Imaging the Cosmic Microwave Background: The BEAST Experiment

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Abstract. We describe the Santa Barbara BEAST experiment, a balloon borne telescope to image the Cosmic Microwave Background (CMB) radiation anisotropy pattern. Some aspects of the map making pipeline are also discussed.

INTRODUCTION

The field of cosmology is rapidly approaching a new era of experimental data abundance. In particular, observations of the anisotropy pattern of the CMB promise to constrain cosmological parameters arising in the context of inflationary models at unprecedented levels [1].

We describe here the Background Anisotropy Emission Scanning Telescope. BEAST, based on the HACME experience [3], has been designed to perform long duration ballooning (LDB) flights around the Arctic or Antarctic polar caps gathering $\sim 8-15$ days of data over a sky region $\approx 5000°$. BEAST has qualified for LDB integration and performed a successful test flight from North America which lasted about 8 hours. Analysis of data from this flight is currently in progress.

BEAST operates in the frequency range $30-100$ GHz. It features cryo-cooled (12 K) InP HEMT radiometers fed by corrugated conic horns. The K_a band (30 GHz) and Q band (42 GHz) receivers operate in total power mode. These receivers have been flown during the test flight and performed well. W band (100 GHz) radiometers are currently being implemented in view of LDB flights. They will operate as correlation receivers rather than in total power mode to limit the contribution from low frequency ($1/f$) drifts in the noise.

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There are striking similarities between BEAST and the Low Frequency Instrument (LFI) onboard the PLANCK satellite. In particular, the W band radiometers are actual LFI prototypes. The BEAST experience will turn out extremely useful to the purpose of optimizing LFI's performances.

I OPTICAL SYSTEM AND SCANNING STRATEGY

BEAST carries on board an off-axis Gregorian featuring a 2.2 m parabolic primary, the largest mirror ever flown on a CMB mission. Made of carbon fiber, it weights less than 9 Kg and is diffraction limited to about 500 GHz so the use of bolometric detectors is a viable option for BEAST. The elliptical secondary, also made of carbon fiber, weights 2 Kg and has a major axis of 0.8 m. Both mirrors are coated with 2.2 μm of Al and over-coated with $\mathrm{SiO_x}$ for protection. Their surface rms deviation from ideal is just 20 μm. The use of off-axis optics is advantageous because it prevents the secondary and the detector array form blocking the collecting area of the primary, resulting in better illumination and, more importantly, excellent sidelobe rejection (> 60 dB for angles $> 20°$ from boresight). A baffle made of low emissivity aluminized mylar, prevents radiation from Earth from being collected by the mirrors. A third flat mirror is part of the telescope. It is slightly canted (typically 2.5°) with respect to its axis, so the normal direction to the surface is a function of its phase. As the mirror spins (@ 5 Hz) the beam profile describes a closed path on the sky which is, to good approximation, an ellipse of major axis 10° degrees wide (for a 2.5° canting). This curve is sampled 250 times per rotation, giving a total sky sampling rate of 1.25 KHz.

Apart from the spinning flat, two other movements contribute to BEAST's scanning strategy. The inner frame of the gondola performs an azimuthal scan (throw) of amplitude in the range zero to 60°. This second movement is slow enough (few tenths of seconds to several minutes depending on the throw angle) to be considered separate from the spinning flat. The last movement contributing to the scan strategy is sky rotation.

The complexity of the scan strategy described above makes BEAST extremely flexible in determining the extent of the area to survey for a given total mission time. Furthermore, and more importantly, very complex and well connected scan patterns are obtained. Having multiple scan paths going through a given pixel at different times is a critical issue in order to ensure proper treatment of the map from artifacts induced by $1/f$ contamination.

II MAP MAKING

Map making is an important part of the data analysis pipeline of a CMB experiment because it allows for a radical compression of the data set under very limited assumptions [4]. It also very helpful when simulating an experiment as it allows to check systematics, to optimize the focal plane design and the scanning strategy.

Map making techniques for a one-horned experiment (like BEAST) are well known. The most powerful rely on a generalized least square (GLS) approach [5]. The idea is to define map making as the problem of estimating some parameters (sky pixel values) out of a large set of sky observations. The pixels can be ordered into a vector $\mathbf{m}$ which we shall call a map. The observations can be hold in a vector $\mathbf{d}$. One assumes that $\mathbf{d}$ depends linearly on the sky through a known pointing matrix P:

$$\mathbf{d} = P\mathbf{m} + \mathbf{n}, \tag{1}$$

where $\mathbf{n}$ is a vector of random noise. The structure of P is, for an experiment like BEAST, very simple: every row has only one non zero element (with a value of 1), corresponding to the pixel observed in a given scan, i.e. $P_{ij} = \delta_{\mathbf{p}_i,j}$ where $\mathbf{p}$ is the temporal succession of observed pixels. The GLS method finds the best map minimizing the quantity

$$\chi^2 = \mathbf{n}^t N^{-1}\mathbf{n} = (\mathbf{d}^t - \mathbf{m}^t P^t)N^{-1}(\mathbf{d} - P\mathbf{m})$$

with respect to $\mathbf{m}$. This yields the (linear) estimator:

$$\tilde{\mathbf{m}} = (P^t N^{-1} P)^{-1} P^t N^{-1}\mathbf{d}. \tag{2}$$

Here $N^{-1}(\equiv \langle \mathbf{n}\mathbf{n}^t\rangle^{-1})$ is the noise inverse covariance matrix which has to be estimated from the data. For BEAST this is not a problem since, given the high sampling rate, the time ordered data are noise dominated (the signal does emerge through multiple observation of the same pixel, of course). An important point is that N^{-1} is non diagonal, due to $1/f$ contribution of the noise. This, and the large number of pixels involved (in the range 10^4 to 10^5 for BEAST) makes the inversion of system (2) computationally challenging. The details will be described elsewhere [2].

As an example of how map making helps the simulation pipeline we simulated a BEAST observation of two different sky regions consisting of the same total area ($\sim$ 400 square degrees) but different scan parameters, so that the regions have different shapes. The first (second), displayed in the right (left) upper panel of figure 1 had a throw angle of 10° (7°) and a flat canting angle of 1.25° (2.5°). We simulated an 8 hours observation time for both regions for a single Q band horn with sensitivity of 250 $\mu\mathrm{K}\sqrt{\mathrm{s}}$ in the white noise limit. The upper panels in figure 1 give the pixel sensitivity obtained when simulating a time stream contaminated by pure white noise (i.e., N^{-1} is diagonal). It turns out that the spread of sensitivity is very similar for the two regions, which is not surprising since the pixels are, in this case, uncorrelated. The lower panels give the sensitivity obtained when we include a $1/f$ contribution (f_{knee} = 50 Hz) to detector noise, leaving the white noise sensitivity unchanged. This sensitivity is obtained via the map's (pixel-pixel) covariance matrix, which is non diagonal due to the presence of $1/f$ noise in the time stream (a fact that makes N^{-1} non diagonal). This matrix is obtained when solving

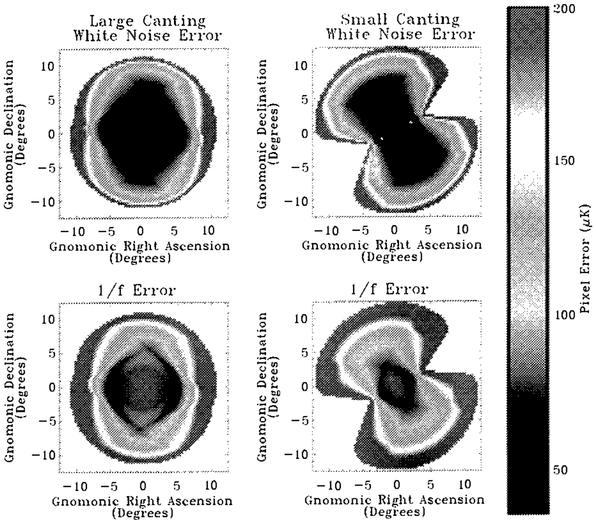

FIGURE 1. Upper panels: error estimates for white noise (radiometer sensitivity of 250 $\mu K \sqrt{s}$) for the regions described in the text. Lower panels: Actual errors, including $1/f$ contribution ($f_{\rm knee} = 50$ Hz), calculated from the maps' covariance matrix. Maps are displayed with a maximum value of 200 μK.

the map making problem (it is indeed the matrix which is inverted in equation 2). An histogram plot confirms that, in this case, a more favorable distribution of sensitivity is attained for the region displayed on the left. This is because the latter region is scanned with a larger canting angle, a thing that gives a richer pixel reconnection scheme and, thus, a lower variance estimator.

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REFERENCES

1. Balbi, A., contribution to these conference proceedings.
2. Natoli, P. *et al.*, in preparation (2000)
3. Staren, J. *et al.*, *Ap. J.* **539**, 52 (2000) (astro-ph/9912212)
4. Tegmark, M., *Ap. J.*, **480**, L87 (1997) (astro-ph/9611130)
5. Wright, E., preprint astro-ph/9612006 (1996)