HIGH PERFORMANCE CORRUGATED FEED HORNS
FOR SPACE APPLICATIONS AT MILLIMETRE
WAVELENGTHS

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Abstract. We report on the design, fabrication and testing of a set of high performance corrugated feed horns at 30 GHz, 70 GHz and 100 GHz, built as advanced prototypes for the Low Frequency Instrument (LFI) of the ESA PLANCK mission. The electromagnetic designs include linear (100 GHz) and dual shaped (30 and 70 GHz) profiles. Fabrication has been achieved by direct machining at 30 GHz, and by electro-formation at higher frequencies. The measured performances on side lobes and return loss meet the stringent PLANCK requirements over the large (20%) instrument bandwidth. Moreover, the advantage in terms of main lobe shape and side lobes levels of the dual profiled designs has been demonstrated.

Keywords: Cosmic Microwave Background, Corrugated Feed Horns, Space Projects

1. Introduction

Corrugated horn antennas exhibit a combination of highly desirable characteristics, such as high beam symmetry, low cross polarization, large bandwidth, low level of side lobes, good return loss and low attenuation (Olver, 1992; Olver et al., 1994). In the past two decades corrugated horns have been extensively used, either alone or coupled to reflectors, in a number of ground based and space astrophysical observations in the microwave and millimeter wavelength range. In particular, high performance designs have been developed for several experiments devoted to the study of the Cosmic Microwave Background

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(CMB), including the NASA space missions COBE/DMR (Toral et al., 1989), and WMAP\(^1\) (Bennett et al., 2003; Barnes et al., 2002).

Corrugated feed horns will be also implemented in the two instruments (LFI and HFI) onboard the ESA Planck satellite\(^2\) (Villa et al., 2003). Both LFI, the Low Frequency Instrument (Mandolesi et al., 1998), and HFI, the High Frequency Instrument (Puget et al., 1998), share the focal region of a 1.5 meter off-axis dual reflector aplanatic optimized telescope (Dubrueil et al., 2000; Villa et al., 2001). Together, they give Planck unprecedented sensitivity and angular resolution over the full spectral range between 30 GHz and 857 GHz, ensuring the imaging power, the redundancy, and the control of systematic effects and of foreground emissions needed to achieve the mission science goals. Both Planck instrument teams selected dual profiled conical corrugated horns as the best option in the range 30 – 350 GHz since they guarantee superior performance compared with linear conical horns.

Specifically, the dual profiled design permits to optimise the radiation characteristics by reaching a nearly perfect Gaussian shape of the main lobe and level of sidelobes well below −30 dB. While in linear horns the pattern is controlled by the diameter and the flare angle, in dual profiled horns five parameters can be optimised, leading to significantly improved characteristics both from the electromagnetic and mechanical point of view.

The LFI is composed by an array of 12 feed horns at 100 GHz, 6 at 70 GHz, 3 at 44 GHz, and 2 at 30 GHz, feeding 46 radiometers each producing two output channels for a total of 94 detectors. Several prototype feed horns have been produced since 1998 from 25 GHz to 140 GHz by the LFI instrument team (Bersanelli et al., 1998; Guzzi et al., 1999; Villa et al., 1997; Villa et al., 1998). A set of three corrugated feed horns have been designed, developed, and tested as advanced prototypes for the LFI feeds, with the purpose of demonstrating the maturity of the design with respect to the flight performance requirements, including the fabrication technology. One feed at 30 GHz has been developed according to the Flight Model mechanical and electromagnetic specifications. One feed at 70 GHz has been developed to be representative both mechanically and electromagnetically of the six Flight Models foreseen. One 100 GHz feed has been developed specifically to investigate the manufacturing capability to reproduce the corrugation detail. For this feed a linear design with 90 corrugations has been chosen and no mechanical requirements have been imposed.

\(^1\) http://map.gsfc.nasa.gov/
\(^2\) http://astro.estec.esa.nl/SA-general/Projects/Planck/
According to the development philosophy of the LFI, these prototypes constitute the Elegant Bread Board (EBB) model.

2. Electromagnetic and mechanical requirements

The baseline design for all the 23 LFI horns foresees a profiled shape of the corrugated section. Dual profiled corrugated horns have been selected for their compactness both in length and diameter and their superior performances in terms of ability to control the shape of the main lobe, the level of the side lobes and the phase center location. In the linear corrugated horn only the hybrid $HE_{11}$ mode propagates. Typically this mode is selected by having a mixture of $TE_{11}$ and $TM_{11}$ that are running in phase and with the same propagation constant inside the horn. In dual profiled horns, other modes are excited in a controlled way to modify the field distribution at the aperture, being the wanted distribution to be as good as gaussian. In this way, the main lobe exhibits a Gaussian shape and sidelobes may be reduced because of the low level of the field at the aperture rim.

On the other hand, the amplitude pattern of this kind of design exhibits a more pronounced variation in frequency compared to the linear corrugated horns (see Figure 1).

Because of the complexity of the LFI Focal Plane Unit layout, different designs are foreseen even at the same frequency. A total of twelve different designs are needed with the length, the diameter, and the location of the phase center varying with the position of the feeds in the focal plane.

The three prototypes were developed using a different approach for each design. The main performances of the horns required by the Flight Models (FM) compared to the EBB models are summarized in Table I.

In order to satisfy the mechanical constraints imposed by the focal plane layout, both the 30 and 70 GHz feeds need to be short without any degradation of the radiation pattern. These mechanical requirements have been maintained in the EBB design, which satisfy also the flight model electromagnetic specifications. The 100 GHz one is a linear corrugated feed horn with very thin grooves on the corrugations near the throat (Table II), mainly to investigate the manufacturing capability.

The baseline performances and characteristics of the LFI feed horns are shown in Table I. Edge Taper values have been defined for each feed horn, depending on its location in the focal plane. LFI horns are located off–axis and each feed horn illuminates the telescope in a different way. As a consequence the edge taper definition may differ.
This is the case of the 70 and 100 horns. The edge taper definition of these horns varies and in table I only the minimum and maximum edge taper values are reported, for simplicity.

With these prototypes, the design, the development and the manufacturing processes have been optimised and completely characterized.

3. Horn design

The design procedure can be summarized as follows. As a first step the aperture diameter was chosen analytically to give the desired co-polar pattern beamwidth. For the linear design, the diameter has been evaluated by means of simulations carried out by calculating the radiation pattern under the pure $HE_{11}$ mode propagation in circular waveguide with a phase distribution given by a spherical phase front with centre in the apex of the horn (Sletten, 1988). This procedure permitted to perform several simulations with different diameters and flare angles in a reasonable time. Since the depth and shape of the corrugations determine the cross-polar radiation characteristics, their geometry was
Table I. Requirements of all the LFI baseline (FM) feed horns (first four lines) and characteristics of the prototypes (EBB). ET is the Edge Taper, SLL is the maximum Side Lobes Level, X-pol is the cross polarization, RL is the return loss and IL is the Insertion loss. For the 70 and 100 GHz horns the ET varies, depending on the position of the feed horn in the focal plane.

| $v_0$ (GHz) | $\Delta v/v_0$ | ET | SLL | X-pol | RL | IL |
|-------------|-----------------|-----|-----|-------|----|----|
| 30          | 20 %            | 30.0 $\circ\ 22^\circ$ | $\leq -35$ | $\leq -35$ | $\leq -35$ | $\leq -0.10$ |
| 44          | 20 %            | 30.0 $\circ\ 22^\circ$ | $\leq -35$ | $\leq -35$ | $\leq -35$ | $\leq -0.10$ |
| 70          | 20 %            | 20.5 - 25.0 $\circ\ 22^\circ$ | $\leq -35$ | $\leq -35$ | $\leq -35$ | $\leq -0.10$ |
| 100         | 20 %            | 21.0 - 23.3 $\circ\ 22^\circ$ | $\leq -35$ | $\leq -35$ | $\leq -35$ | $\leq -0.10$ |

selected to give the minimum level of cross polarization at the center frequency. The corrugations are about a quarter of a wavelength deep and there are at least three corrugations per wavelength in order to well approximate a continuous impedance surface. The junction and the throat region were designed to optimize the impedance match to the smooth wall waveguide. For this purpose the first slot seen by the smooth wall waveguide is approximately half a wavelength deep with the following few slots (about five) constituting a transition region to the quarter wavelength - steady state depth of the remaining part. Also the teeth and groove length need to be varied continuously between the first corrugations and the steady-state region: a good input matching requires thick teeth and thin grooves, which are used at the beginning, while, on the contrary, HE11 propagation is well supported by thick grooves and thin teeth. Having this in mind, the throat geometry has been obtained. In the case of dual profiled designs, an optimization routine has been applied. Six optimization parameters has been used. They are the slot depth, the teeth and groove width of the first and the steady-state corrugation. These parameters have been varied under a linear low and assuming a definite number of corrugations. Finally, the flare angle and the diameter were optimised by attempts, taking into account the length of the horn and the co-polar pattern characteristics. For this optimisation, simulations have been performed considering the
Figure 2. Corrugation profiles of the three horns (same scale for the three panels). Dimensions are in mm. Note the compactness of the 70 GHz horn which is shorter than the 100 GHz one.

detail of the corrugations. The flare angle does not have to be constant along the horn: a profiled horn is a horn with a flare angle which changes along the horn with a sine square profile. If it is used as a feed for a reflector, as in our case, it can produce important improvements like higher gain and efficiency, very low level of cross polarization, low mass and compactness.

Figure 2 reports the corrugation profile of the three designs. In terms of wavelength normalized total length ($L_\nu$, where $\nu$ is the frequency in GHz), the 30 GHz horn is the shortest one, with $L_{30} = 12.7$. For the horn at 70 GHz, the length is $L_{70} = 14.91$. At 100 GHz, the linear horn is $L_{100} = 27$ long. The advantage of the dual profiled design can be appreciated by these numbers: the 100 GHz horn results a factor of 2 longer (in normalized length) than the 30 GHz one; moreover, for a given edge taper (the 30 GHz and the 100 GHz horns exhibit the same edge taper), the 30 GHz horn results 30% smaller in normalised diameter than the 100 GHz one.

The main geometrical characteristics of the prototypes are reported in Table II and Figure 2.

3.1. Linear design

The electromagnetic design of the 100 GHz horn has been obtained by simulations with Mode Matching (Olver et al., 1994). The flare angle
Table II. Geometry of the EBB LFI corrugated horns. $L$: horn length, $R_{th}$: throat radius, $R_{ap}$: aperture radius, $d_{th}$: corrugation depth at the throat, $w_{th}$: corrugation width at the throat, $d_{ap}$: corrugation depth at the aperture, $w_{ap}$: corrugation width at the aperture. All dimensions are in mm. $\alpha_{max}$: flare angle (degrees). For dual profiled horns the flare angle is not indicated. The aperture diameters have been chosen for matching the Edge Taper requirements of the PLANCK telescope. The inner region of each horn has been chosen in order to minimize the return loss.

| Horn | $L$  | $R_{th}$ | $R_{ap}$ | $d_{th}$ | $w_{th}$ | $d_{ap}$ | $w_{ap}$ | $\alpha_{max}$ |
|------|------|----------|----------|----------|----------|----------|----------|---------------|
| 30 GHz | 146.41 | 4.90     | 25.57    | 4.2      | 1.0      | 2.80     | 2.00     | −             |
| 70 GHz | 77.80  | 2.21     | 11.766   | 1.923    | 0.206    | 1.289    | 0.90     | −             |
| 100 GHz | 88.27 | 1.337    | 9.85     | 1.453    | 0.117    | 0.886    | 0.60     | 6.0           |

has been defined at $6^\circ$ in order to maintain the phase error at the aperture at an acceptable level and to prevent pattern degradations. Although the linear designs are well consolidated, this model represents a challenge from the manufacturing point of view due to the corrugation dimensions. No mechanical constraints have been fixed on this prototype, while stringent requirements have been assumed on the return loss and beam symmetry. As suggested by Xiaolei (1993) an excellent return loss could be reached by gradually increasing the corrugations width near the throat section. This scheme has been applied at best by setting the maximum acceptable return loss at $-35$ dB over the whole 20% of bandwidth.

### 3.2. Dual Profiled Design

The corrugation profile applied for the 30 GHz and the 70 GHz horns, is a mixture of a sine–squared section (Olver and Xiang, 1988), starting from the throat, and an exponential section near the aperture plane (Teniente-Vallinas et al., 2001; Gentili et al., 2000). The dual profiled design has been consolidated according to the corrugation profile, $R(z)$,

$$R(z) = R_{th} + (R_s - R_{th}) \left[ (1 - A) \frac{z}{L_s} + A \sin^2 \left( \frac{\pi}{2} \frac{z}{L_s} \right) \right]$$

$$0 \leq z \leq L_s$$

in the sine–squared section, and

$$R(z) = R_s + e^{\alpha(z-L_s)} - 1; \alpha = \frac{1}{L_c} \ln(1 + R_{ap} - R_s)$$

$$L_s \leq z \leq L_c + L_s$$

in the exponential region. Here, $R_{th}$ is the throat radius, $R_s$ is the sine squared region end radius (or exponential region initial radius), $R_{ap}$ is
the aperture radius, \( L_s \) is the sine squared region length and \( L_e \) is the exponential region length. The parameter \( A \) (\( 0 \leq A \leq 1 \)) modulates the first region profile between linear and pure sine squared type. The parameters \( L_e/(L_e + L_s) \), \( A \) and \( R_s \) can be used to control, as far as possible, the position and frequency stability of the phase center and the compactness of the structure.

The electromagnetic simulations have been carried out using a hybrid method based on Mode Matching (MM) technique combined with the Moment Method (MoM) (Coccioli et al., 1996). The MoM is used for the calculation of the radiation pattern taking into account the field distribution on the aperture plane and the currents traveling on the external part of the horn.

This hybrid technique is based on a particular formulation of the equivalence principle and the generalised scattering matrix approach which has the power to give directly the return loss at the throat with the contributions coming both from the internal corrugated region and the external feed shape. Moreover the use of the MoM makes it possible the accurate calculation of the currents on the horn exterior conductor surface and the fields on the aperture, which are the sources of the electromagnetic field. From the sources, the beam pattern is easily computed by using the radiation integral. Finally an optimisation algorithm has been used to match the required electrical performances and mechanical properties by searching for the best horn geometry; edge taper, side lobe level, phase center and return loss have been considered in the cost function to be minimised while the corrugation geometry and the parameters defining the corrugation profile have been used as optimisation variables.

4. Fabrication

Because of the small corrugation size, electroforming has been chosen to manufacture the 70 and 100 GHz horns, while 30 GHz horn has been built using electro-erosion. In the first case, a pure aluminum master is directly machined with the inverse groove pattern, and used to collect copper ions in a low current bath. This technique guarantees very high precisions. The inner corrugation profile has the dimensional tolerances of the master as the electroformed material follows its profile at molecular level. The master is eventually removed with a corrosive chemical solution, and the corrugated internal surface of antenna is cleaned by cycling it in an ultra-sound device. Finally the feed horn is gold plated. Figure 3 reports the difference between the measured and theoretical 100 GHz mandrel dimensions as function of the corrugation.
Figure 3. Differences (μm) between the theoretical dimensions and the measured dimensions of two 100 GHz mandrels. On the abscissa, the corrugation number is reported, from the throat to the aperture. Crosses and circles are referred to the deviation between the measured and theoretical dimensions, along the horn axis, of the grooves. Asterisks (triangles) and diamonds (squares) are the differences of the groove (teeth) dimensions perpendicular to the horn axis.

number from the throat to the aperture: an accuracy < 10μm can be reached.

As the 30 GHz feed horn has larger dimensions, the electro–erosion process of an aluminum cylinder has been used to manufacture it. The choice of aluminum electro–erosion has mainly the advantage of reducing the feed horn mass, which is very important for their use on board a satellite. Electro–erosion, also known as electrical discharge machining, is a process by which conductive materials can be removed from a metal by an electric spark. The 30 GHz prototype has been manufactured by electro-erosion of a piece of Aluminum alloy 6061, frequently employed for cryogenic space applications.
5. Measurements

The measurements were performed with a Millimetre Vector Network Analyzer\(^3\) (MVNA) in a semi-anechoic environment, obtained using a screen of Eccosorb panels around a wooden bench where the test was made. A standard conical horn, with a directivity nearly 21 dBi, was placed at about one meter from the aperture of the feed horn under test and was used as the fixed receiver. With the adopted setup, standing wave effects have been checked to have a negligible effects on the pattern measurements.

The feed horn was mounted on a rotation stage connected to the MVNA, that can drive the angular sweeps directly. Two VNA heads measured the transmission between the horn under test and the measuring one at fixed frequency.

Two translation stages were mounted above the rotation stage. They allowed the feed horn to be moved with good precision along the x,y coordinates in the plane perpendicular to the rotation axis. The x movement (perpendicular to the horn axis) was required for alignment, to adjust the position of the horn so that its axis was exactly intersecting the rotation axis. Otherwise the phasefront measurements would be biased by a spurious contribution due to misalignment. The degree of freedom along the axis of the horn (i.e. y) was used to evaluate the position of the phase center from the measured phase pattern, which was exactly flat when the rotation axis and the phase center were coincident.

Even if the translation stages have 0.01 mm precision, the overall uncertainty is given by the positioning of the horn on the mounts, therefore only ± 0.5 mm.

5.1. Beam Pattern

The radiation pattern in the principal (E and H) planes for the 30, 70 and 100 GHz EBB feed horns are shown in Figures 4 ÷ 6. Typical measurement uncertainty ranges from ±0.2 dB to ±0.5 dB as the power decreases. A comparison with the electromagnetic simulations based on Mode Matching (MM) techniques combined with a Moment Method (MoM) code is also reported for each plane. The far sidelobe level (at off-axis angles greater than 80 degree) is about −60 dB for the feed horns at 30 and 70 GHz, while it is about −55 dB for the feed horn at 100 GHz. The expected sidelobe levels have been met in all cases. It should be noted that the simulations do not take into account the real geometry of the setup like the Eccosorb surrounding the

\(^3\) AB·millimetre Model MVNA 8-350; \texttt{http://www.abmillimetre.com}
horn aperture and supporting structures. Thus, differences between the simulations and the measurements may arise in the sidelobes as noticed in Figure 4.

The main lobe of each beam pattern shows a high degree of symmetry, as expected. A very good symmetry is achieved also at large offset angles, for each feed.

![Figure 4. Comparison between E and H plane patterns measured (triangles) and simulated (solid line) at 30 GHz.](image)

5.2. Return Loss

Return loss measurements were made using a non standard rectangular-circular transition connecting the horn to the MVNA. Time-domain analysis was used to remove the effects of external reflections and the transition. A wide frequency sweep was Fourier transformed, and the resulting time series was cleaned in regions corresponding (via the group velocity) to the transition and environmental contributions. In the design phase of the horns, a return loss better than $-30\text{dB}$ over the full bandwidth has been required. Although a $5\text{dB}$ of return loss degradation due to imperfections and flange connections is still tolerated, Figure 7 shows that the measured return loss of the three horns is close to the predictions and then well within requirements.
5.3. Phase Center

Phase patterns in the principal (E and H) planes have been taken for several displacements of the EBB feed horn under test along its axis, toward the receiver. The curvature of the phase front was estimated with a parabolic fit of its central region, where the pattern can be assumed Gaussian. The coefficient of the quadratic term was plotted versus the displacement of the rotation axis from the aperture. The zero-crossing position marks the point where the rotation axis is exactly through the phase center. The phase centres of the three horns have been measured in this way.

For the 30 GHz feed horn the phase centre resulted at $-10.7 \pm 0.5$ mm and $-13.3 \pm 0.5$ mm from the aperture plane for the E plane and H plane, respectively. For comparison, the requirement has been assumed to be $-12.39$ mm below the aperture plane.

For the 70 GHz horn, the phase center location resulted at $-2.11 \pm 0.5$ mm for the E plane and $-0.71 \pm 0.5$ mm for the H plane. The requirement of the phase centre has been assumed to be at $-2.36$ mm.

At 100 GHz, the phase centre resulted at $-9.87$ mm for the E plane and $-6.33$ mm for the H plane. For this horn the requirement has not been specified.
Figure 6. Comparison between E and H plane patterns measured (triangles) and simulated (solid line) at 100 GHz.

Figure 7. Return loss of the EBB horns; measured data (plus signs) and simulations (solid line). Left: 30 GHz, middle 70 GHz and right 100 GHz.

6. Conclusion

Three high performance corrugated conical feed horns at 30 GHz, 70 GHz and 100 GHz have been designed, fabricated, and tested, as advanced prototypes for the Low Frequency Instrument (LFI) of the ESA PLANCK mission. The horns include linear and dual-profiled designs, and both electro-forming and electro-erosion fabrication techniques.
The 100 GHz horn has been designed as a linear corrugated feed horn while 30 and 70 GHz were dual profiled corrugated horns. The 30 GHz prototype has been manufactured by electro-erosion and the fabrication at higher frequencies has been achieved by electro-formation. The position of the phase center has been evaluated for each feed horn. The measured performances on side-lobes and return loss are met over the large (20%) bandwidth required by the LFI high sensitivity measurements. All the prototypes showed a return loss well below $-30\text{dB}$ ($-25\text{dB}$ if the degradation due to the flanges is considered), as required. The side lobe level, as expected, resulted not exceeding the $-35\text{dB}$ below the peak. Accurate horn models are required in order to compute the optical response of the entire feed–telescope system. Although the cross–polar field of these prototypes has not been measured, the simulation results indicate that the maximum level of cross polarization does not exceed -30 dB. However, in the case of PLANCK/LFI, the cross–polar level is dominated by the telescope, since the LFI feeds are located far from the optical axis where aberrations become important.

Typically, the predicted pattern (in amplitude and phase) of the horns are used as input for reflector antenna codes in order to simulate the radiation pattern of the telescope. These codes require that the horn pattern must be known in several azimuthal cuts, both in amplitude and phase, in order to accurately predict the currents on the reflectors. This is not easy to do by measurements. The excellent agreement between the simulated and measured pattern, as in the case of the horns described here, allows the use of the simulated pattern for precise optical calculations.

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