figure 7 (right) in the case of QUBIC. We performed a fit of the above noise normalization for QUBIC to our Monte-Carlo error-bars leading 2.7 and 3.7 $\mu\text{K}\cdot\text{arcmin}$ at 150 and 220 GHz respectively. This is shown as dashed lines in figure 8. However these numbers are hardly comparable with the case of a standard imager for which the noise is white: for each frequency we overplot the expected shape for white noise with the same normalization. The significant noise reduction with respect to the white noise case is particularly visible at the scales of the recombination peak near $\ell = 100$, giving QUBIC an enhanced sensitivity at those scales. At scales larger than the separation between peaks in the synthesized beam however, the error-bars increase sharply. The first bin at 220 GHz exhibits significantly larger error-bars for all spectra. This is not surprising as we have kept the same $\ell_{\text{min}} = 40$ for both channels. In reality, the multiple-peaked shape of our synthesized beam is such that we have little sensitivity to multipoles corresponding to angular scales larger than the distance between the peaks (8.8 and 6 degrees at 150 and 220 GHz respectively). As a result, the optimal ℓ_{min} at 150 GHz is slightly too low for 220 GHz, resulting in larger error-bars for the first bin. This will be optimized when analyzing real data.

The right panel of figure 8 shows the posterior on the tensor-to-scalar ratio which, in the absence of foregrounds, was the only free-parameter for this power-spectrum-based likelihood (simple χ^2 accounting for sample variance [53]) with all parameters but r fixed to their fiducial values⁷. We calculate the likelihood at 150 and 220 GHz separately as well as jointly. These simulations show that QUBIC has the statistical power (without foregrounds, atmospheric fluctuations and systematics) to constrain the B-modes down to a tensor-to-scalar ratio $r < 0.015$ at 68% C.L. ($r < 0.03$ at 95% C.L.) with three years of data from our site in Argentina. This is to be compared with the most accurate constraints achieved as of today by the combination of BICEP2, KECK, WMAP and Planck data: $r < 0.06$ at 95% confidence level [46].

In the presence of foregrounds, the numbers above are to be understood as our statistical sensitivity to effective B-modes including the contribution from primordial tensors as well as dust polarization. Assuming we use the 220 GHz to subtract foreground contamination from the 150 GHz channel together with data from other surveys such as the Planck 353 GHz polarized channel, the statistical sensitivity of the 150 GHz alone is a reasonable estimate of our sensitivity of primordial B-modes and corresponds to $r < 0.021$ at 68% C.L. The spectro-imaging features of QUBIC are unique in the CMB experimental field by having sub-bands within our two physical bands. This will allow QUBIC to make very specific and powerful foreground analyses and constraints that are explored in the next section.

⁷We have used a fiducial cosmology with parameters [$h = 0.675$, $\Omega_b h^2 = 0.022$, $\Omega_c h^2 = 0.122$, $\Omega_k = 0$, $\tau = 0.06$, $A_s = 2e - 9$, $n_s = 0.965$]

3.3 The foregrounds challenge

3.3.1 Overview

Instrumental systematic effects and polarized astrophysical foregrounds are the main challenges to current and future generation B-mode experiments. Indeed, polarized emissions from foregrounds are brighter than the B-mode signal over the entire sky, and the only way to separate the CMB signal from the foregrounds is to make measurements at several frequencies in a range from a few GHz to several hundreds GHz.

The polarized foregrounds are dominated by the synchrotron emission, generated by cosmic ray electrons spiraling around the Galactic magnetic field, and by Galactic dust emission, caused by magnetized grains, heated by starlight and aligned with the direction of the Galactic magnetic field (see [54] and references therein). The frequency scaling law of the synchrotron emission reflects the energy distribution of the electrons and can be described with a power law characterized by a spectral index $\beta_{\text{synch}} \sim -3$. The dust behaves like a gray-body with a temperature of ~ 18 K and an emissivity with spectral index $\beta_{\text{dust}} \sim 1.5$ [54, 55]. These parameters, however, vary across the sky and display spatial correlations that are essentially unknown.

The scenario is made even more complex also by other emissions that could impact B-mode measurements. The anomalous microwave emission (AME), for example, is correlated with the dust and emits at low frequencies as a result of spinning grains [56]. Carbon-monoxide (CO) lines [57] correlate with Galactic gas clouds. Extra-Galactic foregrounds are generated by radio and infrared sources in a wide frequency range between one and several hundreds of GHz, with brightness temperatures that may decrease (radio sources) or increase (infra-red sources) with frequency [55, 58].

A thorough analysis of WMAP, Planck and S-PASS data carried out by Krachmalnicoff et al [59, 60] has shown that there is no sky region that is clean enough from foregrounds contamination to allow a significant B-modes detection below $r = 0.01$. Furthermore they found a correlation of the order of 10% between synchrotron and dust emissions on large angular scales. This clearly shows that the control of foregrounds and of its detailed spectral behavior is mandatory for any B-mode experiment.

Another compelling evidence of the impact of foregrounds is provided by figure 34 of [54], which shows that if $r < 0.05$ then there is essentially no region in ℓ space and/or in frequency where the cosmological B-modes are brighter than the foregrounds.

Because the B-mode signal from tensor modes is orders of magnitudes below the foregrounds, the final uncertainty is dominated by the residuals after component separation, caused by our current limits in the detailed understanding of the foreground signal distribution in space and frequency. If, on the one hand, the issue of space coverage and resolution will be addressed by stage-3 [3–6, 8, 10] and stage-4 CMB experiments [9, 14–16], on the other hand frequency resolution requires a different approach in the instrument design. QUBIC, with its design able to discriminate sub-bands in each frequency band, is the instrument that is able to respond to such a challenge.

Figure 9 highlights the potential of QUBIC in providing enhanced frequency resolution compared to state-of-the-art and future experiments. In the left panel we see a spectrum of the polarized dust emission and a CMB B-mode spectrum ($r = 0.001$) in brightness temperature units. Overplotted to the dust line we see the frequency bands of the Simons Observatory [9], while in the middle panel we see the bands expected for the LiteBIRD satellite [16]. The right panel is an expansion of the region around the two QUBIC bands

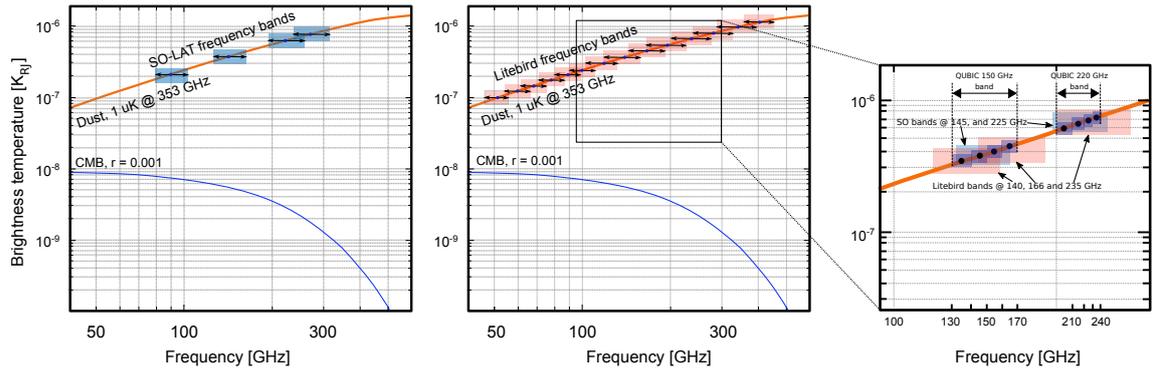


Figure 9. Improvement in frequency resolution achievable with the QUBIC spectral imaging capabilities. **(left):** polarized dust emission and CMB B-mode spectra in brightness temperature units. Simons Observatory [9] frequency bands are overplotted on the dust spectrum. **(middle):** same as left panel with the frequency bands of the Litebird satellite [15, 16]. **(right):** expansion of the region around QUBIC frequencies. We can appreciate the ~ 1 GHz frequency resolution provided by spectral imaging (here with four sub-bands in each wide-band).

centered at 150 and 220 GHz, where we appreciate the improvement in frequency resolution achievable with QUBIC (here with four sub-bands in each of our bands).

A unique feature of the spectro-imaging power of QUBIC is the ability to recognize the presence of foreground residuals remaining in the data after component separation. This is discussed in detail in section 3.3.4.

3.3.2 QUBIC Technological Demonstrator expected performance

In this section we discuss the expected scientific performance of the QUBIC TD. Our prototype will prove its spectral imaging power by observing the brightest regions of our Galaxy and reconstructing the spectrum of the dust emission in total intensity and polarization with a frequency resolution of ~ 4 GHz.

In our assessment we have simulated the observation of a circular 15 degrees-wide sky patch centered at $(\ell, b) = (0, 0)$ and containing interstellar dust emissions from the PySM d1 model that assumes a modified back body emission with pixel-dependent parameters (dust temperature and spectral index)⁸. We have simulated the input sky considering 15 equally-spaced frequencies in the 25% bandwidth around the 150 GHz central frequency. In the left panel of figure 10 we show a HEALPix map ($N_{\text{side}} = 256$) of the input sky convolved at the instrument angular resolution (width of the peaks in the synthesized beam), while in the right panel we plot the spectral energy distribution (SED) in the pixel marked in red on the map. The dots correspond to the five sub-frequencies reconstructed by QUBIC.

Simulation procedure. First we have calculated 100 realizations of the reconstructed maps of the observed sky patch using the fast simulation pipeline described in section 3.1 with $N_{\text{side}} = 256$ and degrading the pixel resolution to $N_{\text{side}} = 64$ for total intensity maps and $N_{\text{side}} = 8$ for polarization maps. Then, for each pixel we have computed the average $I(\nu_j)$, with its 68% confidence interval for each sub-band frequency ν_j . We calculated the

⁸See <https://pysm-public.readthedocs.io/en/latest/models.html>

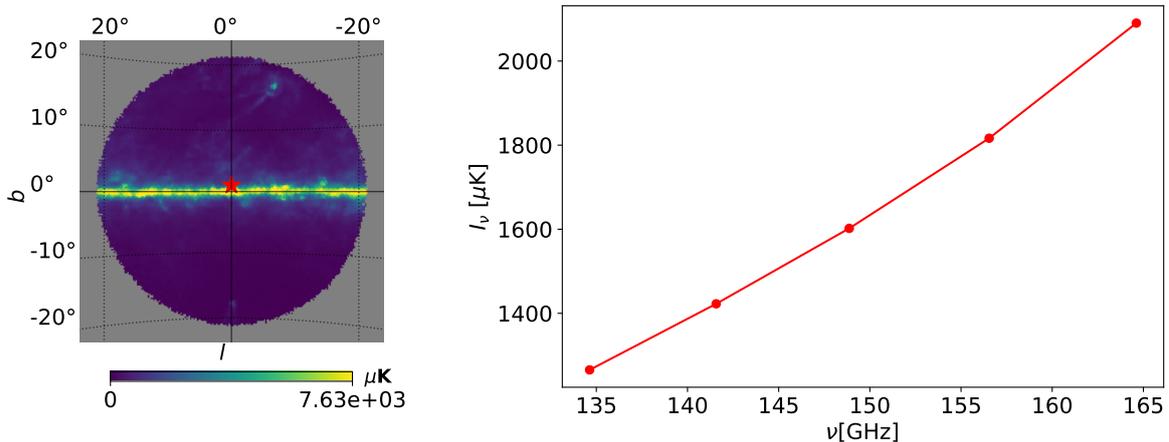


Figure 10. (left): HEALPix intensity map of the input sky convolved with the instrument beam ($N_{\text{side}} = 256$). The red cross represents a pixel for which we display the SED of emission in the right panel. (right): SED of the sky emission computed in the pixel shown in the left panel.

confidence interval by modelling the SED as a modified black-body:

$$I(\nu) = a \times B_{\nu}(T_{\text{dust}} = 19.6 \text{ K}) \times \left(\frac{\nu}{353 \text{ GHz}} \right)^{\beta}, \quad (3.3)$$

then we performed a Monte-Carlo-Markov-Chain exploration of the posterior likelihood of this model given our full band-band covariance matrix (see figure 6). This provides us with a chain of (a, β) parameters that sample the likelihood. From these samples, we then calculate the 68% confidence interval for the model at each frequency in the band, obtaining the light red areas represented in figures 11 and 12.

We verified that the shape of the confidence interval does not depend on the model we assumed for the MCMC exploration. Indeed, we obtain almost identical regions with a second order polynomial instead of the modified power law⁹.

In table 2 we list the main parameters used in our simulations.

Results. In figures 11 and 12 we show how we can reconstruct the SED of the dust emission in total Intensity and Polarization with one year of observations with the QUBIC TD in its 150 GHz band. More in detail, in the left column we show the SED reconstructed in particular pixels with its 68% confidence interval. In the center and right columns we show the input and reconstructed maps with the corresponding pixel highlighted with a red mark.

Our results show that with one year observations with the QUBIC TD it is possible to reconstruct the SED of the dust emission on angular scales of the order of ~ 1 degree and frequency resolution of ~ 4 GHz in total intensity. We can also detect the dust emission SED in polarization on larger scales (~ 7 degrees) close to the Galactic plane, where the signal intensity is larger.

⁹It is worth noting that the angular resolution of our reconstructed maps in each sub-band is not constant and improves with frequency [27]. As a result, fitting a modified power law without accounting for this change of resolution does not lead to a β parameter that can be compared with the usual β dust spectral index that needs to be corrected for varying angular resolution [61]. This is not a problem here as this analysis is just intended to show our ability to measure SED with spectro-imaging.

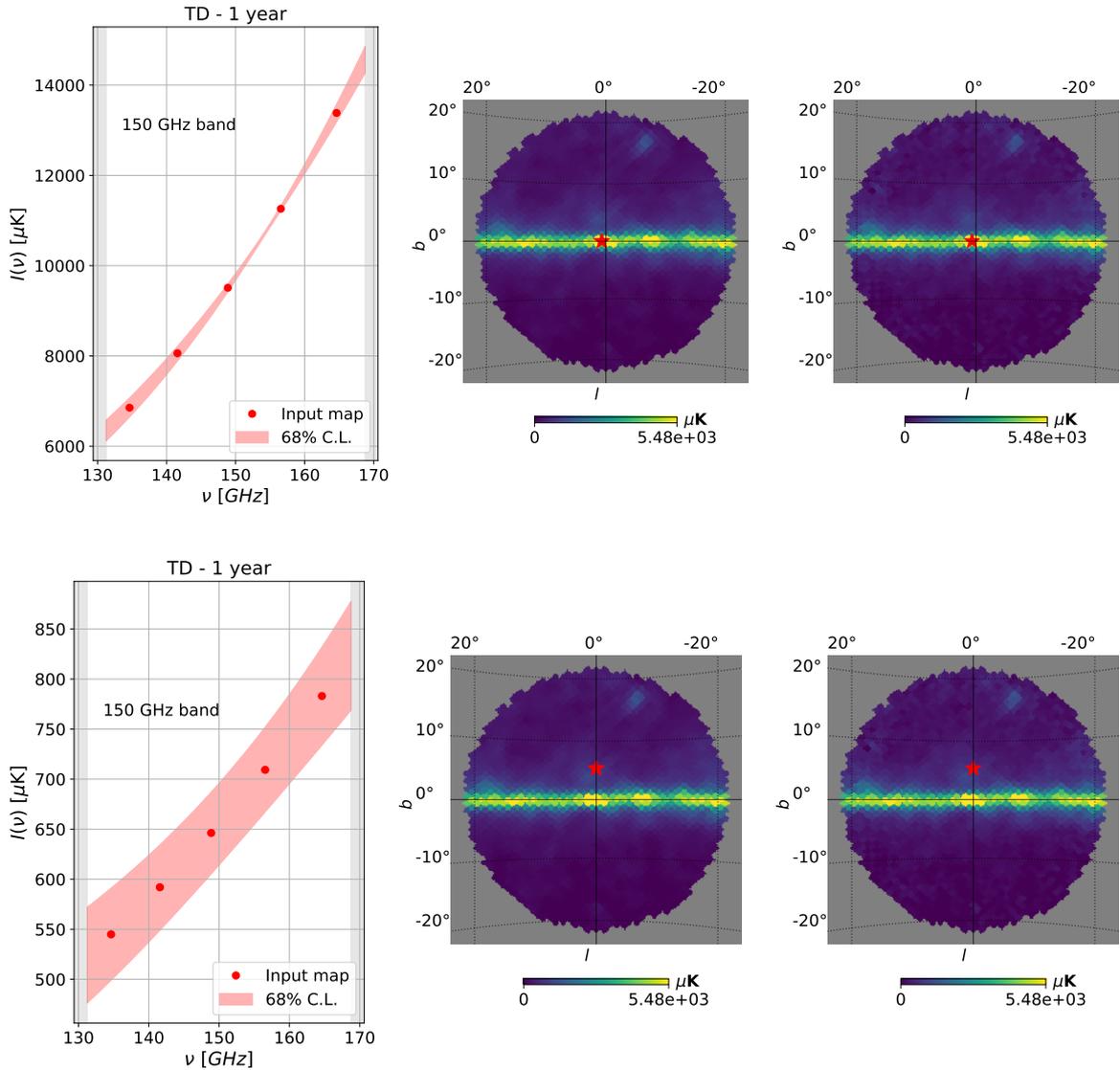


Figure 11. Reconstruction of the interstellar dust SED in total intensity with the QUBIC TD in the 150 GHz band. The two rows show the result in ~ 1 degree pixels ($N_{\text{side}} = 64$) at two different distances from the Galactic center. In the left column, we show the input values for the selected pixel (red circles) as well as the 68% C.L. region for the measured SED (see text). The middle column shows the input map while the right column shows the reconstructed map. The red marks indicate the pixels chosen for the SED computation. The maps are in Galactic coordinates, centered towards (0,0) with grid spacing in latitude and longitude 10 and 20 degrees respectively.

3.3.3 QUBIC Full Instrument expected performance

We now perform the same exercise as in the previous section, but with the expected sensitivity of the QUBIC FI and two focal planes (at 150 and 220 GHz). We explore our ability to constrain the dust SED independently in our two wide physical bands. The results in total intensity and polarization are shown in figure 13 for one year integration toward the Galactic center and three years integration on the QUBIC clean patch centered on (RA=0

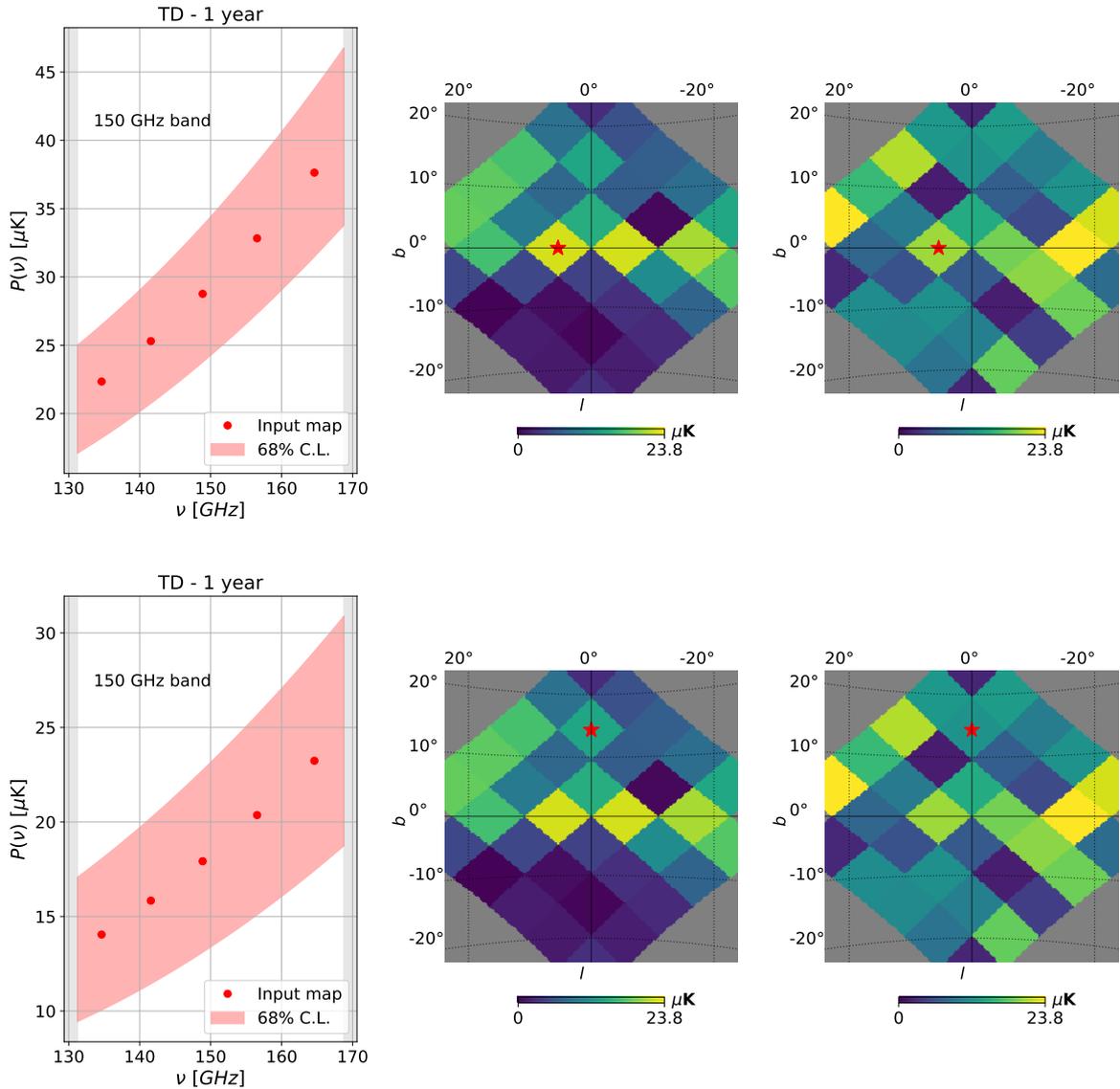


Figure 12. Reconstruction of the interstellar dust SED in polarization with the QUBIC TD in the 150 GHz band. The two rows show the result in ~ 7.3 degree pixels ($N_{\text{side}} = 8$) at two different distances from the Galactic center. In the left column, we show the input values for the selected pixel (red circles) as well as the 68% C.L. region for the measured SED (see text). The middle column shows the input map and the right column the reconstructed map. The red marks indicate the pixels chosen for the SED computation. The maps are in Galactic coordinates, centered towards (0,0) with grid spacing in latitude and longitude 10 and 20 degrees respectively.

and DEC=-57). These results show that with QUBIC FI and spectro-imaging we will be able to measure in detail the dust SED in our two bands independently, for both total intensity and polarization, not only near the galactic plane, but in the B-mode search patch itself, allowing us to control in a unique way dust contamination in our primordial B-mode search. Such an approach will allow for more robust constraints of the actual shape of the dust SED, including possible variations within a single wide-band of the dust spectral index without

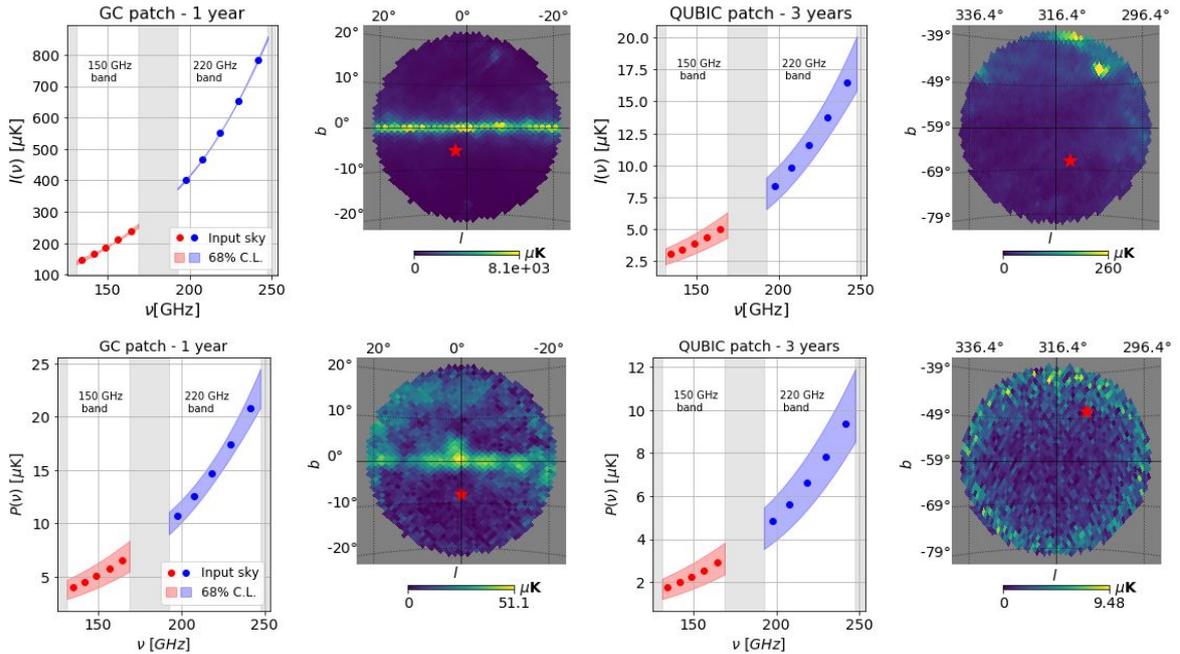


Figure 13. Results of our forecasts on the SED measurement with the QUBIC FI using spectro-imaging with five sub-bands performed independently in both of our wide physical bands (150 and 220 GHz in red and blue respectively). The grey regions corresponds to the unobserved frequencies outside our physical bands. The top row corresponds to total intensity while the bottom one to polarization (with the same fitting model as in equation 3.3). Observations with one year centered on the Galactic center are shown on the left column while the right column shows results in the QUBIC patch $[0, -57 \text{ deg}]$ (Galactic Coordinates) with three years integration. The red points in the SED are the input convolved to our resolution while the 68% C.L. regions for our forecasted measurements are shown in light colors. In each case, the corresponding pixel in the reconstructed maps is shown as a red mark. We have used $N_{\text{side}} = 64$ corresponding to ~ 1 degree pixels. The maps have a grid spacing in latitude and longitude equal to 10 and 20 degrees respectively.

relying on extrapolations between distant frequencies.

3.3.4 Ability to recognize the presence of dust residuals with spectro-imaging

In this section, we assume that the component separation has already been done and we show that spectro-imaging gives the ability to detect the presence of dust residuals at the tensor-to-scalar likelihood level. Here, we have considered the FI after 3 years of observation in the 220 GHz wide band split into 2 sub-bands.

Using the library PySM3 [62], we simulate 2 sub-band maps containing dust residuals made with a 0.7 % fraction of a dust map (d1 PySM model) added to a pure CMB sky with $r = 0$. From those 2 maps, we compute the 3 BB Inter-Band Cross Spectra (IBCS) at effective frequencies $\nu_{\text{eff}} = \sqrt{\nu_1 \nu_2}$ where ν_1 and ν_2 are the central frequencies of the 2 sub-bands. Then, we perform a likelihood to estimate the tensor to scalar ratio r assuming a pure CMB model (no component separation). The error included in the likelihood estimation is the full multipole-space covariance matrix between the 3 BB IBCS and the bins in l of the spectra obtained with Monte-Carlo simulations. As the sky also contains dust residuals, the likelihood is biased leading to a detection of non-zero tensor-modes which we called r_{dust} .

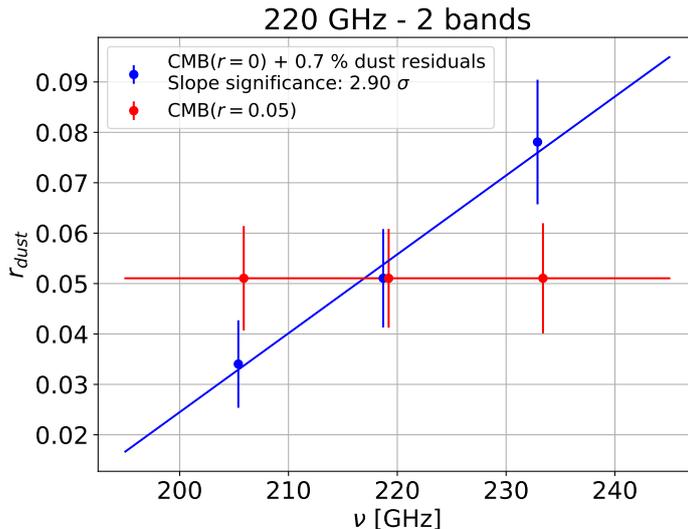


Figure 14. Constraints on the tensor-to-scalar ratio r , from a Likelihood analysis, for a sky containing CMB and dust residuals. We consider the 220 GHz wide band split into two sub-bands. This leads to three Inter-Band Cross Spectra (IBCS) at effective frequencies $\nu_{\text{eff}} = \sqrt{\nu_i \nu_j}$ where ν_i and ν_j are the central frequencies of the two sub-bands. We can distinguish between a pure CMB sky with $r = 0.05$ and a sky with CMB ($r = 0$) but having 0.7 % dust residuals. In the first case (red), the measurement of r_{dust} is constant with the frequency while the presence of dust leads to a slope (blue) which we detect at the 2.9σ level. In that case, the likelihood estimation was performed on each IBCS separately using the full multipole-space covariance matrix (in contrast with Fig. 8 where we have only used the diagonal in order to remain conservative).

Instead of having a global estimation of r_{dust} over all IBCSs, we can compute a likelihood for each IBCS separately. This gives an estimate of r_{dust} for each effective frequency. As the dust emits like a modified black body spectrum, increasing with frequency, the r_{dust} estimate increases with frequency. On the contrary, for pure primordial B-modes, the estimated tensor-to-scalar ratio does not depend on frequency. Measuring the evolution of the estimated r_{dust} as a function of frequency within the band using spectro-imaging is therefore a powerful tool to estimate our dust contamination independently of any dust modeling. In Fig. 14, we show an example where we are able to distinguish the case of pure primordial tensor modes with $r = 0.05$ from a sky with no primordial tensor-modes ($r = 0$) but 0.7 % dust residuals. Indeed, in the first case, the measurement of r_{dust} is constant with the frequency while the presence of dust leads to a slope that is detected at the 2.9σ level.

4 Conclusions

In this article, first of a series of eight, we have given an overview of the QUBIC instrument. QUBIC is the first CMB polarimeter using a new technology called “Bolometric Interferometry” that combines the background limited sensitivity of bolometric detectors (transition edge sensors) with the clean measurement of interference fringes. QUBIC has been designed to observe the large-scale B-modes of the CMB to detect the elusive tensor perturbations (primordial gravitational waves) created during inflation. A first version of the instrument, with reduced number of horns (64) and detectors (248) operating at 150 GHz, the QUBIC Technological Demonstrator (TD), will be deployed in 2021 and is intended to demonstrate

on-sky the capabilities of Bolometric Interferometry. The TD will subsequently be upgraded to the Full Instrument (FI) with the nominal 400 horn array and 992 detectors in each of the two focal planes operating at 150 and 220 GHz.

We have described the general design of QUBIC and have shown that it can be considered as a classical imager that would scan the sky with a beam composed of multiple peaks. These are separated by an angular distance given by the distance between two apertures in the interferometer horn array (in wavelength units), while the resolution of the peaks is given by the maximum size of the interferometer horn array (in wavelength units). We have emphasized two main features of QUBIC. First, the possibility of performing self-calibration [42], similarly as in a classical interferometer, allows us to control finely instrumental systematic effects. Second, a bolometric interferometer has simultaneous spatial and spectral sensitivity, thanks to the spectral dependence of the synthesized beam within the physical band of the instrument. This is what allows us to carry out spectro-imaging [27].

We have used an extensive set of simulations to make forecasts of the QUBIC performance for both the primordial B-mode search and for foreground mitigation using spectro-imaging. These forecasts assume the detector noise measured during the QUBIC calibration campaign [28] and a stable atmosphere corresponding to the QUBIC site in Argentina at 5000 m a.s.l. These simulations show that the QUBIC TD will be able to demonstrate spectro-imaging with one year of observations of a field centered on the Galactic center. The QUBIC TD will measure the SED of bright regions in both intensity and polarization. After the upgrade to the FI, QUBIC will reach its nominal configuration allowing us to reach a sensitivity to B-modes corresponding to a 68% C.L. upper-limit on the effective tensor-to-scalar ratio (primordial tensors + dust) $\sigma(r) = 0.015$ with three years of observations. Assuming we use the 220 GHz, as well as data from other surveys such as the Planck 353 GHz polarized channel, to constrain foregrounds, our sensitivity on the primordial tensors can be estimated from that of the 150 GHz alone without foregrounds and corresponds to $\sigma(r) = 0.021$. We have also shown how QUBIC FI will be able to put constraints on the dust contamination through direct measurement of the dust SED and properties in the reconstructed maps at multiple sub-frequencies within a physical band, or through a study of the evolution of the recovered tensor-to-scalar ratio in sub-bands as a function of frequency.

Future studies will explore in detail how spectro-imaging can lead to improved component separation using classical techniques as well as techniques specific to bolometric interferometry.

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