Optimization of the Coupling of High-Frequency Horn Antenna Array to the ESA PLANCK Submillimeter-Wave Telescope

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Abstract We study the electromagnetic coupling of the array of Gaussian and multimoded horn antennas to the dual-re-ector submillimeter-wave telescope on the ESA PLANCK Surveyor designed for measuring the temperature anisotropies and polarization characteristics of the cosmic microwave background. In this paper, we present the results of our analysis concerning the measurement of polarization with tilted o-axis dual-rector Gorgonian telescope and the propagation of multimoded beams through such a system.

I. Introduction

The dual-rector submillimeter-wave telescope on the ESA PLANCK Surveyor is being designed for measuring the temperature anisotropies and polarization characteristics of the cosmic microwave background (CMB).

PLANCK will carry two highly complex focal-plane instruments, giving the whole frequency coverage (30 GHz to 850 GHz) and high sensitivity (T = 10⁻⁶) necessary to allow for the clean separation of the CMB from confusing foreground sources of radiation and the determination of the power spectrum of the CMB anisotropies on angular scales down to 5 arcmin.

Our research is concerned with one of these key instruments, the Far-IR High Frequency Instrument (HFI), which will cover six frequency bands centered at 100, 143, 217, 353, 545 and 857 GHz (wavelength range from 3 m down to 350 m) [1]. At the telescope focal plane the HFI consists of an array of 36 horn antenna structures (Fig. 1) feeding the ultra-sensitive bolometer detectors which will be cryogenically cooled to a temperature of 100 mK.

One objective of our research is the optimization of the HFI optical design and the determination of the complete set of HFI beam patterns. The challenge of the problem is that the telescope is electrically large (D = 4300 m = 350 m) and consists of two essentially defocused ellipsoidal mirrors providing a very large field of view at the focal plane in order to accommodate the two focal-plane instrument ends.

The latter has a detrimental effect on the quality of the imaging introducing coma and astigmatism even at the center of the field of view where the highest frequency channels are placed. Furthermore the focal surface of least confusion has quite an unusual shape and it is extremely important to precisely place the phase centers of the HFI horn antennas on this surface.

Another objective is the characterization of the non-conventional polarization properties of the multi-beam telescope system. The CM B polarization is expected to be at a level of only 10% of the temperature anisotropy quadrupole, and the success of the measurements will depend crucially on the precise knowledge of the polarization properties of the telescope.

II. Formulation of the problem

While the performance of the antenna structures can be thoroughly tested in terrestrial conditions, the coupling of the HFI with the telescope is, basically, optimized through the computer simulations. Such simulations are also needed for the data retrieval from the raw PLANCK measurements once in orbit.

The most intricate part of the problem is the computation of the polarization patterns of the telescope beams from the linearly polarized horns and the power patterns of multimoded beams of extremely
high frequencies (the beam s of 12 m odes at 545 GHz and of 30 m odes at 857 GHz).

Among various simulation techniques, physical optics (PO) is the most adequate one for the given purpose. However, conventional implementations of the technique [2, 3] do not fit the size of the problem. Commercially available packages are also very limited in their capacity to rigorously answer this sort of questions. For example, even the best commercial software requires about one week of computation of the main beam of the telescope at the relatively low frequency of 143 GHz, while all conventional physical optics codes collapse at the highest frequencies of 545–857 GHz.

To solve the problem, we developed a special PO code [1] that allowed us to overcome the limitations of a generic approach for large multi-element systems and perform typical simulations of the telescope in the order of minutes. With recent improvements, it requires only 2 minutes for the fairly accurate PO simulation of the telescope beam at the frequency of 143 GHz and about 30 minutes for the beam of 30 modes at 857 GHz using a PC Pentium III (500 MHz) under the Linux operating system.

In this paper, we consider the beam of the Gaussian horn HFI-143-1 designed for the separate measurement of the efficiencies of two orthogonal linear polarizations, 'a' and 'b', which correspond to the electric field at the beam axis in the sky tilted with respect to the local vertical (defined below) by the angles $\alpha_a = 45^\circ$ and $\alpha_b = +45^\circ$, respectively (the angle is measured clockwise from the local vertical as seen from the telescope).

We also provide the results of our simulations of the defocusing effect of the 30-mode horn HFI-857-1 from the old layout of the focal plane unit.

The electric field at the aperture of the Gaussian horn HFI-143-1 is linearly polarized and specified by the formula

$$ E(r) = E_0 \exp \left( -r^2/a^2 \right) e_a; \quad 0 < r < a $$ (1)

where $r$ is the radial coordinate, $a = 2.58$m is the beam waist at the aperture, $E_0$ is the aperture radius and $e_a = e_{\alpha_a}$ is the unit polarization vector ($\alpha_a = 0$ outside the aperture).

Both the power and phase patterns of such a feed coincide perfectly well with the available experimental data. The far-field pattern of this particular feed satisfies the edge taper requirement of being below 25 dB at the angles of 75°.

H-857-1 is a 30-mode back-to-back conical corrugated horn [4] with the electric field at the aperture specified by the set of hybrid modes similar to those used in [1] for the HFI-545-1 horn. The total far-field pattern is defined as a non-coherent superposition of all the modes of all polarizations.

Amplitudes of the aperture fields are normalized so that each polarized mode has the total power $P_m = 1$.

III. Polarization of the Gaussian beams

Fig. 2 shows the power pattern of the telescope beam H-143-1 as projected on the plane normal to the telescope line-of-sight at the (0;0) point $a_x$ and $a_y$ are the horizontal and vertical axes on the plane, respectively, $m$ measured in degrees). The beam axis is at the point $a_x = 1365$, $a_y = 1^\circ97$ which is defined as the point of maximum power of the beam. The beam is well shaped down to 30 dB below the maximum and can be approximated by a Gaussian function (at this level, the pattern does not depend on polarization) with a full beam width of $W_m = 8.4^\circ$ arcm and $W_{m,ax} = 92'$ arcm measured at 3 dB.

The polarization of the beam is generally elliptical except precisely at the beam axis where it remains linear. In order to achieve the required orientation of the polarization pattern in the sky, we should orient the polarization vector $e_a$ properly on the horn aperture [1].

For immediate comparison of polarizations, we consider
Figure 3. Deviation of the major axis of polarization ellipse from local vertical for the telescope beam HF1-143-1a and HF1-143-1b with (a) \( \alpha = 45 \) and (b) \( \beta = +45 \), respectively.

Figure 4. Magnitude of the minor semi-axis of polarization ellipse in the far field of the telescope beam HF1-143-1a (both cases \( \alpha = 45 \) and \( \beta = +45 \) are rather similar).

The deviation of the major axis of the polarization ellipse from the local meridian as a function of the observation point within the beam in each of the two cases is shown in Fig. 3, (a) and (b), respectively.

When the polarization vector is properly oriented, the cross-polarized component of the far field measured along the respective orthogonal direction in the sky is minimized. In such a case, the power pattern of the cross-polarized component is, basically, determined by the power pattern of the minor axis of the polarization ellipse at each observation point of the beam, Fig. 4.

The latter is very much the same as for any orientation of the polarization vector and can be approximated as follows

\[
P_{cr} = P_{cr0} \left[ (\xi = 0) \sin(\gamma \phi) \exp\left( - (\gamma \phi)^2 \right) \right]
\]  

where \( P_{cr0} \ dB \) is the maximum power of the minor axis component achieved at the points specified by the polar angle \( \phi \) and the azimuth angles \( \phi_0 \), \( \gamma \), \( \phi_1 \), and \( \phi_2 \).
in this approximation depend on the position of the horn considered).

IV. Simulation of multi-modeled horns

Multi-modeled horns are designed for receiving maximum microwave power within the required angular resolution consistent with the requirements on the beam taper at the primary mirror of a level of 25 dB with an aspect angle of 25 degrees. These are rather restrictive and contradictory requirements resulting in the large aperture area of the corrugated conical horns specially optimized for the given application [4].

Since the phase front of the aperture field of a conical horn is convex, the effective focal center is located inside the horn at a distance $R_C$ from the aperture. The horn position is specified by the aperture focus parameter $R_A = R_F + R_C$ where $R_A$ is the distance from the focal plane to the horn aperture measured along the horn axis and $R_F$ is the similar distance to the geometric focus on this axis as found by the ray-tracing software.

One may try to make an estimate of $R_C$ by considering the basic mode of the horn as a Gaussian beam propagating through the horn aperture. For the horn HFI-857-1 (old layout) with the slant length $L = 28 m$ and the aperture radius $a = 2.55 m$, the estimate is $R_C = 11.9 m$ while $R_F = 91 m$ that results in $R_A = 21.9 m$.

A more accurate simulation shows, however, that such an estimate is very misleading. When computing the gain $G$ defined as $G = 10 \log(4 \cdot P(0) - P(0))$ where $P(0)$ is the power of the total multi-modeled field on the beam axis and $P(0)$ is the radiated power of a single polarized mode, one can nd that $G$ as a function of the aperture focus parameter $R_A$ has a maximum at $R_A = 13.5 m$ (Fig. 5).

The accurate value of $R_A$ is different from the rough estimate above by $R_A = 8 m = 23$ that results in an extra gain of about 25 dB. Thus, the multi-modeled horns should be placed slightly further from the secondary mirror compared to the estimates based on the Gaussian approach of the basic mode applied to the optimal focus positions as found by the ray tracing techniques.

V. Conclusions

A fast physical optics simulator has been developed for the analysis of the dual-sector sub-mm far-wave telescope on the ESA Planck Surveyor. The code overcomes the limitations of a generic approach for large multi-sector quasioptical systems and can perform typical simulations of the telescope in the order of minutes.

A study of the power patterns, polarization characteristics, defocusing effects and modal structure of the telescope beams from both Gaussian and multi-modeled horns has been performed. Analysis of the beams from the linearly polarized Gaussian horns have shown that the far-field of the telescope is generally, elliptically polarized except precisely at the beam axis where linear polarization is preserved.

When rotating the polarization vector of the horn field about the horn axis, the major axes of the polarization ellipses remain basically unchanged. Systematic deviations from this basic rule which occur mainly in the peripheral part of the beam can be successfully simulated and taken into account.

Even for the most tilted Gaussian horns located at the edge of the horn array, the power associated with the minor axes of the polarization ellipses in the telescope beam remains at the level of one third of the maximum power of the beam.

In order to achieve maximum angular resolution with multi-modeled horns, the latter should be located slightly further from the secondary mirror compared to the estimates based on the Gaussian approximation of the basic mode applied to the optimal focus positions as found by the ray tracing techniques.

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