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SHAPED CORRUGATED HORNS FOR COSMIC MICROWAVE BACKGROUND ANISOTROPY MEASUREMENTS

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Abstract: Novel corrugated horn have been modelled, manufactured and measured which give low-sidelobe patterns required by CMB Anisotropy experiments. These horns have a Back-to-Back structure with mode filtering at their centres. They are corrugated to give axial symmetric low-sidelobe patterns, profiled to reduce their length, and have a Gaussian flare at their entrance apertures to further suppress sidelobes to –40dB. Modelling and experimental results show excellent agreement to well below 50 dB

Key Words: Anisotropy, Back-to-Back, CMB, Corrugated, Gaussian, Profile.

1. Introduction

Cosmologic Microwave Background (CMB) experiments, because of their scientific objectives, are in need of the very highest sensitivity as well as a high level of sidelobe rejection to be able to detect the weak CMB signal emission. The sidelobes of the telescope and feed must be

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sufficiently low so that strong sources such as the Earth, Sun or Moon do not contaminate the measurements. Hitherto a simple horn such as a smooth conical or Winston horn, acting as the telescope feed and put directly in front of the detector has been sufficient to reach the level of rejection required. This is no longer adequate given the requirements of new CMB anisotropy experiments to reach μKelvin sensitivities. Moreover, the scientific goals of these new projects include not only the detection of CMB anisotropies, but also the state of polarisation of the CMB. For these we need to employ optics which will not affect the polarisation of the incoming signal.

It is clear that below 200 μm in wavelength the best detectors are photoconductors, whereas at longer wavelengths up to 3mm (where HEMT's become competitive) bolometers are more sensitive if broadband measurements are required. Thus, most of the CMB experiments in this region of the spectrum use bolometric detectors, cooled to below 1 K. For example, SuZie, DiaBolo, Pronaos, Maxima, Boomerang and Archeops have operated in this region and some of these are now undergoing upgrades. The work described in this paper is mainly concerned with the High Frequency Instrument (HFI) on ESA's Planck Surveyor [1].

Heterodyne detector do not provide the large bandwidths needed (typically 25%), although they also do not require optical filters since the mixing process does the frequency selection. This is not the case for bolometric detection where the frequency selection has to be done by optical filters, the bolometers being sensitive to all incident radiation. An important issue is to determine the optimum position at which to put such filters so they have the least effect on the beam pattern. From past experience we know that it is not sensible to have filters in front of the horn which will be coupled to the telescope because that increases the sidelobe level and the spillover. Taking as a baseline a design put forward for a previous proposed mission [2] we have chosen to use a triple horn configuration for each detector channel as shown schematically in Figure 1. Here radiation from the telescope is focussed onto the entrance of a Back-to-Back horn pair. With no optical components in front of it the control of the desired beam is close to ideal (see section 3). A lens at the exit aperture of the second horn creates a beamwaist where wavelength selective filters can be placed. Lastly, a second lens on the front of the third horn matches it to the beam thus coupling efficiently the radiation onto the spider web bolometric detector [9] placed at its exit aperture. One significant benefit of this arrangement is that the various components can be placed on different temperature stages to create thermal breaks and thus reduce the level of background power onto the bolometer and fridge.

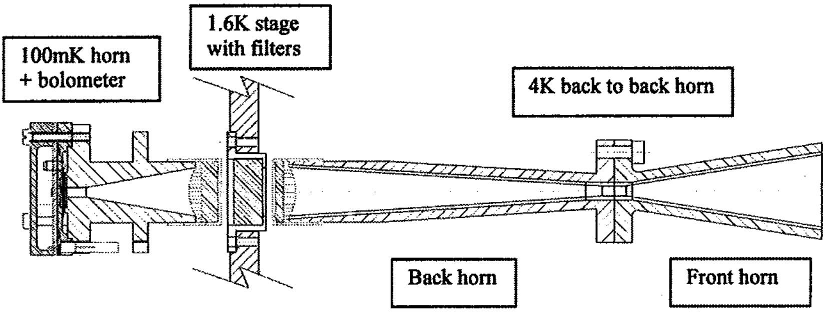

Figure 1: Optical configuration for a single detector channel

The Back-to-Back horn pair is constructed from two horns separated by a corrugated waveguide section, which at a given wavelength determines the throughput of the horn $A\Omega$. For a given throughput the sidelobe response, beamwidth on the sky (via coupling through the telescope) and spillover are precisely controlled by the design of the front horn. The waveguide is critical in that it defines the spectral high pass cut-on for the band and controls the allowable modes that propagate from the telescope to the detector. This component will be cooled down to 4.2 K in order to decrease the background load onto the detectors.

A second lens in front of the final 100 mK stage (the temperature at which the bolometers will be operated) matches the beam to the bolometric detector via a horn and a further waveguide section. The diameter of this waveguide is set to be larger than the first Back-to-Back waveguide to ensure that it does not modify the mode propagation (i.e. throughput) of the feed system. The low pass band edge-defining filter is also located on the front of this horn at 100 mK. In the following section we will focus on the development of the Back-to-Back horns.

2. The development of Back-to-Back horns.

Following the development of a profiled horn geometry by Del Rio and Gonzalo known as a Gaussian horn [3, 4], which has better predicted sidelobe performance than the classic conical configuration, it was decided to investigate such an option for the HFI. In order to compare the performances of conical and profile-flared horns, three Back-to-Back horns optimised for 150 GHz were manufactured with similar waveguide diameters and identical FWHM beam widths (13 degrees). The waveguide diameters ensure that the cut off frequency is at about 130 GHz, and the horns become multimoded at 170 GHz. The Gaussian horn actually has a complicated profile which is a combination of a standard profiled horn [5, 6] with a flared section added which has a Gaussian shape (see Fig.2).

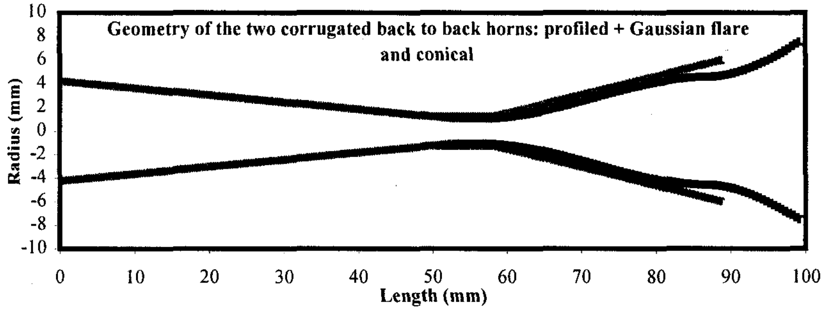

Figure 2: Superposition of the geometry of the two corrugated prototype horns.

The three prototype systems comprise:

- P01 is a corrugated conical Back-to-Back horn with a corrugation pitch of 0.5mm (λ/4).

- P05 is a corrugated profile-flared Back-to-Back horn with a corrugation pitch of 0.5mm ($\lambda/4$).
- P07 is smooth walled conical Back to Back horn with similar characteristics to P01.

Both P01 and P05 are corrugated along their entire length. This includes the wave-guide which not only has an effect on the spectral transmission but also gives a better coupling with free space and reduces the sidelobes [5]. The diameter of the waveguide and the depths of the corrugation slots determine the low and high cut-off frequencies as predicted by the complex dispersion relationship of corrugated structures, see [7]. The other beneficial effects of the corrugations for systems where only one polarisation is coupled to the detector is a symmetric beam pattern with very low cross polarisation levels (provided the horn carries only the balanced hybrid HE_{11} mode [5]). Such symmetric beam patterns have been measured with a bolometric system (sensitive to both polarisations) where the polarisation is selected by the source (Gunn diode giving E or H plane polarisation). Figures 3a and 3b show the beam profile measurements of these 2 polarisations for the corrugated horn P01 and the smooth walled horn P07 using a Gunn diode at 150GHz.

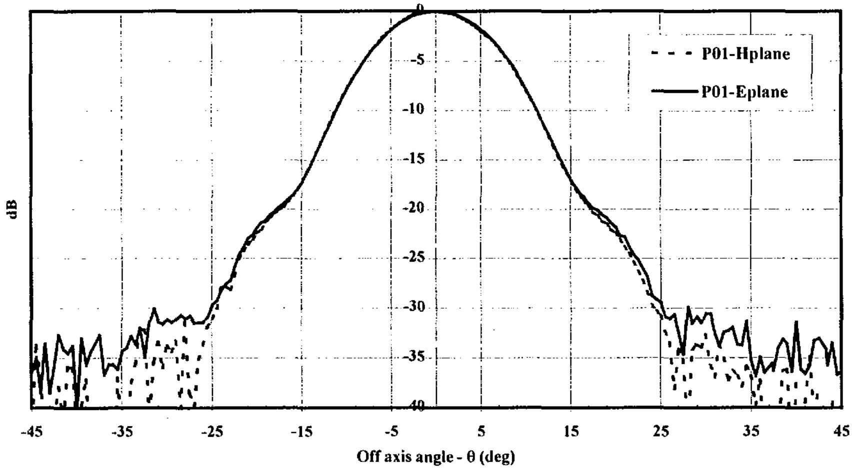

Figure 3a: Polarisation (E and H) measurements on a conical corrugated horn. The beam patterns are identical down to at least 30dB.

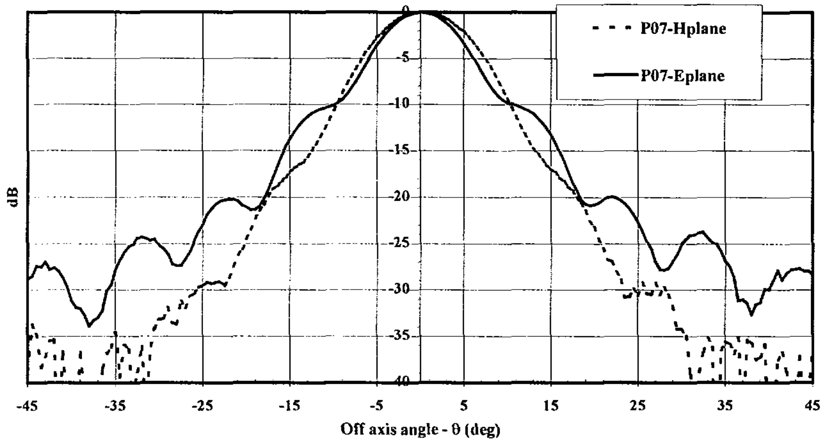

Figure 3b: Polarisation (E and H) measurements on a conical smooth walled horn.

3. Beam pattern measurements

We have used two experimental systems to measure the characteristics of the beam patterns of the Back–to-Back horns: A broadband system to simulate as closely as possible the Planck optical layout which has a limited field of view because of vignetting by the window of the dewar, and a single frequency system (Back Wave Oscillator [BWO] from ELVA-1) allowing for the measurement of the beam pattern over a larger range of angles with a higher dynamic range (made possible by the large optical power delivered by the BWO). These measurement systems are describe in [7].

Figure 4 shows the beam pattern measurement made using the BWO at 148 GHz on the two prototypes superimposed with the results predicted by our models (mode matching models [CORRUG from SMT Consultancies Ltd] and [7]). We can see good agreement between the experimental data and the model which provided confidence for the design modelling process of the Planck-HFI instrument. However, the most important result is the quality of the beam profile generated by the profile-flared horn in comparison to the conical one. For the same

FWHM beam, not only we get more power in the main lobe but, more importantly, the level of the sidelobes is dramatically reduced. In the case of P01 we start to see a sidelobe at about 16 degrees at a level of –20 dB whereas with P05 there is no sidelobe down to –40 dB which corresponds to an off-axis angle of 25 degrees. The advantage is then a purer Gaussian beam and a reduction in the spillover. The BWO allowed beam patterns over a range frequencies to be measured and figure 5 represents such measurements for P05 over a bandwidth of 25%. For the integrated bandwidth detected by the bolometers, we then expect to have a sidelobe level lower than -35 dB and a total spillover of the order of 0.8 %.

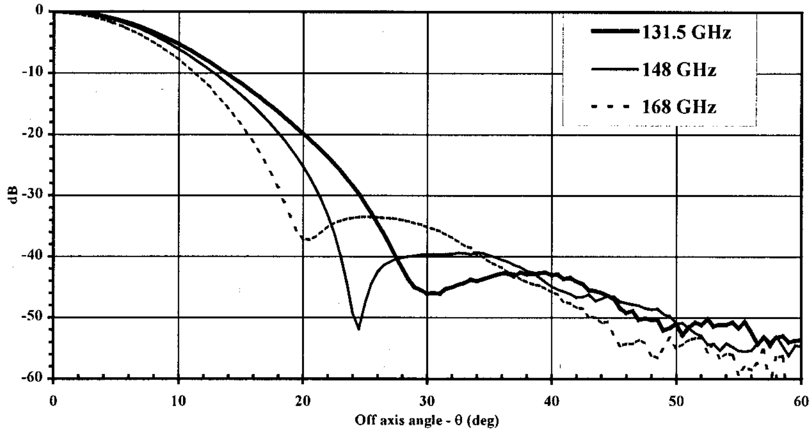

Fig 4 Comparison between model and data taken at 148 GHz

The phase centre location of standard corrugated conical horns is easy to calculate, as long as care is taken in the definition of the centre [8]. However there is no simple approach to predict the location of the Profile-Flared horn phase centre, and one is forced to rely on mode matching models.

Using an AB Vector Network Analyser at Bern University, we have been able to measure the phase as a function of the off-axis angle for each horn. To do so, the horn was rotated around an axis perpendicular to its symmetry axis and the phase was recorded during the rotation (a similar set up to the beam profile measurement). This measurement has been repeated for various positions of the rotation axis along the horn axis.

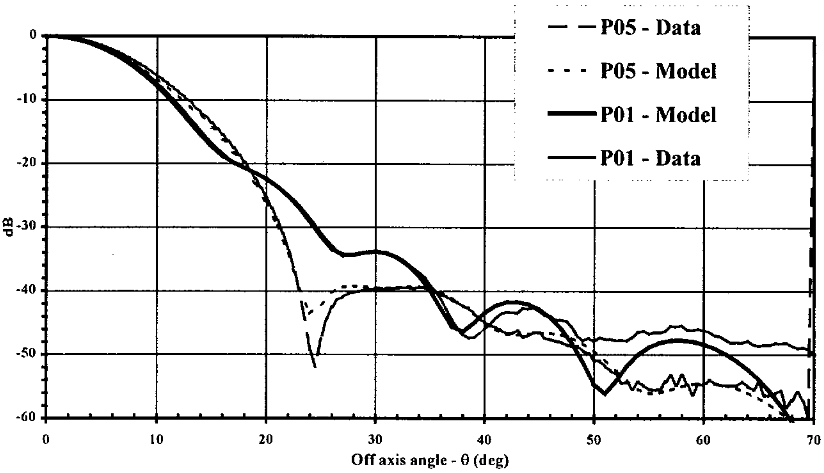

Fig 5 Superposition of P05 beam patterns at various frequencies

A set of these measurements is shown in figure 6 and comparisons between measured results and CORRUG predicted patterns, shown in Figure 7 below, show good agreement. It should be noted that modelling confirms that the phase centre location is strongly dependent on the shape of the flare: The more open the flare is, the closer to the profile section the phase centre is located. If the flare is less open, the phase centre moves towards the mouth of the horn.

The other benefit of this new design is that the phase varies quadratically over a wider angular range compared to the conical horn. This indicates that the field across the aperture is more truly Gaussian than for a conical horn. In the far-field the phase only starts to change once one has passed the main lobe and entered the first sidelobe region.

4. Spectral Filtering

The continuous corrugated structure has one additional, and rather unexpected (not that unexpected see [7]), benefit. In addition to the conventional long wavelength cutoff, present in the smooth horns, the dominant HE11 mode has a high frequency cutoff. Broad-band measurements using a Martin-Puplett interferometer show clearly this high frequency cutoff. The spectral filtering of the corrugated horn can be seen in figure 8.

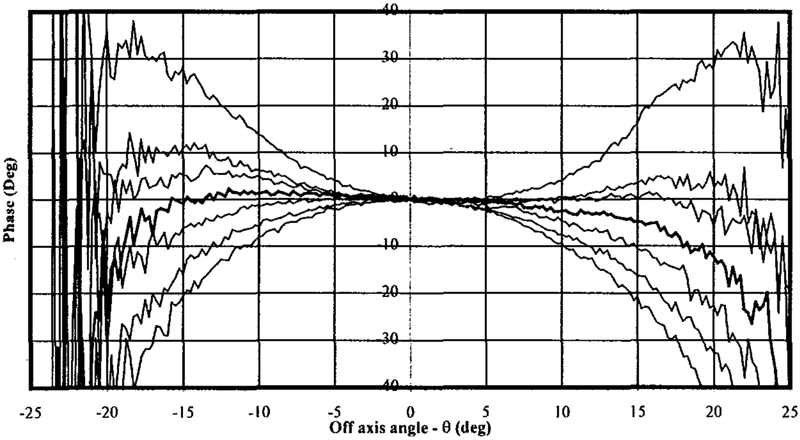

Figure 6: Phase measurements as a function of the off axis angle for various positions of axis horn rotation along the horn

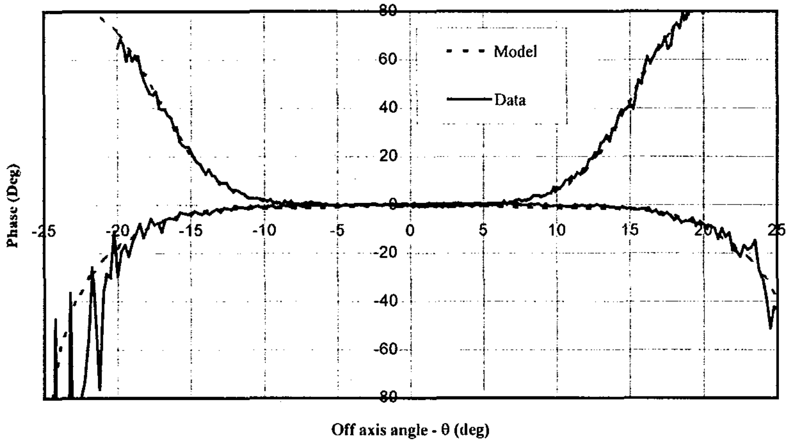

Figure 7: Phase function of the off axis angle with horns rotating around respective phase centres. Comparison between measurements and model

This filtering has the significant advantage in reduction the level of blocking filtering required to shield the detectors from Infrared radiation. As all such blocking filtering generate loss, the sensitivity of the detection system is improved.

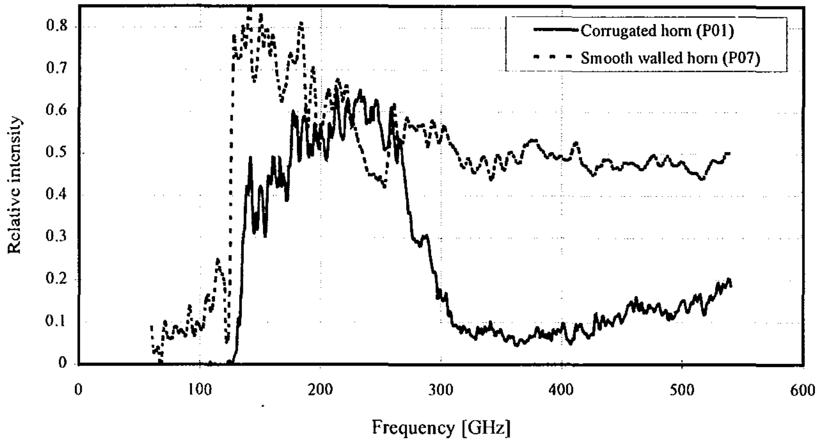

Figure 8: Spectral transmission of 2 Back-to-Back horns, corrugated and non corrugated.

5 Conclusions

We have confirmed, by manufacturing a prototype and measuring its characteristics, the improved performances of Gaussian or Profile-Flared horns predicted by Del Rio and Gonzalo [3, 4]. CMB anisotropy experiments, such as Planck-HFI, will use this approach to meet their difficult sidelobe and spillover requirements.

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