Study of corrugated Winston horns

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ABSTRACT

Smooth walled Winston horns have been extensively used as light collectors for bolometric instruments. Used in multimoded operation without a waveguide, the beam shape is top-hat like and a simple equation is sufficient to define its Full Width Half Max. On the other hand, it is well known that corrugated feed horns are more efficient than smooth walled horns and much better well behaved with respect to polarization characteristics and sidelobe rejection. We present in this paper a study of corrugated Winston feed horns which could be used for future Astronomical instruments devoted to Cosmic Microwave Background (CMB) polarization measurements. We show that in this case low cross-polarization can be expected in single moded operation and that they could produce lower sidelobes levels compared to conical or profile shapes.

Keywords: CMB experiments, corrugated feedhorns

1. INTRODUCTION

For decades feed horn optics have been extensively studied for radio and millimetre spectral domains. In the particular field of mm and sub-mm Astronomy, they have been associated most of the time with coherent receivers through rectangular waveguides, this technique being the only way to couple the incoming radiation to this type of detectors. The result is then in general a single moded receiver which is sensitive to one polarization only, (due to rectangular waveguide) and a reduced spectral bandwidth (the latest heterodyne receivers have a bandwidth of 25% maximum). On the other hand, direct detection technique such as bolometers or photoconductors can be operated associated with a feedhorn or as a bare detector. The fact that bolometers are sensitive to any kind of radiation allows in principle a very large bandwidth. They are however optimised for a spectral band, but can be used in multimoded operation through a circular waveguide due to the fact that they are incoherent detectors. For that reason, overmoded horns have been used traditionally in far-infrared bolometric instruments, especially Winston horn because of their well-defined flat top beam when operated with many modes.

The big step forward in the field of experimental cosmology in the last decade has heavily relied on the use of feedhorn coupled bolometric detectors because of their very high sensitivity. Experiments dedicated to the observation of the Cosmic Microwave Background and its anisotropies have shown how important the definition and the knowledge of the beam are in order to get an accurate reconstruction of the CMB power spectrum, and how crucial are other parameters such as sidelobe rejection and sensitivity. Moreover, the current and next generations of cosmological experiments will have the goal of measuring the polarization of the CMB which is much fainter than the signal from the anisotropies. For that purpose we then need the unbeaten sensitivity of the bolometers in the sub-mm/mm spectral range coupled to very low cross-polarization feedhorn optics.

Two different avenues are investigated in term of future CMB polarization experiments. Large focal plane arrays to increase the number of detectors and therefore the overall sensitivity, each detector having an associated horn to couple the radiation from the telescope, and bolometric interferometry where the horn is looking directly to the sky without any mirrors in front of it to limit the systematic effects that become an important limiting factor in the data analysis. On the one hand we then want to have horns with a small aperture to pack as many detectors as possible in a limited focal plane size (as the optics for bolometers as to be cooled down to typically 4K) and possibly with a phase centre located not too far from the aperture to get a good imaging capability. This latest point is also important in order to avoid efficiency losses when trying to couple the radiation between to horns facing each other as it is the case in the focal plane configuration adopted for many CMB experiments such as Planck-HFI [1], Archeops [2] or Boomerang [3]. On the other hand we also need larger aperture (comparatively to the operating wavelength) feedhorn optics in order to get one or few

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degrees resolution without the use of a telescope. In any cases, both type of feedhorn will be required to have low sidelobe rejection and low cross-polarization level, keeping in mind that the horn length should be kept to a minimum for mass and dimension restrictions inherent to cryogenic instruments.

2. SMOOTH WALLED WINSTON HORN

Winston horns [4] have been used for many years to couple radiation to bolometers. It can be described as an off-axis parabolic profiled geometry based on three interlinked parameters defining its shape: the length L, the front aperture diameter D and the exit aperture diameter d (fig. 1). In multimoded operation when many modes are allowed to propagate, a top hat like far-field beam pattern can be obtained which can be well modelled by ray-tracing techniques. The maximum acceptance angle α for which the incoming rays reach the exit aperture of the cone is then given by:

$$\sin(\alpha) = \frac{d}{D} \quad \text{(eq. 1)}$$

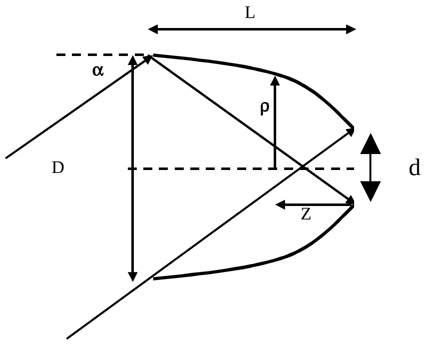

Fig 1: Winston horn diagram with defining parameters

However, ray-tracing becomes a poor approximation when only a few modes or a single mode are transmitted, and more sophisticated modelling should take place such as mode matching or finite element techniques. Indeed, using a mode matching software, the single-moded beam pattern is then predicted to be close to a Gaussian shape. We can see in fig 2a showing models of the beam pattern of three smooth walled Winston horn with a different aperture, that the beam does not have a flat top anymore and that the acceptance angle α calculated following equation 1 does not give the correct Full Width Half Maximum.

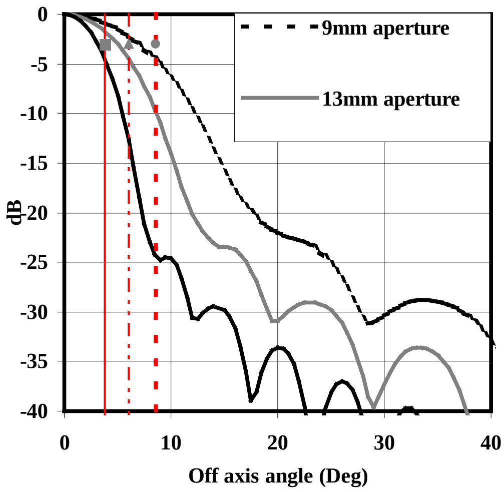

Fig 2a: Beam pattern of 3 smooth walled Winston horns with various apertures. Dot, triangle and square are showing α for 21, 13 and 9 mm apertures respectively

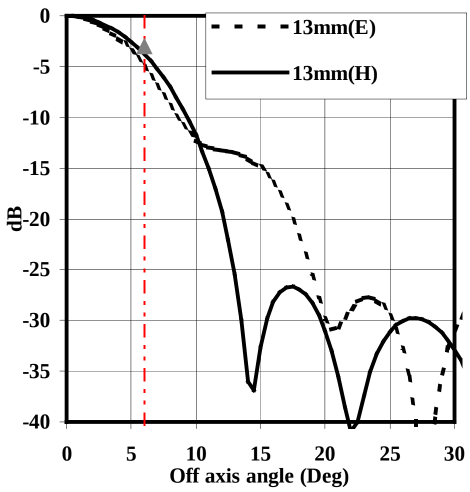

Fig2b: E and H plane of polarization for a 13mm aperture smooth walled Winston horn. Triangle is showing α

It is well known [5] that for smooth walled single moded horn, the radiation pattern will not be the same depending on the direction of polarization. We can see in figure 2b that for a smooth walled Winston horn having an aperture of 13mm, the E-plane beam profile is different from the H plane one. Not only this effect make the horn polarization dependent but it also increases the sidelobes level. The solution is then to use corrugated horns.

3. CORRUGATED WINSTON HORN

Corrugated horns have a much lower return loss due to a better match between free space and the horn, and their beam pattern is much better behaved with respect to sidelobe rejection. Moreover, in single moded operation (Hybrid mode HE11) selected through a corrugated circular waveguide, these horns have a very low cross-polarization level. It is then logical to study the properties of a corrugated Winston horn if we want to use it for the detection of polarized signal or when sidelobe rejection matters. Figure 3 shows clearly the advantage of having a corrugated versus smooth walled Winston horn. While the mode matching software we are using has been cross-checked in the past with other software and experimental data, we took also the opportunity to cross validate the far-field horn beam pattern between a mode matching technique and with HFSS package. Results on a small aperture (5λ - 150GHz) corrugated Winston horn are shown in figure 4 where we can see the good agreement between both computations. From then on we will use the mode matching technique to predict the far-field beam pattern as it runs much more quickly, keeping in mind that HFSS allows us to get much more information such as the near-field which are not presented here.

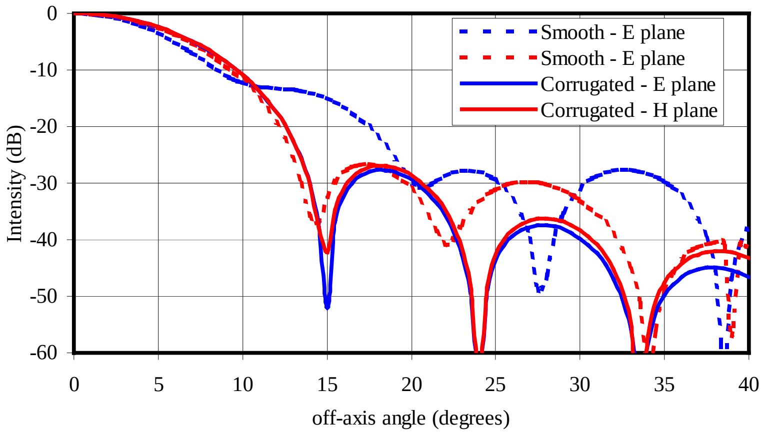

Fig 3 Comparison of smooth walled and corrugated Winston horn beam patterns for both E anf H plane of polarization

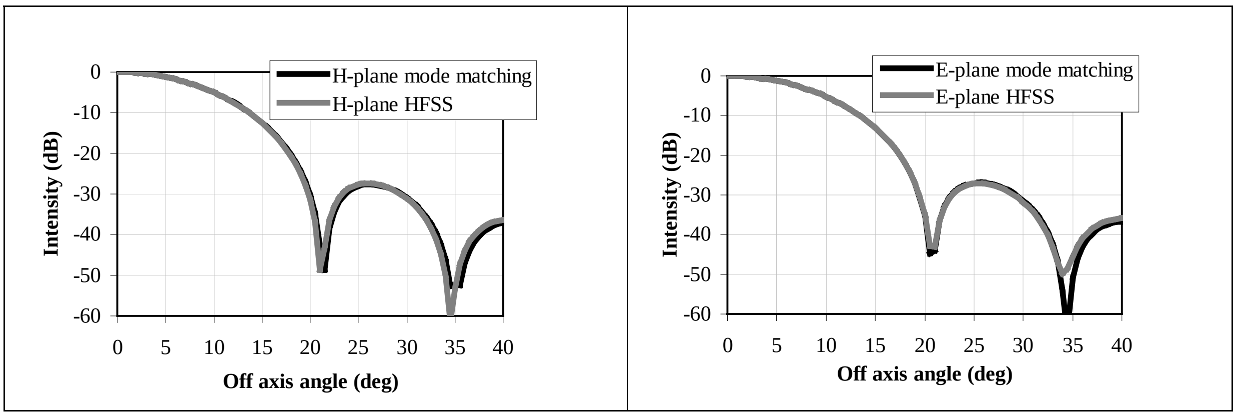

Fig 4 H and E planes of polarization for a corrugated Winston horn. Mode matching technique compared to HFSS modelling

We known that it is possible to get very low sidelobe rejection by adding a flared or Gaussian section at the end of a profiled horn [6][7]. However, this flare usually makes the aperture of the horn quite large without any gain in term of throughput as this one is constant and is given by $A\Omega=\lambda^2$ (eq 2) for a single moded horn where A is the collecting area (horn aperture), Ω is the solid angle defined by the horn beam pattern and λ the observed wavelength. In the case of an array of detectors, this will result in a larger and heavier focal plane or possibly reducing the number of pixels that could be fitted, thus reducing the sensitivity. So we will constrain our study in the case where no flared section is added and we are presenting, below, results for various aperture diameters (in order to get a range of beam resolution) to be compared with two other classical geometries, conical and profiled shapes.

3.1 10λ aperture diameter

One of the first study, in the frame of a new project, was to study a horn for a central frequency of 150GHz (2mm wavelength) giving a Full width half maximum of about 7.5 degrees. In this case we had to target an aperture of about 20mm diameter. For the reason stated above we do not want to use a flare section but still want to get the best sidelobe rejection possible. The three geometries considered are conical, profiled and Winston horns 100mm long.

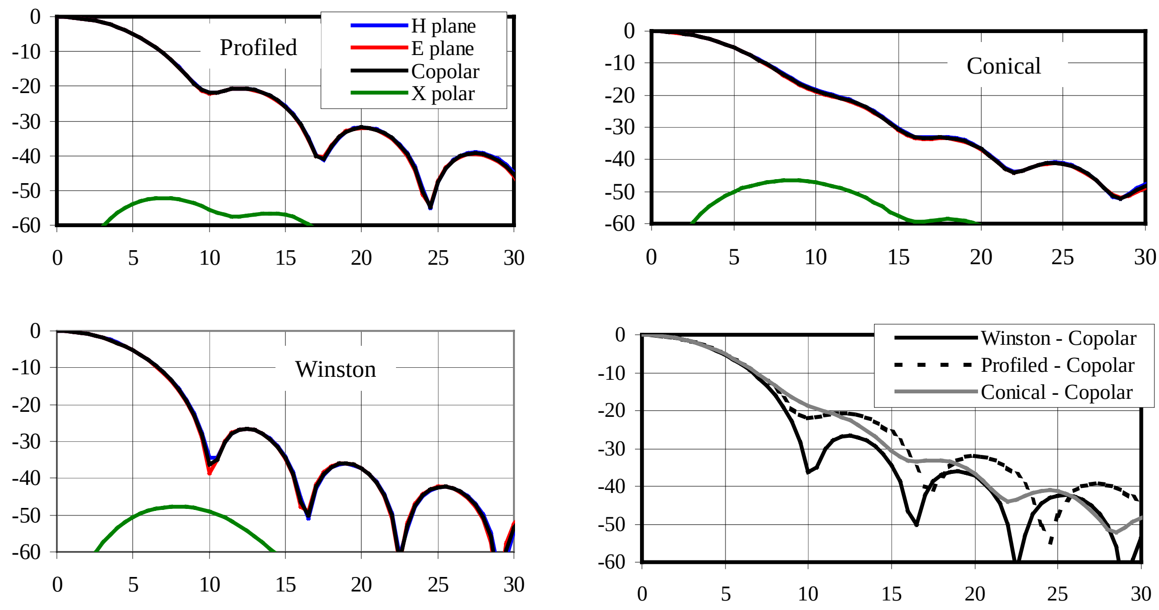

Fig 5 10λ aperture horns: Individual plots are showing E and H planes, co and cross-polarization. Bottom right plot is showing the comparison of the co-polarization for the three geometries

From fig 5 we can see as expected [5] that all the geometries are giving a low cross-polarization level in single moded operation (hybrid more HE11) down to a level of about –45dB. However, the co-polarization comparison between the three different geometries (Winston, Conical and Profiled) shows that it is possible to get lower sidelobe levels with a Winston horn. In this case, while the full width half maximum is the same for the three geometries, the sidelobe level is lowered by 5dB. Other simulations not shown in this paper are indicating that for small apertures (below 10λ), while the difference is smaller, the Winston geometry is showing still a better sidelobe rejection.

3.2 20λ aperture diameter

For some experiments such as interferometry where horns can be used without a telescope, the resolution will then be given by the baseline defined as the distance between the centres of the apertures of two horns. Cosmological observations are in need of sub-degree resolution in order to measure the CMB power spectrum at small angular scale. Typical baseline could then be of the order of 40mm for a wavelength of 2mm. On the other hand, while for single moded optics, the throughput is constant and follows the equation 2, it is suitable to use horns with an aperture as large as possible in order to optimise the experiment. So the first study is base on 40mm aperture diameter horns. To be used with bolometric detectors, these horns will have to be cooled down to a few Kelvin, making the mass and dimensions very important parameters.

Starting with a horn following the exact Winston equation, a 40mm aperture horn single moded at 150GHz should be 500mm long. Obviously too long, we then compare it with a truncated Winston horn 200mm long with the results displayed on Figure 6. We can see that even by reducing the length by more than a factor 2, the impact on the beam profile is minor. The cross-polarisation within the main beam is slightly increased while the sidelobe level is still below 23dB (increased by about 5dB). From then, we are considering two sets of horns (40mm aperture-20λ - case 1, 200mm long, and 30mm aperture-15λ, 100mm long- case 2) with different geometries and compare how the optical characteristics are changing. Drawings of the various shapes are represented in figure 7 while the beam pattern comparison for the co-polarization is shown in figure 8 (case 1) and figure 9 (case 2).

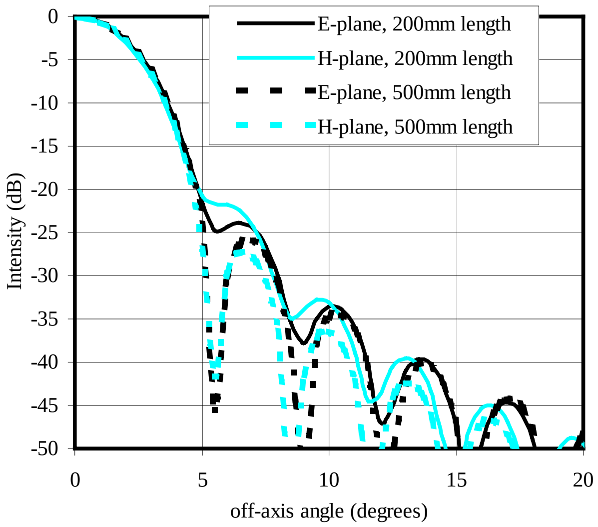

Fig 6: Corrugated Winston horns with 40mm aperture. Comparison between a length of 500mm and 200mm

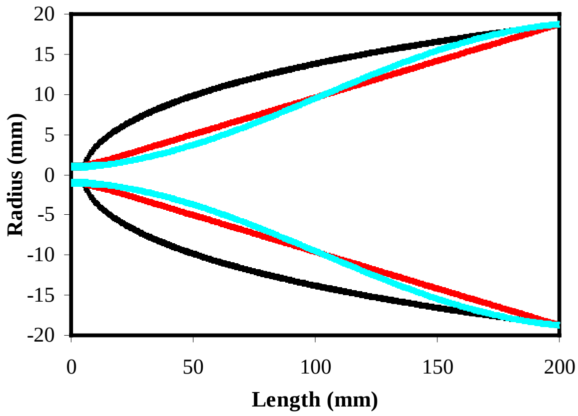

Fig 7: Geometry comparison: Winston (black), Conical (red) and profiled (light blue) horns

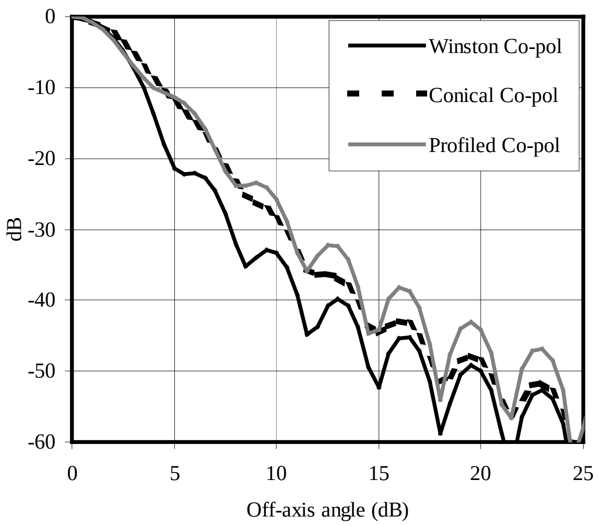

Fig 8: 40 mm aperture corrugated horns at 150GHz. Comparison between 3 geometries, 200mm long (case 1)

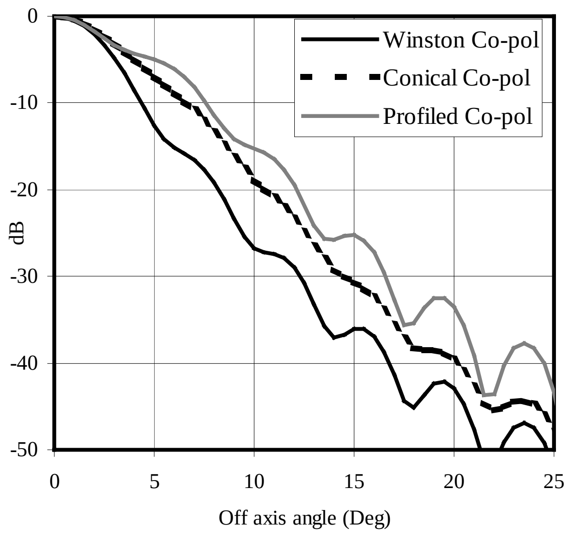

Fig 9: 30 mm aperture corrugated horns at 150GHz. Comparison between 3 geometries, 100mm long (case 2)

From these two figures we can see that when the aperture is large in comparison to the wavelength and when the ratio between the aperture and the length is increasing, the beam pattern produced by a corrugated Winston horn is more Gaussian-like. For case 1 the sidelobes still are below 20dB, quite lower than the conical and profiled horns, while even in an extreme example such as case 2, the results from the Winston horn might be acceptable still.

Table 1 is giving a summary of the return loss and directivity for each of the cases we have studied for this paper. Again, if for small apertures the three shapes are giving similar results, when the ratio aperture/length is increasing the Winston horn is a better alternative.

Geometry	Winston		Conical		Profiled	
	Rtn Loss	Directivity	Rtn Loss	Directivity	Rtn Loss	Directivity
10mm aperture, 43mm length	-19.2	22			-21	22.2
20mm aperture, 100mm length	-19.1	28.2	-19.3	27.8	-17.7	27.7
40mm aperture, 200mm length	-24.6	33.7	-18.7	32	-17.4	32.4
30mm aperture, 100mm length	-22.8	31.5	-19.9	28.8	-18.5	27.6

Table 1: Return loss and directivity for various horn apertures

3.3 Phase centre location

When using the full length of a corrugated Winston horn, the phase centre is located at the aperture independently to the diameter of this one. That could have indeed advantages in some cases (horn coupling in Planck-HFI detection assembly configuration). Even when truncated down to a reasonable length, the phase centre still is located not too far from the aperture. A 20mm aperture horn well suited for the horn coupling at 150GHz aforementioned the phase centre will be located at 2mm, 8mm and 15mm from the aperture for a Winston, profiled and conical corrugated horn respectively

In the case of the 40mm aperture Winston horn, we have seen that the full length will have to be of the order of 500mm. When truncated down to 200mm (less than half the length), models are showing that the phase centre is at a distance of about 30mm from the entrance while for similar dimensions a profiled horn will have its phase centre at 50mm from the aperture and a conical will have his well inside the horn (100mm – middle of the horn).

4. CONCLUSION

We have shown that corrugated Winston horn could have better optical characteristics than other horns. They have a low level of cross-polarisation like other corrugated horns but are showing a lower sidelobe level in most cases. While the difference is relatively small for small apertures, the sidelobe rejection is well improved for large aperture horn. This beam improvement is even clearer when the aperture diameter – horn length ratio is large (0.3-0.4). This type of horn is then well suited for application where cross-polarisation and sidelobe rejection are of concern and when the dimension of the device could be an issue. They could have then a direct application in the field of experimental Cosmology where the measurement of the CMB polarization will require all these criteria.

Moreover, we have seen that these horns could also have a use in close packed arrays of detector for which the dimensions are a real issue. Providing that for such experiments the beam quality requirements can be slightly relaxed, Winston horns could be shorter inducing a slight decrease in optical performances only but keeping a well behaved main beam still.

5. REFERENCES

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