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Event: SPIE Astronomical Telescopes + Instrumentation, 2004, Glasgow, United Kingdom

Planck-HFI focal plane concept

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ABSTRACT

The future ESA space mission Planck Surveyor mission will measure the Cosmic Microwave Background temperature and polarisation anisotropies in a frequency domain comprised between 30GHz and 1THz . On board two instruments, LFI based on HEMT technology and HFI using bolometric detectors. We present the optical solutions adopted for this mission, in particular the focal plane design of HFI, concept which has been applied already to other instruments such as the balloon borne experiment Archeops.

Keywords: CMB experiments, bolometers, corrugated feedhorns, cold optics

1. INTRODUCTION

The Cosmic Microwave Background (CMB) provides direct information about the origin of the universe and our current understanding of the cosmological evolution of the Universe is heavily based on measurements of the CMB radiation. Over the past 15 years several experiments provided us with a vast amount of information about the power spectrum of the CMB temperature anisotropies. Despite these discoveries, it is now becoming clear that temperature anisotropy alone will not provide the complete picture of the early universe. The anisotropy must be combined with additional information in order to break the degeneracy in the cosmological models. This can only be done by an accurate measurement the CMB power spectrum at small angular scale, and by measuring the polarisation caused by Thompson scattering of CMB photons at the last scattering surface. The signal can be decomposed into a curl and a curl-free component, known as the B- and E-mode respectively. While earlier missions were mainly devoted to the measurement of the temperature anisotropies, present and future CMB experiments will try to measure the polarisation of the CMB. However, the signal from the E-mode is much fainter than the temperature anisotropies, while the B mode signal is expected to be another order of magnitude smaller. The experiment DASI has produced the first detection of the E mode signal followed by WMAP. The future ESA mission Planck Surveyor will measure the temperature and the E mode polarisation of the CMB with an unmatched accuracy up to an angular scale of l~2000, within 9 spectral bands to carefully remove the foregrounds.

CMB experiments, because of their scientific objectives, are in need of the very highest sensitivity as well as a high level of sidelobe and spectral rejections to be able to detect the weak CMB signal emission, reducing to a minimum the measurement contamination due to strong sources such as the Earth, Sun or Moon. The latest missions such as Boomerang [1], Archeops [2] and WMAP [3] have shown how critical the optical quality of such systems has to be in order to reduce the systematic effects and have a good reconstruction of the CMB anisotropy power spectrum.

It is then in this context that Planck-HFI [4] is developed, its optical concept being based on bolometric detectors, corrugated feed-horns and interference filters in order to achieve the highest sensitivity achieved so far at these frequencies, keeping the induced systematic effects to a minimum.

Optical, Infrared, and Millimeter Space Telescopes, edited by John C. Mather,
Proceedings of SPIE Vol. 5487 (SPIE, Bellingham, WA, 2004)
0277-786X/04/$15 · doi: 10.1117/12.552577

2. PLANCK PAYLOAD

The Planck Surveyor payload comprises a two-mirror off-axis Gregorian telescope offering an unblocked aperture satisfying the Mizuguchi-Dragone [5,6] condition, which allows the system to operate without significant degradation in a large focal plane array, while simultaneously giving a very low level of cross-polarisation. Both carbon fibre (CFRP) mirrors have been designed to obtain diffraction limited performances at wavelengths longer than 0.8mm and will be passively cooled down to 60K to reduce the radiative background level on the detectors. The primary mirror has a projected diameter of 1.5m while the secondary has been oversized (~1m) to reduce under-illumination of the primary.

At its focus, two instruments: LFI (Low Frequency Instrument) based on HEMT technology comprising 3 spectral bands (centered at 30, 44 and 70GHz) and HFI relying on bolometric detectors to cover the spectral range between 100GHz to 850GHz. HFI will use the central part of the focal plane to minimise aberrations at high frequency with LFI being located around it (figure 1). While the two instruments are based on different detector technology, both are using feed-horn cold optics to focalise the incoming radiation from the telescope onto the detectors. The horn phase centres are distributed across the focal plane surface without any components in the path between the front horns and the telescope to avoid unwanted beam distortion, and careful attention has been taken to avoid shadowing between and within the two instruments in order to avoid any diffractive effect that will impact the cleanliness of the beams. That resulted in an additional constraints while designing the cold optics above the usual requirements in term of mass, dimensions, thermal properties and amongst all optical quality. In order to avoid shadowing, modelling has shown that a boresight angle of +/-45 degrees respectively to the axis of each feedhorn has to be clear of any diffractive element (such as another horn) so that the impact on each horn beam pattern will be minimal (below 40dB).

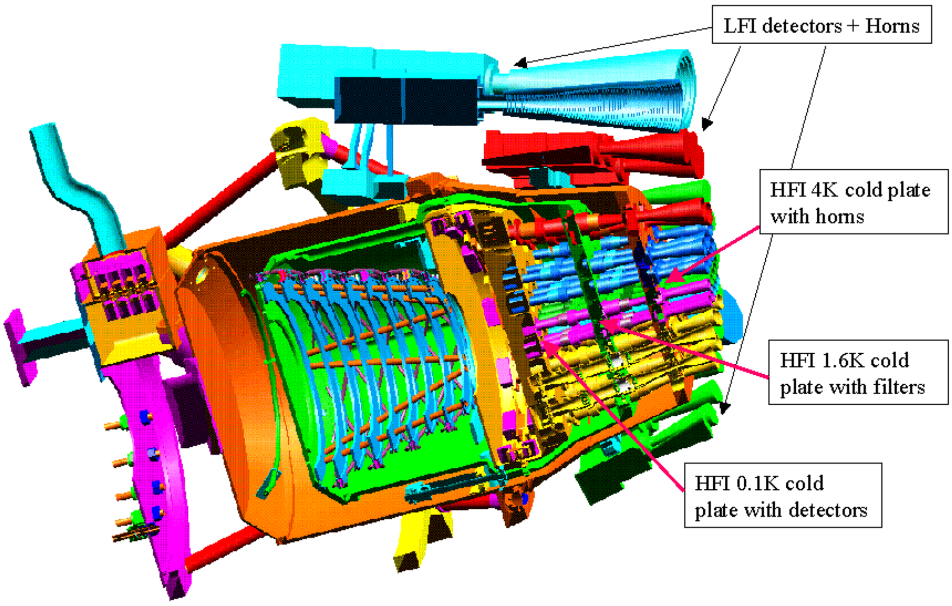


Fig 1: Planck focal plane showing both instruments.

3. THE HIGH FREQUENCY INSTRUMENT

HFI is a multi-frequency photometer comprising 6 spectral bands in order to properly remove the foregrounds contributions to the received signal. These bands are centred at 100, 143, 217, 353, 545 and 857GHz (Table 1 gives a summary of HFI focal plane definition). The four lowest frequency bands are single-moded and have dual-polarisation capabilities using Polarisation Sensitive Bolometers (PSB), while the two high frequency bands will be multi-moded without polarisation determination (total power using Spider Web bolometers). In this case, each mode bringing its own contribution to the detected signal, the sensitivity is largely increased.

Each band has a bandwidth set to 33% resulting from a compromise between having only one fundamental mode present over the whole spectral band for the single-moded channels and opening the bandwidth to increase the sensitivity of each detection assembly.

Band	Polarised channels	Unpolarised channels	Modes	Bandwidth (GHz)
100GHz	4	0	Single	83.5 – 116.5
143GHz	4	4	Single	119.5 – 166.5
217GHz	4	4	Single	181 - 253
353GHz	4	4	Single	295 - 411
545GHz	0	4	Few-moded	455 - 635
857GHz	0	4	Multi-moded	716 - 999

Table 1: Focal plane composition

For such an experiment it is crucial to have a good control and an even better knowledge of the antenna beam shape. In order to meet the scientific goals a set of optical requirements have been fixed, translated in terms of resolution, edge taper and spill-over requirements that are related to each other and will end-up in a trade-off. One can start from the illumination of the telescope produced by the horns that is well approximated by a Gaussian (in the case of the single-moded channels). The main parameter that is left for optimisation is the width of the illumination of the reflectors by the horns. Increasing this width also increases the illumination of the edge of the mirrors (Edge taper) and the amount of energy that falls outside of the reflectors (spill-over). It also has the effect of improving angular resolution, because the electromagnetic fields in the far field beam and that on the main reflector are basically Fourier pairs. In consequence, to improve angular resolution, one must widen the "illumination" of the main mirror, which also increases the Edge Taper and the "spillover", and therefore the straylight.

This simple physics determines the nature of the trade-off that has to be done between angular resolution and straylight. The acceptable level of straylight is fixed by the requirement that the energy collected from non-CMB sources (mainly the galaxy, the Sun and the Earth) remains less than the instrumental noise. Therefore, the HFI ambitions in terms of sensitivity have the immediate consequence that the requirement on straylight must be tighter than in any previous experiment of the same type.

However, due to the limited data transfer rate, and to avoid under-sampling, it has been chosen to have a maximum resolution of 5 arcmin. This is irrelevant on the low frequency bands (where we are reaching the maximum resolution possible) but has some consequences on the high frequency bands (353-545 and 857 GHz) as we explained later.

3.1 Focal plane

In addition to redundancy, having enough detectors helps getting a correct sampling of the sky in the cross-scan direction. The nominal scanning strategy supposes that every hour, the spin axis of the satellite will be shifted by 2.5 arcmin, which makes the 1°/day needed to approximately follow the Sun–Earth axis. This Delta angle is too large to offer a proper sampling of the sky in channels with a 5-arcmin beam. Choosing a smaller depointing angle would mean increasing the frequency of the depointing, and therefore losing more time for manoeuvres and post manoeuvres activities. It was decided to stagger the detectors of the same channel by a small amount (1.25 arcmin), in order to sample the cross scan orientation according to the Nyquist criterion or better.

The horns that couple the detectors with the sky are distributed following this "staggering" constraint. The high frequency channels are located near to the central part of the focal plane, since they are the most sensitive to aberrations, which are minimal in this place. They are put in a curve that compensates for the distortion of the telescope so that they look at aligned fields of view on the sky, along the scanning orientation (Figure 2). Moreover, due to the curvature of the focal plane following the optimisation of the telescope optical configuration to limit the beam distortion for the detectors located at the edges of the focal plane, and taking into account the possible shadowing from one horn onto the other, each front horn had to be specially tailored not only to meet the optical requirements but also depending on its location in the focal plane.

Each polarised channel having a dual-polarisation capability (two orthogonal directions within the same device – see later), the orientation of the PSBs within the same band had to be carefully studied in order to be able to properly extract the Stokes parameters. Having for PSBs per band, two orientations have been chosen to get 4 polarisation orientations and to have redundancy if one channel happened to fail.

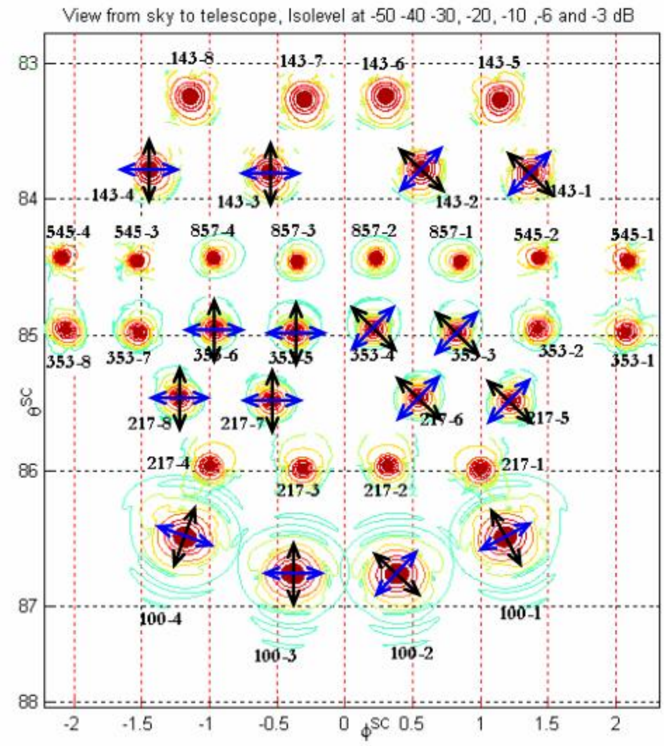


Fig. 2: HFI focal plane distribution

The high sensitivity of HFI can be met by using bolometers cooled down to 100mK using a space qualified He^3/He^4 dilution system [7] allowing the a time response of a few milliseconds, quick enough to reach the Nyquist sampling while the satellite is rotating at a speed of about 2 rounds per minute conjugated with a spatial resolution of the order of 5 arcmin. Operating bolometers at such a low temperature makes the cryogenic chain complicated and coupled to the optics design. Careful attention had to be paid thermal and photometry designs to avoid unwanted radiation reaching the coldest stage, increasing its temperature or even stopping its operation, and increasing the radiation background on the detectors. For this purpose, the thermal architecture relies on several enclosed thermal stages (following a Russian doll structure) each radiatively shielding the following one (figure 1). Starting from a common LFI-HFI 20K stage cooled by a close cycle Hydrogen Joule-Thomson (J-T) cryocooler from which LFI is operated, another mechanical cryocooler based on Helium J-T expansion is providing a 4K stage on which HFI in anchored. From then the dilution system is operated providing two other thermal stages at 1.6K and 100mK. Each HFI channel will then be distributed over the 4K, 1.6K and 100mK stages to form a detection assembly.

Photometric modelling is showing that the detector will be photon noise limited. The main photon noise contribution will come from the scientific signal (CMB and foregrounds), the contribution coming from the 60K telescope and the 4K horns and filters being the next major contributors.

3.2 Detection assembly

The requirements of high level of spatial rejection and sensitivity, and low level of cross polarisation, cannot be met by the use of smooth walled horn and corrugated horns have been adopted. However, to further improve the sidelobe rejection, new profiled-flared horns [8] have been developed and successfully integrated for the balloon borne experiment Archeops.

Because HFI is using bolometric detectors, spectral filtering based on optical filters has to be achieved in each channel. 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 coupling the incoming radiation from the telescope because of a resulting increase of sidelobe and spillover levels. Taking as a baseline a design put forward for a previous proposed mission [9] we have chosen to use a triple horn configuration for each detection assembly as shown schematically in Figure 3.

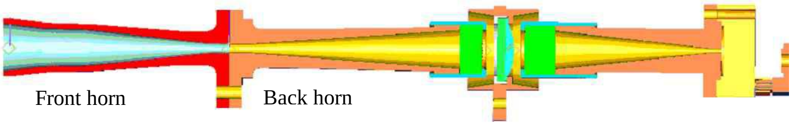


Fig 3: Detection assembly scheme

The 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 given by the profiled-flared front horn is close to ideal, thus 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. A lens located in between the back horn and the detector horn, in conjunction of the profiled geometry of both horns, creates a beamwaist where wavelength selective filters can be placed, and allows the radiation to be properly coupled to the bolometric detector. 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 cooling system.

The interference filters based on hot-pressed technology are distributed across the three temperature stages to reduce the thermal load. Past experience with Archeops which relied on the same focal plane concept, has shown the importance to get the filtering right in order to operate properly the dilution system. Moreover, five filters per detection assembly are being used to meet the required spectral rejection and to be sure that no spectral leakage can occur. The filter stack has been designed to get a maximum in-band transmission of 80% with an out of band radiation rejection given in table 2 compared with the requirements.

Band	Near band to 300μm	300 to 30 μm	30 to 0.3 μm
Requirement	10^{-3}	10^{-6}	10^{-9}
Typical measured rejection	10^{-4}	10^{-10}	10^{-13}

Table 2: Interference filter stack spectral rejection. Required and measured rejections

The bolometric detectors developed by Caltech/JPL are of two kinds. Spider web NTD Germanium bolometers (fig 4a) [10] to detect the total radiation intensity are being used extensively in submm-mm Astrophysics. Most of the past CMB experiments in the last 8 years have relied on this technology (Boomerang, Maxima, SuZie to name a few) and they are still used for large format array (Bolocam, Herschel-SPIRE). In the Spider web principle, the absorption of radiation is achieved thanks to a grid or a mesh of resistive metallic film, while the temperature variation is detected by Doped germanium thermometers. Because much emphasis is now on the detection of the CMB polarisation, it has been decided a few years ago to rely on the Polarisation Sensitive Bolometer (fig 4b) [11] technology to be able to detect two orthogonal polarisation orientation within the same device. A PSB consists of parallel resistive wires, sensitive uniquely to the radiation with the electrical field parallel to the wires. A second bolometer is just behind the first one and detects the orthogonal polarization that is not affected by the first absorber. This technology already used on Boomerang is now being integrated not only for Planck-HFI but also for ground based experiments such as Biceps [12] and Quad [13].

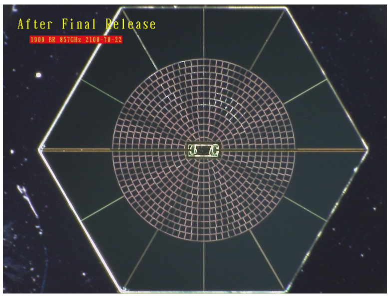


Fig. 4a: Spider Web detector at 857GHz (JPL/Caltech)

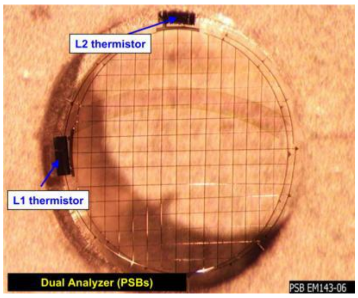


Fig 4b: Polarisation Sensitive Bolometer (JPL/Caltech)

Following our goal to reach the highest possible sensitivity, careful study of each component was carried out through modelling and experimental data. In particular we had to study the radiation coupling between the back and detector horns, as past experience has shown that this part can be the cause of a high efficiency loss. Experimental data in agreement with HFSS modelling (High Frequency Structure Simulator), confirmed by the latest measurements on one of the 143GHz detection assembly of the Cryogenic Qualification model have shown that the end to end efficiency for the whole detection assembly (from the front horn aperture to the detector, including detector, cold optics and filter efficiencies) can be as high as 50%. This value is matching our goal and is well over the requirement which was fixed to 25%.

3.3 Single moded channels

The Back-to-Back horn pair is constructed from two horns separated by a corrugated circular waveguide section, which at a given wavelength determines the throughput of the horn $A\Omega$. The waveguide is critical in that controls the allowable modes that propagate from the telescope to the detector. In the case of the single moded channels, the waveguide is designed such as only the fundamental hybrid mode HE11 mode can propagate. In this case the throughput $A\Omega = \lambda^2$ and the waveguide defines the spectral high pass cut-on for the band, frequency below which no mode can be transmitted. The corrugation period is set to $\lambda/4$ across the horn while the depth is $\lambda/4$ excepted in the waveguide where the ratio r_0/r_1 (r_0 internal radius and r_1 external radius of waveguide) determines the modes that propagates.

Using a mode-matching software to predict their radiative beam pattern, all the single moded horns have been designed to be compliant with the opto-mechanical requirements. Following the trade-off argument mentioned before between resolution and straylight, the horn beam pattern optical requirements can be quoted in term of Full Width Half Maximum (FWHM), edge taper and spillover. To reach the maximum targeted resolution, the FWHM has to be between 19 to 17 degrees with an edge taper ranging from –25dB to –30dB at 25 degrees for the bands 100GHz to 217GHz respectively while keeping the spill-over below 1%. The case of the 353GHz band is different. As stated above, we do not want a higher resolution than 5 arcmin. We then had to under-illuminate the telescope making the edge taper target easier to reach (-40dB), leading to a FWHM of 11degrees. Fig 5 shows a typical set of data coming from tests on one of HFI 100GHz horn. The radiation beam pattern of each horn is being measured using a polarised monochromatic source so both E and H plane of polarisation can be measured in amplitude.

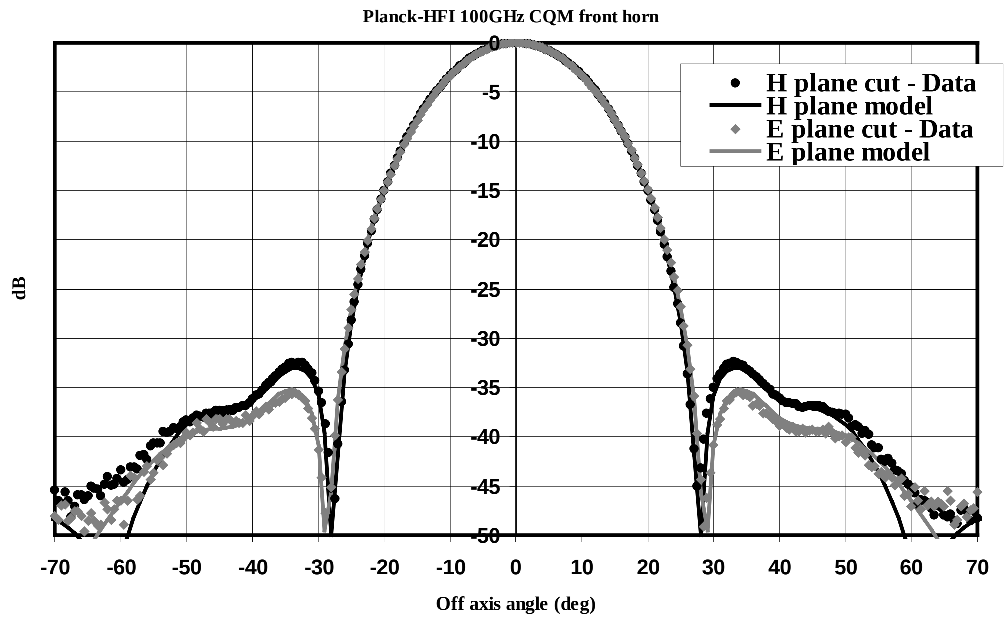
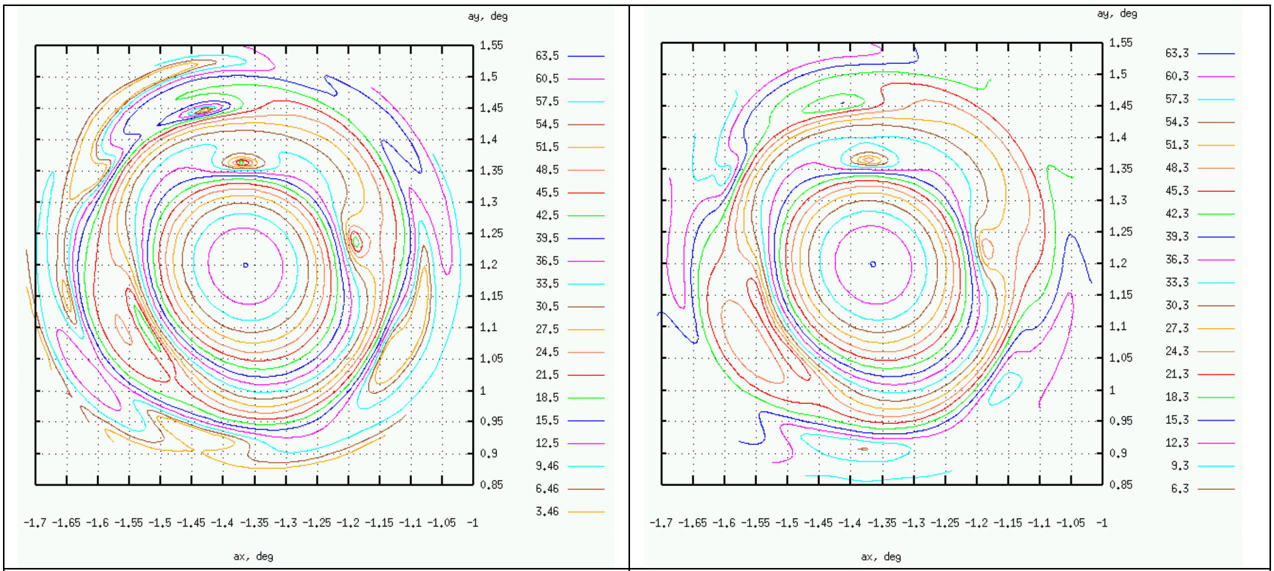


Fig. 5 : Planck-HFI Cryogenic Qualification Model 100GHz horn: Model and experimental measurements. Monochromatic beam pattern at 100GHz

Starting from the horn beam patterns propagated through the telescope, the antenna beam patterns of the single moded channels have been computed with the help of three different models for cross-validation (GRASP 8, Zemax and scattering matrix approach developed at Maynooth University), giving the resolution, gain and polarisation characteristics for each channel. While we get a very good agreement between the three models for the resolution and gain, polarisation characteristics are better defined using GRASP8 and S-matrix simulations. The antenna beam simulation for one of the single moded detector (143-1, 143GHz position 1) is shown in figure 6, both for the central frequency (a) and integrated over the whole spectral band (b). The main beam is almost non affected by degradation down to a level of –25dB from the maximum. Figures 7a and 7b show the integrated cross-polarisation over the whole 143GHz spectral band for the two detectors of the same PSB. This has been calculated considering a perfect optical system and do not take into account the cross-polarisation of the detector itself which will be the major contributor, and as expected in this case, the maximum cross-polarisation is below –30dB.



(a) Monofrequency 143GHz (b) Broadband

Fig 6. Iso-contour levels of the antenna beam for the detection assembly 143-1

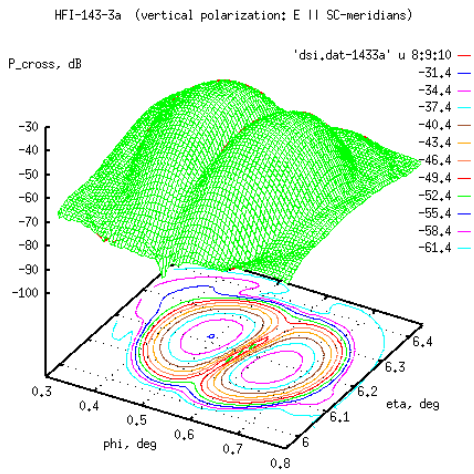


Fig. 7a Cross-polarisation of PSB detector 143-3a

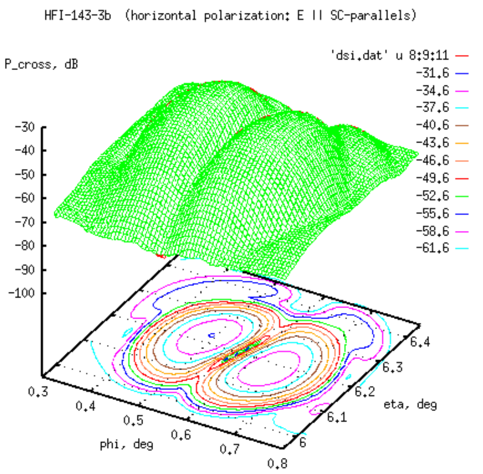


Fig. 7b Cross-polarisation of PSB detector 143-3b

3.4 Multi-moded channels

In order to get the limited resolution due to limited data transfer previously mentioned, two approaches can be considered. One will be to dramatically under-illuminate the telescope resulting in a beam with very low edge taper and spillover but very poor efficiency. The adopted solution is to use multimoded optics. In this case, to meet the required non-diffractive limited resolution, few moded corrugated horns are used to maintain high throughput efficiency for a constant spatial resolution of 5 arcmin. Selection of the transmitted modes is achieved by the corrugated waveguide. While for the single moded bands we were relying on the cut-on frequency of the first mode to define the low frequency edge of the band, the same rule cannot apply when the horn is in multimoded operation. We then have to introduce an additional interference filter to define the low frequency edge of the band.

Single-moded optics is very well understood and the theory gives excellent predictions. The theory is not quite at the same level of maturity in the case of multi-moded optics. For that reason, effort has been devoted to understand this specific field. Models are giving now good representation of multi moded horn beam pattern if compared to experimental measurements [14, 15]. The various modes are independent and the horn beam pattern can then be predicted by computing the quadratic sum of the radiation pattern of each mode. However, the various modes will not couple exactly the same way to the detector. Each optical component, misalignment and mismatch will affect each mode in different ways, making the final beam shape strongly dependant on this coupling. While waiting for experimental results from the real Planck-HFI hardware, the best horn beam pattern prediction for one of the multimoded channel (545GHz) is given in figure 8a.

The antenna beam has been computed for such feed horns using S-matrix simulations (fig 9) and the same calculations are on-going using Grasp8 (fig 8b) for cross-validation using the same assumptions that lead to the multimoded horn beam patterns. We can see that even for multimoded channels, both software are giving the same results. The 545GHz antenna beam shown has been computed for one of the most extreme locations in the focal plane (545-1).

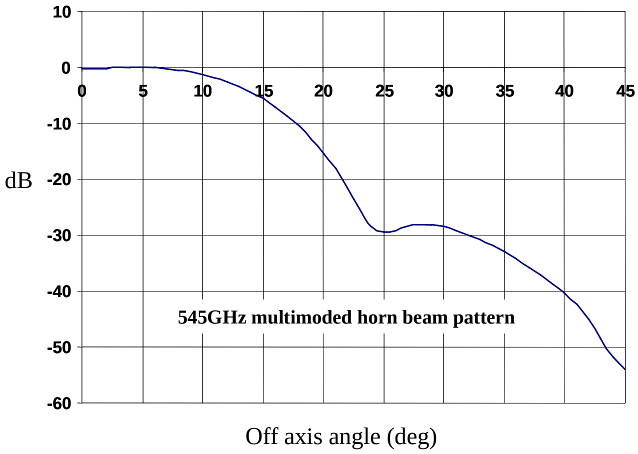


Fig 8a: Predicted horn beam pattern at 545GHz

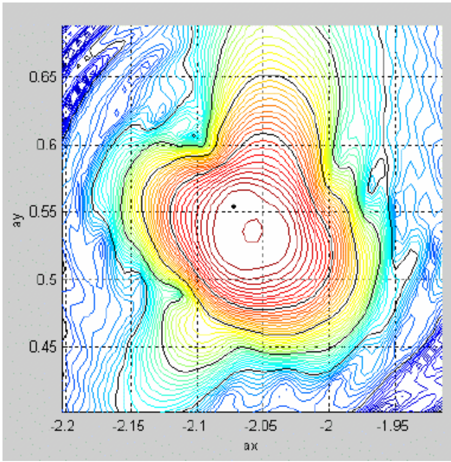


Fig 8b 545-1 Antenna beam predicted with GRASP8

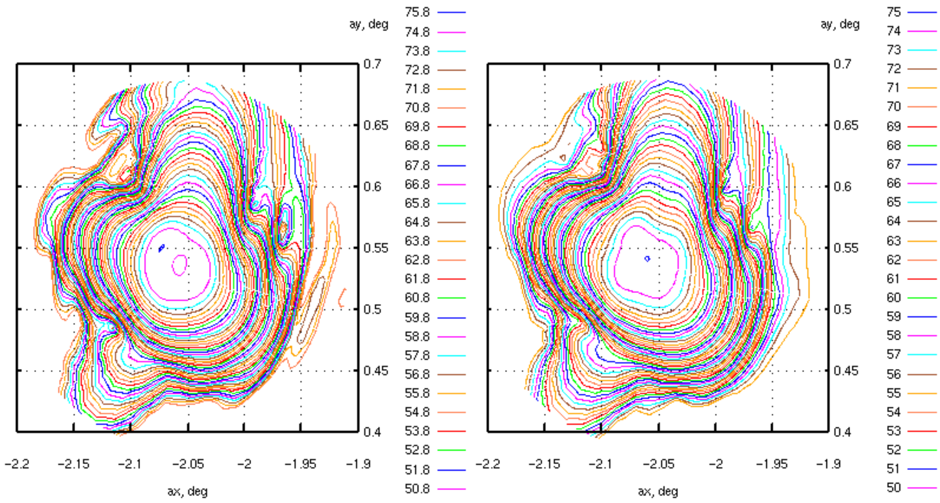


Fig.9. Power patterns of (a) mono-frequency and (b) broad-band telescope beams from the multi-mode horns HFI-545-1 computed by the scattering matrix approach

4. CONCLUSION

Based on the HFI optical described in this paper and on the modelling performed using various software, the beam characteristics predictions are given in table 2. The HFI Qualification Model is being manufactured integrated and tested. Measurements and calibration of focal plane optics is taking place over spring-autumn 2004 and preliminary antenna beam will follow. However, due to the nature of the instrument concept, exact flight-like end to end optical performance measurements including the telescope will not be possible on the ground. Only complementary series of tests will allow us to measure the beam characteristics before launch in 2007.

Band (GHz)	Resolution	Edge taper
100	9.5 arcmin	< -25 dB
143	6.9 to 7.1 arcmin	< -28 dB
217	4.7 to 5 arcmin	< -30dB
353, 545, 857	5 arcmin	< -30dB

Table 2: Beam characteristics prediction.

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