Characterization of the BEAST Optics at Millimeter Wavelengths

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Abstract

The Background Emission Anisotropy Scanning Telescope (BEAST) is observing the sky from the 3.8 km altitude University of California White Mountain Research Station since late July 2001. The aim of the experiment is to map the sky at 30 and 40 GHz and to reconstruct the anisotropy power spectrum of the Cosmic Background Radiation at these frequencies.

The telescope consists of a 2.2 meter off–axis Gregorian telescope fed by a cryogenic focal plane unit, currently consisting of 6 Q band and 2 Ka band corrugated feed horns coupled to cryogenic HEMT amplifiers.

A 2.5 meter diameter spinning flat mirror, tilted from its rotation axis and located in front of the primary mirror, provides a modulation of the signal coming from the sky.

In this paper we present the characterization of the BEAST telescope in terms of optical performance. Physical Optics calculations have been performed for each detector assembly. We report the calculation results and we discuss the optical parameters which are strictly related to the scientific performances of the experiment.

Keywords: Cosmology, mm–wave telescopes

1. INTRODUCTION

Firstly detected by the NASA COsmic Background Explorer (COBE) satellite [1][2], the Cosmic Microwave Background (CMB) anisotropies contain the cosmological information of our universe, such as the age, the constituents (baryonic density, dark matter density, dark energy), the expansion rate (the Hubble constant) and other parameters which describe the history and physics of the universe itself. Recently, the satellite WMAP measured the anisotropies over the whole sky with high sensitivity [3] and together with balloon–borne and ground–based experiments in the last fifteen years (see [4] for a review of the pre–WMAP experiments) moved the cosmology science toward the so called "Precision Cosmology" for which the CMB science is a unique tool for the recovery of the physics of the early stage of the universe. For this reason ESA planned a space mission, Planck, dedicated to the measurements of the CMB anisotropies and polarization with unprecedented angular resolution and sensitivity. Planck will be launched in 2007.

The anisotropies of the CMB appear as spatially dependent small intensity fluctuations – at the level of $30\div100$ μK – of the primordial 2.728 Kelvin blackbody radiation [5]. The main cosmological content is embedded in the small scale (in the sub–degree range) anisotropies or equivalently at high multipole range of the anisotropy power spectrum (see [6] for a complete overview of CMB science). The optimal frequency range for observations is approximately between 30 GHz and 300 GHz, being the 60 – 100 GHz the range at which the foregrounds (synchrotron, dust, and free–free emissions, extragalactic unresolved sources) are at minimum level simultaneously. As a consequence, the optimal way to perform CMB measurements is to measure the sky at millimeter wavelength by using reflector antennas coupled with radiometric and/or bolometric cryogenically cooled detectors.

The Background Emission Anisotropy Scanning Telescope (BEAST) is a microwave telescope dedicated to the measurements of the CMB anisotropies. BEAST is an high sensitive experiment that permits to map the sky at 30 GHz and 41.5 GHz with an angular resolution between 20 and 30 arcmin. BEAST has been installed in January 2001 at the University of California White Mountain Research Station at 3.8 Km of altitude. In early August 2001 BEAST started the observations of the sky [7].

In this paper a description of the BEAST experiment is reported. Specifically, the characterisation of the optics is investigated in detail.

2. INSTRUMENT DESCRIPTION

BEAST is composed by an array of cryogenically cooled HEMT based receivers coupled to an off–axis Gregorian telescope by a set of eight corrugated horns. Each detector sees the sky through the telescope in different region simultaneously, so that the entire field of view of the telescope is filled by eight independent beams. A spinning flat mirror dish is located in front of the primary mirror and provides the modulation of the signal coming from the sky, being the rotation axis tilted at 2.2 degree from the perpendicular (see Fig. 1). As the flat mirror rotates, each beam observes the sky along an elliptical path about 9 degree wide.

The BEAST focal plane unit is composed by 2 Ka–band and 6 Q–band detector radiometer chain assemblies. Each assembly is constituted by one corrugated feed horn, a front–end module in which the Low Noise Amplifiers (LNAs) are cooled, the back–end module at ambient temperature, which provide additional signal amplification and signal filtering and detection. The front–end and the back–end sections are connected through a set of coaxial cables which decouple thermically the cold and the warm parts. The signal of one of the Q–band channel is divided into two orthogonal linear polarizations by an Orthomode Transducer (OMT), immediately after the horn, in order to extract the polarization information and to perform a cross–check of the systematic errors.

During the 2001/2002 observational campaign the BEAST focal plane worked in a configuration composed by 2 Ka–band radiometers and 4 Q–band radiometers, two of which connected to a single horn. The array of feeds and LNAs are housed in a dewar and cooled at 15 Kelvin. A window of about 180mm in diameter is located in front of the horns and is made of polypropylene foam. Between the horns and the window, an IR filter has been mounted in order to limiting the infrared radiation could enter through the window directly to the horns (see Fig. 2).

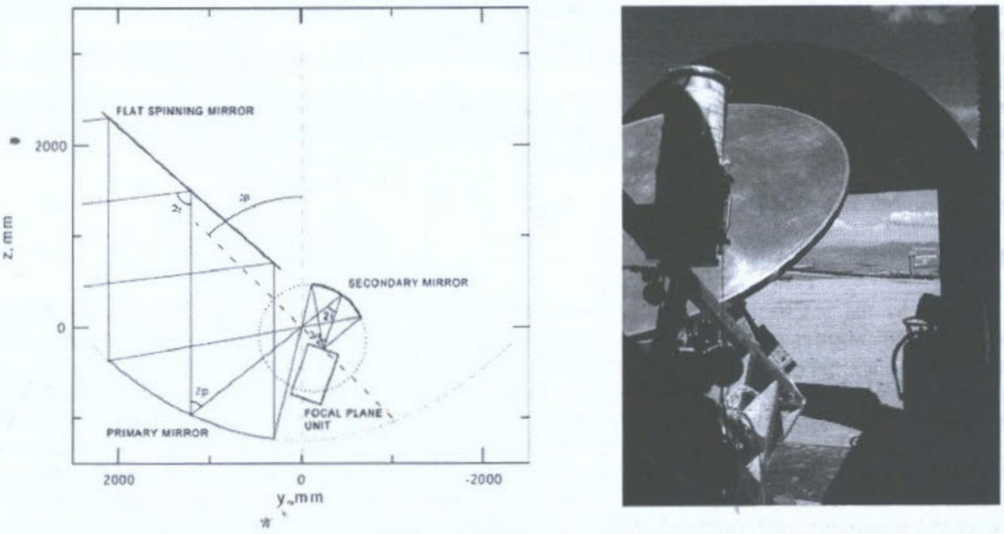

Fig.1 The BEAST three mirror optical layout (left). The experiment installed at White Mountain (right)

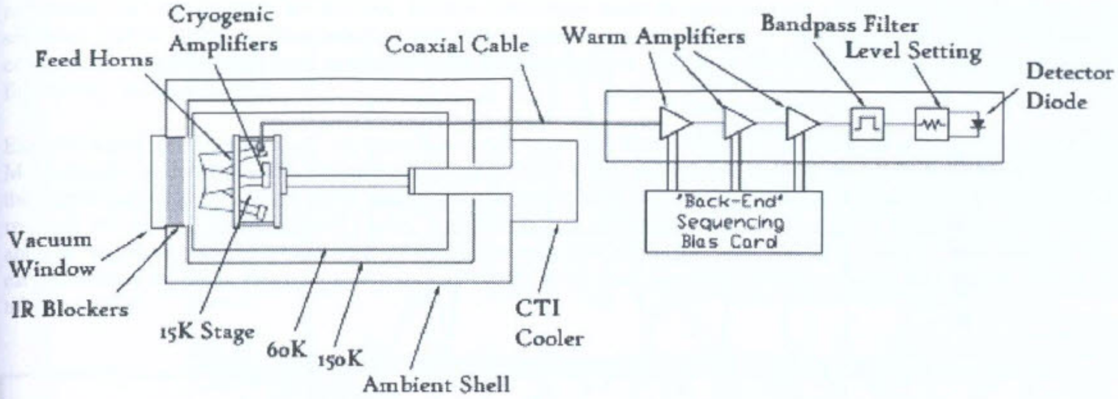

Fig. 2. The schematic view of the focal plane unit and detection unit

Corrugated horns have been employed because of the superior performances with respect to other designs in terms of return loss, beam symmetry, side lobe levels over a large bandwidth. Specifically designed for BEAST [8], the feeds were manufactured in aluminium using a direct numerical controlled lathe machine. The corrugation dimensions were chosen in order to have the best compromise between the machinability and the electromagnetic performances. Table 1 reports the main characteristics of the feed designs.

Table 1. BEAST feed horns main characteristics

	Ka–Band	Q–Band
Frequency (GHz)	25 ÷ 35	38 ÷ 45
Aperture Diameter (mm)	37.71	27.16
Waveguide Diameter (mm)	12.66	9.04
Flare Angle (degree)	7°	7°
Flare Length	102.77	74.34
Slot Width (mm)	2	1.45
Ridge Width (mm)	1	0.72
Number of Corrugation	34	34
FWHM (degree)	20	20
Return Loss (dB)	-30	-30

No particular profile has been selected for the corrugations. Linear profiled horns guarantee a good illumination of the telescope necessary for the overall performances of the instrument. In Fig. 3, the simulations of the return loss has been reported as calculated using mode matching algorithms. Fig. 4 shows the measured pattern of the Ka–band horn.

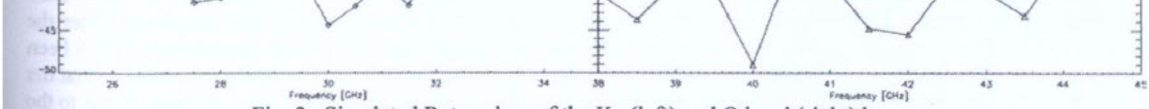

Fig. 3. Simulated Return loss of the Ka (left) and Q band (right) horns

In order to suppress the sidelobes, a pair of quarter–wavelength chokes has been machined in the aperture plane. The effect is evident in the E –plane at the first lobe level (see Fig. 4).

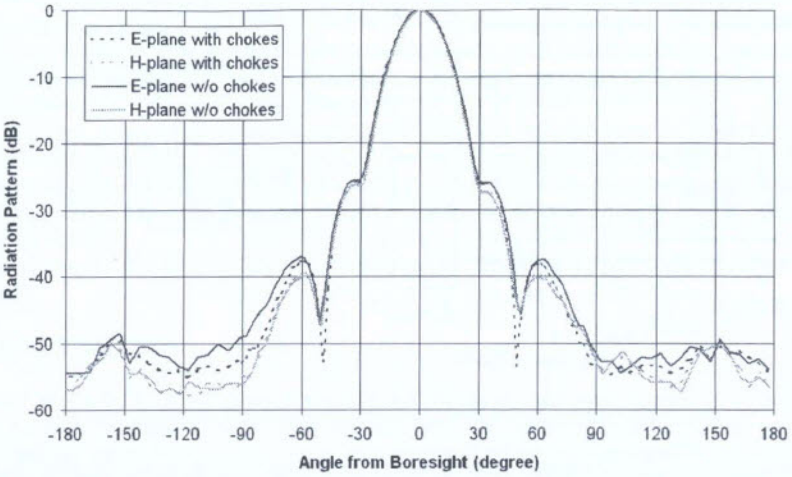

Fig. 4. Measured radiation pattern at 28GHz for the Ka–band horn. Black solid (dashed) line: E–plane without (with) chokes. Grey solid (dashed) line: H–plane without (chokes).

3. THE BEAST TELESCOPE

The optical scheme of the telescope is based on a Gregorian off–axis system which offers the advantage of an unblocked aperture [9]. The primary and secondary reflectors are an off–axis section of a paraboloid and ellipsoid respectively. The symmetry axes of the mirrors are tilted one respect to each other and the focal plane is arranged in a way that the Dragone–Mizuguchi condition is satisfied for the central horn of the focal plane unit. The design of the optics (see left panel of Fig. 1) has been achieved in order to have a beam size smaller than 21 arcmin at 41.5 GHz, an edge illumination on both mirrors lower than –30dB, and a maximum primary mirror diameter of 2.2 meters. With this configuration the projected aperture diameter resulted of 2 meters and the tilt between the primary and secondary mirror axes is 45 degree. The design has been optimised using the gaussian beam propagation theory.

Both the primary and the secondary reflectors were manufactured from lightweight carbon fiber. Then the surfaces received a coating of 2 μm of aluminium to enhance the conductivity. To prevent oxidation, the coating was covered by SiOx. The rms surface accuracy resulted less than about 25 μm for the primary and few times this value for the secondary reflector.

4. THE CHARACTERIZATION OF THE OPTICS

During the design phase of the BEAST optics the gaussian beam propagation has been used extensively. The mirrors illumination as well as the far field Full Width Half Maximum has been found for each beam. The electromagnetic field has been propagated from the feeds to the far–field, through the reflectors. The illumination characteristics have been found in a dummy plane surface perpendicular to the chief ray on each reflector. The edge taper has been found lower than –30dB for both the primary and secondary mirrors. The angular resolution has been calculated at a distance of 10^6 meters and results of 29 arcmin and 20.4' for the Ka– and Q– band channel respectively.

Independent simulations have been carried out using PO (Physical Optics) codes. In this case the feeds have been modelled as pure gaussian beam launchers, but the currents on each reflector surface have been calculated under the Physical Optics approximation. A map of each beam has been obtained and the main beam characteristics have been carried out. For each beam the copolar and crosspolar components have been mapped in amplitude and phase so that the polarization characteristics have been calculated also. The peak of the crosspolar component has been normalized to the copolar component peak; Stokes parameters, as a function of the (u,v) coordinates have been calculated and finally the depolarisation parameter has been evaluated [10].

Because of the beam aberrations, the angular resolution is function of the azimuthal cut of the beam (i.e. the beam, is not circular). To evaluate the angular resolution, an elliptical Gaussian fit of the beam in the (u,v) plane has been performed. Then, the maximum, minimum and average FWHM has been carried out from the fit. The characteristics of the main beams as carried out by Physical Optics calculations are reported in Table 2. Fig. 5 reports an example of main beam calculation, performed on the channel F at 30GHz, and the gaussian elliptical fit from which the angular resolution and the ellipticity are derived. All the calculations have been performed considering the primary and the secondary mirror, without considering the flat dish in front of the primary. However to check the possible effects the central beam has been calculated propagating the field through the flat mirror also. The comparison is reported in the first two columns of Table 2.

Experimentally, the telescope performances have been measured. Firstly the main beams have been measured using the Moon transit obtaining 20' ± 2' for the central beam. Then a near sidelobe measurements has been obtained recording the signal coming from a Gunn diode source several tens of meters away. At 20 degrees from boresight the telescope response resulted of –60dB below the peak, comparable with the detector sensitivity used in this measurement (actual antenna response at angles greater that 20 degrees maybe reasonably less than –60 dB). Finally, beam size has been estimated from the maps, resulting in a beamwidth of 23' in Q–band including pointing effects, pixelization effects, and telescope jitter.

Table 2. Main beam characteristics. Numbers reflect the focal plane symmetry.

	O With Flat mirror	**O Without Flat Mirror**	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Copolar max (dBi)	55.70	55.70	55.56	55.56	55.36	55.36	55.28	53.04	53.04
Crosspolar max (dB)	–59.86	–59.97	–27.80	–27.80	–31.59	–31.59	–35.31	–31.63	–31.63
Depolarisation Factor %	0.0003	0.0003	0.0897	0.0897	0.0852	0.0852	0.0806	0.0870	0.0870
FWHM along X (arcmin)	18.74	18.75	18.94	18.94	20.27	20.27	20.53	24.67	24.67
FWHM along Y (arcmin)	18.75	18.75	19.18	19.18	18.68	18.68	18.82	26.19	26.19
Ellipticity	1.00006	1.00041	1.013	1.013	1.085	1.085	1.091	1.061	1.061

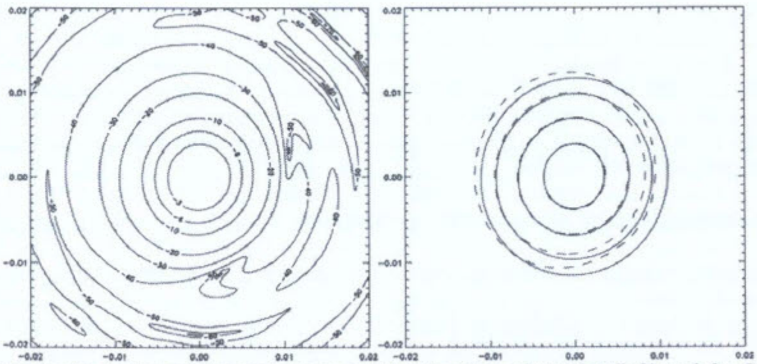

Fig. 5. Contour plot in the (u,v) plane of the main beam at 30 GHz of the channel F (left) and the Gaussian elliptical fit of the same beam (right). The dashed lines are the contour plot of the beam superimposed to the contour plot of the fitting function.

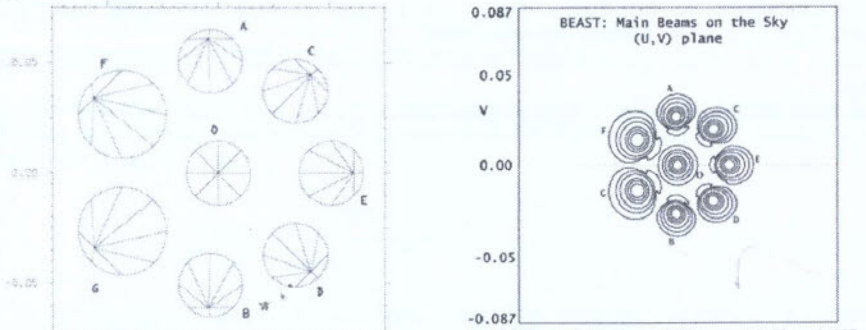

Fig. 6. Feed horn location (left) and corresponding main beam contour plots in the 10°x10° wide LOS centered (u,v) plane.

6. FUTURE AND PERSPECTIVES

The work on the BEAST optics presented here is the first step towards the full characterisation of the telescope system, since one of the main source of uncertainties in the CMB anisotropy measurements is related to the knowledge of the optics. Several simulations need to be performed in order to predict the feed/telescope responses in an more accurate way. In future works, the real response of the feeds, the measured mirror surfaces, the shield and metallic surfaces around the telescope, will be entered to the Physical Optics code and possibly the radiation patterns will be calculated over the whole 4π solid angle. Moreover, the BEAST focal plane is going to be updated in frequency by using a set of W–band receivers sensitive to polarization. For this reason the focal surface of the telescope is going to be mapped using ray tracing routines and Wave Front Error minimizations. This will permit to obtain the best focus at which the phase centre of the horns needs to be positioned.

ACKNOWLEDGMENTS

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