Simulation of Multi-Mode Feed Horns and Telescope Beams for the ESA Planck Deep-Space CMB Mission

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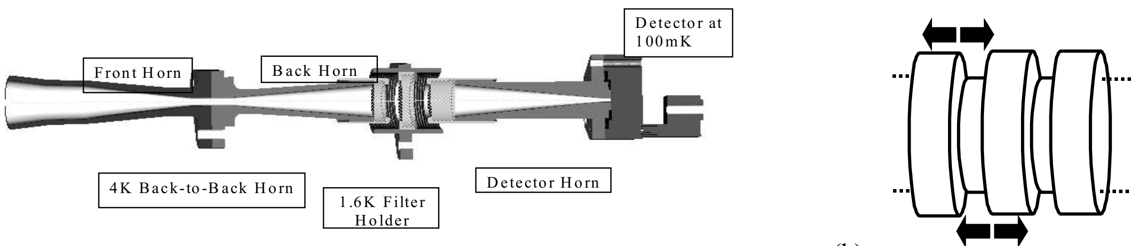
Abstract: *We present fast physical optics simulations of the ESA PLANCK HFI beams based on the scattering matrix modeling of corrugated horns feeding bolometric detectors. The main beams of polarized and non-polarized channels are computed with account of the broad frequency bands and the final design positions of the HFI horns.*

1. Introduction

The ESA PLANCK Surveyor is the third-generation deep-space submillimeter-wave telescope being designed for measuring the temperature and polarization anisotropies of the Cosmic Microwave Background (CMB). The telescope will be equipped with two focal plane instruments, the Low-Frequency and High-Frequency Instruments, for detecting the radiation in the frequency range from 30 GHz to 1000 GHz in nine bands. The High-Frequency Instrument (HFI) will operate in six frequency channels centered at 100, 143, 217, 353, 545 and 857 GHz [1]. Four channels (100 - 353 GHz) will use mono-mode quasi-Gaussian horns, half of them feeding polarization sensitive bolometers (PSB) [2]. The other two channels (545 and 857 GHz) are feeding non-polarized bolometers and use profiled multi-mode horns. All the HFI horns are broadband, the bandwidth being about 30% of the central frequency. The system is designed to meet the extreme requirements on both the primary mirror edge taper (-25 dB) and the angular resolution on the sky (about 5 arcminutes at the frequencies of 217-857 GHz). The feed horns for the HFI channels require a very special design and the telescope beams need to be computed with extreme accuracy and reliability since full-scale testing of the whole system is impossible on the ground and is very limited in flight. Here we present our simulations of broadband multi-mode profiled corrugated horns and their respective telescope beams for the highest frequency channels of the Planck HFI.

2. Simulation Technique for the Profiled Corrugated Horns with Bolometric Detectors

The profiled corrugated horns were accurately modelled using a rigorous electromagnetic mode matching technique [3] generalized for partially-coherent multi-mode horn operation. The technique views the entire horn as a sequence of cylindrical waveguide segments, the radius varying between each sequential segment (Fig. 1). It is assumed that the normal TE/TM modes propagate but are severely scattered by the corrugated structure into forward and backward propagating modes. Higher-mode excitations and interactions are included so evanescent TE and TM modes can also be modelled. The total transverse field in conjoined segments is matched at their junction to conserve total complex power and the usual boundary conditions apply to the fields at the conducting walls.



(a) (b)

Figure 1. (a) Corrugated horn and (b) waveguide segments. Modes are severely scattered at the segment junctions.

A scattering matrix that describes the relationship between the input and output mode coefficients at each segment junction is constructed. A diagonal matrix with elements describing the phase evolution of the modes can be used for modal propagation. The matrices for each junction and section can then be cascaded to give a scattering matrix for the entire horn structure [4]. All of the modes at the entrance to the waveguide section of the horn are assumed to be equally excited. The scattering matrix determines which modes, and in what proportion, propagate to the horn aperture. The calculation of the radiation pattern (including diffraction effects) then amounts to simply summing in quadrature the radiation pattern of each mode weighted by the appropriate mode coefficient.

3. Simulations of the Feed Horns for the ESA PLANCK Surveyor

We have used our scattering matrix code to calculate the aperture field patterns of the HFI 100, 143, 217, 353, 545 and 857 GHz horns when considering the black-body bolometric detectors in the integration cavities at the rear side of horns as the radiation source. We found that the lowest 20 radial and 3 azimuthal modes were sufficient to determine the horn far-field patterns while comprising nearly 99% of the total beam power (Fig. 2).

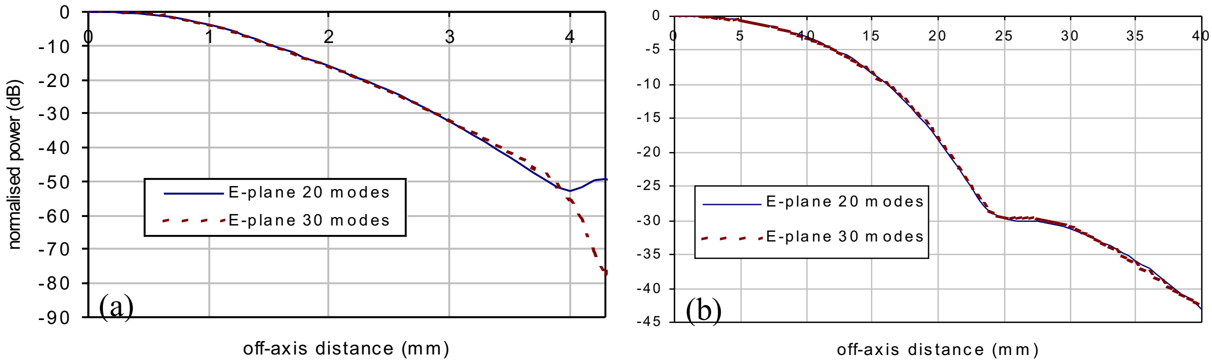


Figure 2. (a) Aperture and (b) far-field beam patterns for the 545-GHz horn (calculated at 545 GHz). The patterns were calculated using 20 and 30 radial modes and 3 (n = 0,1,2) azimuthal modes.

Once a horn aperture field had been determined at a given frequency, its individual TE and TM modes were propagated through the PLANCK telescope optics as described in the following section. These were then summed to give total beam patterns on the sky.

4. Physical Optics Simulations of the Dual-Reflector Telescope Beams

Simulations of the PLANCK HFI beams are extremely challenging because of the asymmetric dual-reflector geometry of the telescope, the large primary mirror having projected diameter D = 1.5m (D/λ_{min} = 5000), the very wide field of view, the broadband and multi-mode structure of the horn fields, and the extreme accuracy required. Physical optics (PO) is the best technique for this kind of computation. Conventional commercial software, however, cannot cope efficiently with problems of this size in full PO+PO mode of simulations.

As an alternative, we have developed a dedicated fast PO simulation method [5] which is specifically designed for large multi-beam multi-reflector systems with broadband channels and multi-mode horn field structure. The method allows us to perform rigorous PO+PO TE/TM-mode simulations of the main beams of large telescopes such as PLANCK in a few minutes for mono-mode mono-frequency channels and in about an hour for the broadband polarization-averaged multi-mode channels of the highest frequencies.

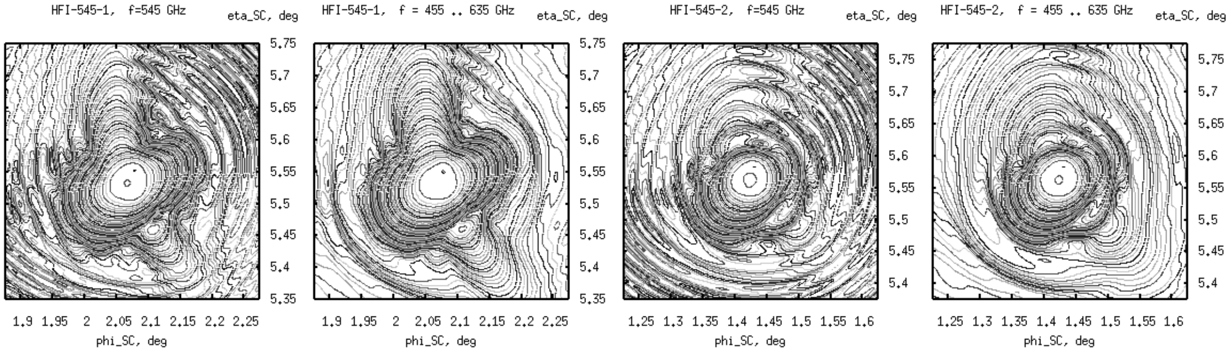
We compute the beam patterns of the IQUV Stokes parameters on the sky by propagating the source field from the apertures of the corrugated horns through the telescope mode-by-mode, integrating over the frequency band and taking account of all polarizations in the non-polarized channels. The aperture fields of the horns were computed by the scattering matrix approach as explained above. The effective modes of the electric field at the horn aperture are represented via the canonical TE-TM modes of a cylindrical waveguide and so can be propagated from the horns to the secondary mirror analytically.

The total beam power after field propagation through the telescope is calculated as the sum of the powers of all modes propagated to the sky. Similarly, the broadband beam patterns of the Stokes parameter are the sums of the relevant patterns of all the modes at all representative frequencies within the bandwidth. The beam data are computed assuming smooth telescope mirrors of ideal elliptical shape, of perfect electrical conductivity, and the ideal positioning of mirrors and horn antennas.

5. Broadband Multi-Mode Beams of the ESA PLANCK Telescope

Simulations of multi-mode beams require the propagation of each mode for a few times with different polarization angle for proper averaging of polarization. The reason is that, unlike the power patterns of conical or Gaussian horns, the modes of the profiled horns are not axially symmetric and the mode pattern in the sky depends on the polarization angle on the horn aperture. Also, because of broad frequency bands (~30%), averaging over frequency is needed as well. Using nine sampling frequencies with uniform distribution across the band appears to be sufficient for the adequate representation of the main beams in the area of about 0.5 – 1 degree of radius in the sky with about 0.1% accuracy in power patterns.

As an example, Figure 3 shows the mono-frequency (f = 545 GHz) and broadband (f = 455-635 GHz) power patterns of the telescope beams from the profiled corrugated horns HFI-545-1 and HFI-545-2 computed by the scattering matrix approach with averaging over polarization angle. Each horn is placed at the actual design position with nearly optimal axial refocus providing both the maximum gain and the best resolution of the telescope.



(a) (b) (c) (d)

Figure 3. Power patterns of (a,c) mono-frequency and (b,d) broadband telescope beams from the multi-mode horns (a,b) HFI-545-1 and (c,d) HFI-545-2 computed by the scattering matrix approach.

The beams are computed with the horns optimized for the required angular resolution of the telescope (the full beam width on the sky W=5 arcminutes) when satisfying the edge taper requirements on the primary mirror. The distortion of the beams at this resolution is mainly due to coma (aberrations of the wider beams are mainly due to astigmatism). Each beam has a well-defined flat top of the angular diameter W = 4.4 – 4.8 arcminutes when measured at the level of –3 dB which appears to be just the edge of the flat top. Below –10 dB, the beams are rather complicated because of significant aberrations of the telescope for these off-axis horns. The beam structure varies with the frequency in the bandwidth of the channel and improves noticeably for the broadband beams.
Compared to the very off-axis HFI-545 beams, the multi-mode HFI-857 beams are nearly perfect, with a smooth symmetrical flat top that is due to both the greater number of modes propagating through the horns and the most favourable location of horns at the centre of the field of view of telescope.

6. Conclusions

In this paper we present simulations of the HFI feed horns and broadband beams of the ESA PLANCK Surveyor. The beams are computed by a multi-mode physical optics propagation of the source field from the apertures of corrugated horns which are simulated using a scattering matrix approach. Fast and accurate PO simulations of the high-frequency beams based on TE-TM mode scattering matrix horn simulations allowed us to represent the shape of multi-mode HFI beams in their complexity while using affordable computational resources. We have also studied the quality of the telescope beams from the viewpoint of scientific requirements of the PLANCK project.
The broad frequency bands of the HFI channels are shown to improve both the beam power and polarization patterns. Perfect alignment of polarization along the required directions is confirmed by small and symmetric deviations of the Q and U Stokes parameters from the ideal values across the beam patterns. Peak difference of power patterns of orthogonal polarization channels, due to the usage of orthogonal pairs of polarization sensitive bolometers in the individual horns, is less than 1%, while it is 5% to 8% for the different beams of complementary pairs of horns designed for the polarization measurements.
The new simulation technique that we have developed for large electromagnetic systems proves indispensable for multi-reflector antennas with a very wide field of view, large number of beams and complicated structure of propagating waves, particularly when efficient and rigorous simulations of the main beams are needed.

7. Acknowledgements

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8. References

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