QUEST — A 2.6–m mm–wave telescope for CMB polarization studies

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Abstract. We describe QUEST (**Q** and **U** **E**xtra–galactic **S**ub–mm **T**elescope), a CMB polarimeter, operating at millimetre wavelengths. Interesting features of its design are outlined.

INTRODUCTION

Studies of the Cosmic Microwave Background (CMB) have demonstrated their worth in improving our understanding of the early Universe. Measurements of its black–body spectrum and spatial variation of its temperature have helped to constrain cosmologies to an ever–tightening parameter space.

Since the COBE DMR detection of CMB anisotropy [7] and the direct observation of individual structures (for example Hancock et al. [3]), sensitivities have improved to the extent that the first peak of the CMB spatial frequency (C_ℓ) spectrum may be identified with confidence, and there is increasingly strong evidence for second and third peaks (see for example results from DASI [2], MAXIMA–1 [4] and BOOMERANG [5]). The spectrum will be even better determined by forthcoming measurements from new balloon experiments and satellite missions such as *MAP* [1] and *Planck* [8].

With the anticipated improvement of data quality from new and revised ground–based, balloon and satellite experiments we expect better to determine values such as the total energy density and curvature of the Universe. However, despite improved statistics, degeneracy in parameter determination based on temperature anisotropy data will continue to be a problem. But by measuring the third characteristic of the CMB radiation field, its polarization, this problem may be addressed.

THE INSTRUMENT

The following paragraphs describe QUEST as it is currently being designed and built at institutions in Cardiff and California.

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FIGURE 1. QUEST Mechanical Layout. A cryostat holding re–imaging optics, the wave plate and the focal plane assembly is mounted behind the primary mirror. This assembly may rotate about the '$\mathcal{Z}$' axis. This in turn is mounted on an az. / el. platform.

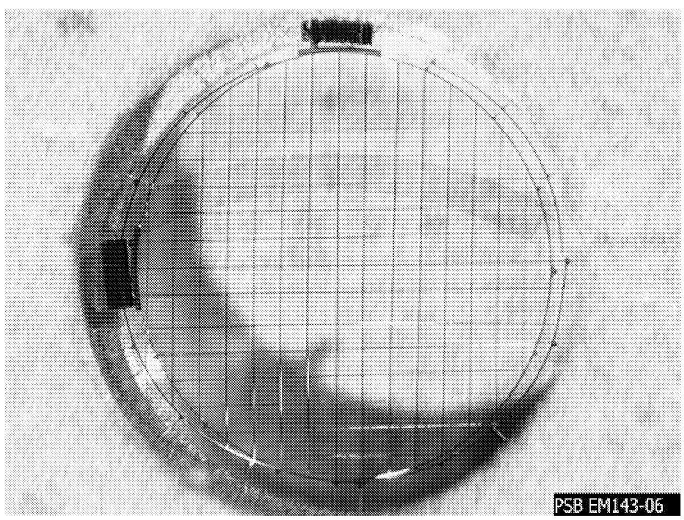

FIGURE 2. Polarization–Sensitive Bolometer

Optical Layout

An entirely on–axis optical design has been chosen. Millimetric radiation falling on the primary mirror is reflected onto a secondary mirror and thence to a Cassegrain focus. Lens elements are used to form a $1^\circ\!.5$ image at the focal plane, with a resolution of $5'$.

A disadvantage of the classical Cassegrainian layout is the blockage caused at the centre of the primary by the secondary mirror. This 'hole' in the field distribution will result in an increased side lobe level aside the primary beam. However, removing this blockage by adopting an off–axis layout has its own problems; such a system has an in–built

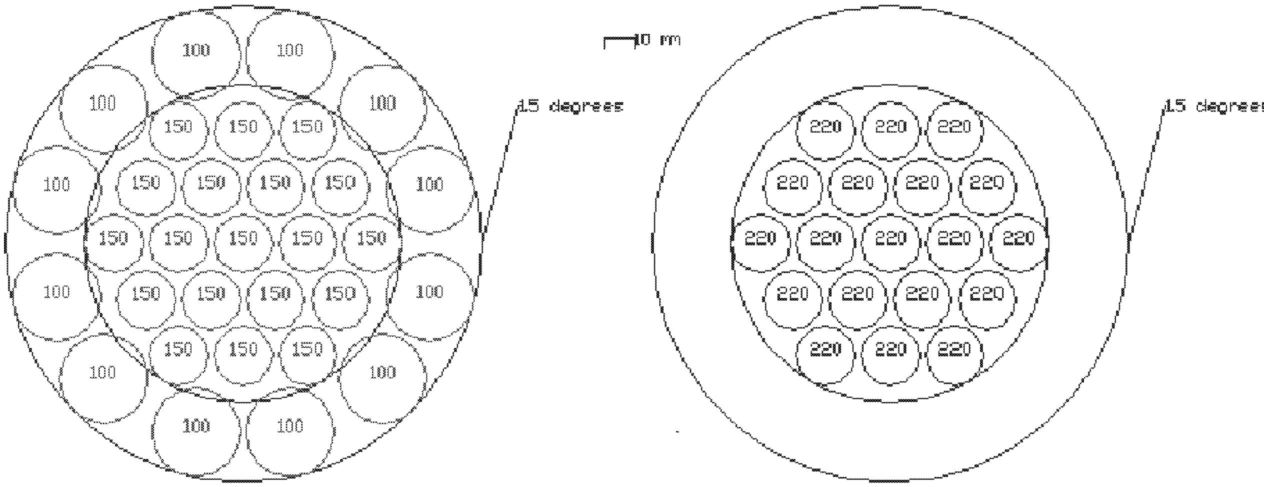

FIGURE 3. QUEST Focal Plane

standing offset in polarization due to the loss of circular symmetry in the geometry of the reflecting surfaces.

We avoid problems of blockage and reflection from mirror supports by suspending the secondary above the primary on a cone formed of expanded polystyrene foam. This absorbs very little mm–wave radiation (attenuation less than 1 per cent), so the degradation of system noise temperature is not significant. A similar arrangement is in use on COMPASS [6] at Ka band, for which the contribution of a few Kelvin has been measured.

Wave Plate

Immediately ahead of the focal plane is a half wave plate. This rotates incoming linear–polarized radiation. For each rotation of the wave plate the plane of polarization is rotated twice; so the signals at the polarization–sensitive detector outputs are modulated at four times the rotation rate. This modulation will be used to permit instrumental offsets to be distinguished from sky signals.

Currently we are studying the feasibility of building a cooled wave plate mechanism. In case the difficulties inherent in such a device prove insurmountable, we retain the option with our cryostat design to have the wave plate at ambient temperature. Also the re–imaging lenses may or may not be cooled.

Mechanical Structures

The mirror structure is mounted on a typical elevation above azimuth mount; but in addition, we add a third rotation about the '$\mathcal{Z}$' or 'field' axis of the antenna — see Figure 1. This will introduce another means of modulating the polarization of signals falling on the detectors, to better distinguish instrumental from sky signals. Also, it allows greater flexibility in our scanning strategy.

Wavelengths

QUEST will be a ground–based telescope. Therefore the wavelengths used for observation must be chosen to fall within the windows of low atmospheric absorption. These are at 100 GHz and 150 GHz, with an option for future upgrade to add detectors for the 220–GHz window. Band–pass filters will define a fractional band–width of approximately 20 per cent.

Detectors

Rather than using polarizers and separate detectors for each polarization, QUEST will employ *polarization sensitive bolometers* (PSBs) — see Figure 2. These comprise two thermometers in a single module, each with its own absorbing mesh, perpendicular to the other. The two outputs correspond to orthogonal linear polarizations. Since both detectors share a single module, coupled to the telescope optics through the same feed horn, they look at the same sky pixel through a common column of atmosphere. Therefore after differencing the two outputs to measure the level of polarization, there is less sensitivity to sky conditions than with a beam–switching temperature anisotropy experiment.

The arrangement of detectors in the focal plane is shown in Figure 3. Our primary science band is 150 GHz, so the nineteen detectors for this frequency are grouped in the central region where the spurious instrumental polarization signals are lowest. The twelve 100–GHz detectors are placed in a ring around the outside edge of the focal plane. The field of view is 1°.5. A second focal plane consisting of a further nineteen PSBs at 220 GHz may be added as a future upgrade.

SURVEY DESIGN AND EXPECTED SCIENCE RESULTS

We have optimised the design of the QUEST survey to (i) detect EE and ET modes, and (ii) measure in detail the polarization power spectra C_ℓ^{EE} and C_ℓ^{ET}. The first of these aims, the detection of polarization, suggests the strategy of integrating over a small patch of sky, a few degrees, until polarization is detected. This will be easiest in the ET cross-polarization, combining the QUEST data with the MAP temperature field, but a similar strategy will provide a first early detection of EE modes. To satisfy the second requirement, the survey area is increased to a few hundred square degrees. Figures 4 and 5 show the expected signal and noise properties of the EE, ET and BB spectra. The B-modes are not expected to be detected from this type of survey, although interesting limits may be set. In addition to a detection and measurement of the E-mode polarization power spectra, the signal/noise ratio per pixel will allow us to make maps of the polarized sky, which will help point source extraction.

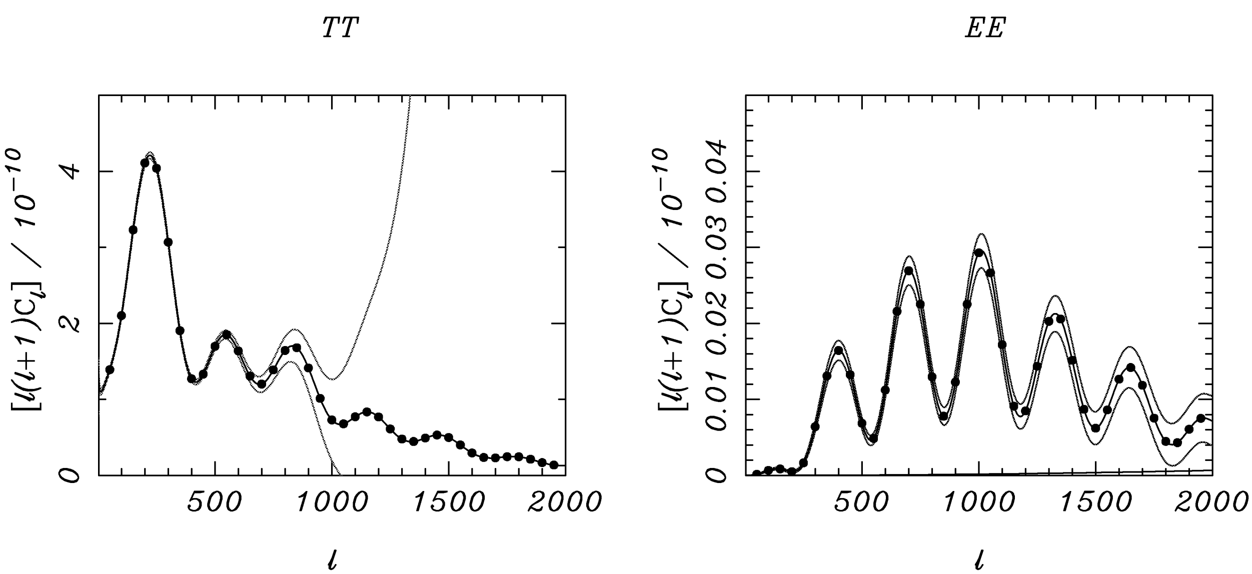

FIGURE 4. *LHS: TT power spectrum expected from MAP with expected measurement errors. RHS: Expected EE polarization power spectra and uncertainties from QUEST, for a survey with 5' pixels, covering an area of* 300 *sq. deg. and sensitivity of* $\sigma = 3.2\mu K$ *per pixel.*

Measurement of the EE polarization power provides new information on the epoch of reionization, and helps break the degeneracy between the magnitude of the mass power spectrum and the optical depth to ionization. In addition the peak oscillations of the polarization spectra provide additional information on the baryon abundance and Hubble parameter. While these are the major improvements on measurements of the temperature field, they help break a

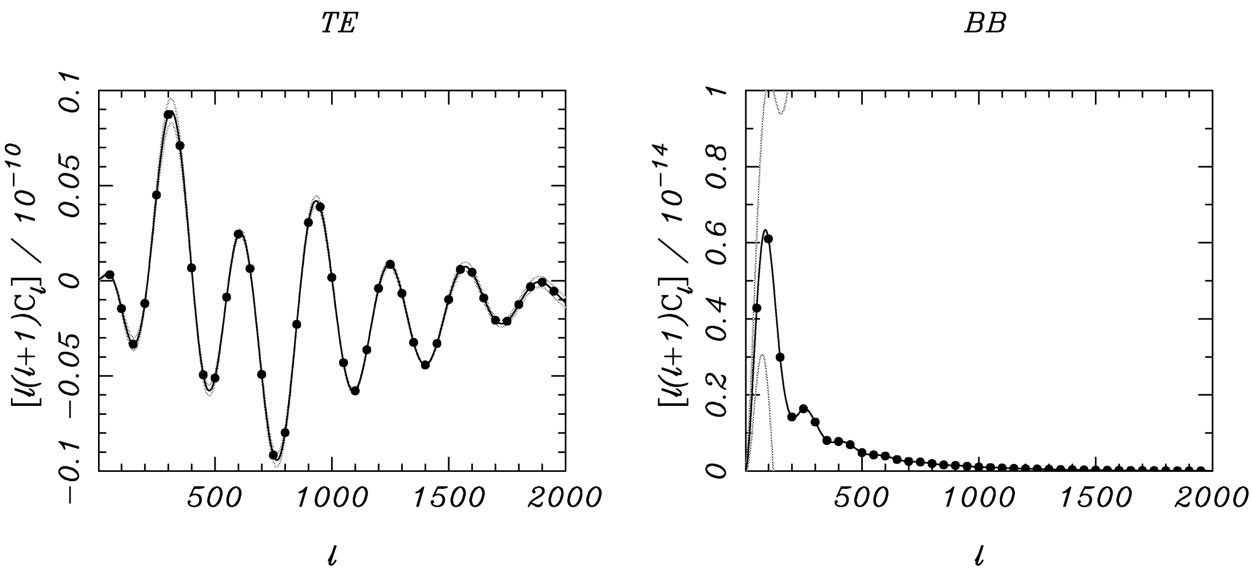

FIGURE 5. *LHS: ET power spectrum expected from cross correlating with MAP. RHS: BB power spectrum, for a survey with 1' pixels, covering an area of* 300 *sq. deg. This would suggest that B-type polarization would be only marginally detectable, but interesting limits may be set.*

number of major degeneracies in the parameter estimation, substantially reducing the uncertainties on parameter estimation as a whole. For example we expect a factor 5 improvement in the estimation of the combination $\Omega_B h^2$.

As well as parameter estimation, measurement of the polarization signature in the CMB will also allow us to test the paradigm of adiabatic perturbations, and probe the epoch of reionization in detail. The latter should allow us to investigate such questions as when reionization occurred and whether the reionization was homogeneous or inhomogeneous.

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