Multiple flare-angle horn feeds for sub-mm astronomy and cosmic microwave background experiments

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ABSTRACT

Context. The use of large-format focal plane imaging arrays employing multiple feed horns is becoming increasingly important for the next generation of single dish sub-mm telescopes and cosmology experiments. Such receivers are being commissioned on both general purpose, common user telescopes and telescopes specifically designed for mapping intensity and polarisation anisotropies in the cosmic microwave background (CMB). Telescopes are currently being constructed to map the CMB polarisation that employ hundreds of feeds and the cost of manufacturing these feeds has become a significant fraction of the total cost of the telescope.

Aims. We have developed and manufactured low-cost easy-to-machine smooth-walled horns that have a performance comparable to the more traditional corrugated feed horns that are often used in focal plane arrays. Our horns are much easier to fabricate than corrugated horns enabling the rapid construction of arrays with a large number of horns at a very low cost.

Methods. Our smooth walled horns use multiple changes in flare angle to excite higher order waveguide modes. They are designed using a genetic algorithm to optimise the positions and magnitudes of these flare angle discontinuities. We have developed a fully parallelised software suite for the optimisation of these horns. We have manufactured prototype horns by traditional electroforming and also by a new direct drilling technique and we have measured their beam patterns using a far-field antenna test range at 230 GHz. We have developed a new type of high performance feed horn that is fast and easy to fabricate. Having demonstrated the efficacy of our horn designs experimentally, we are building and testing a prototype focal plane array of 37 hexagonally close packed horns. This prototype array will be an important step towards building a complete CMB mapping receiver using these feed horns.

Key words. instrumentation: detectors – instrumentation: photometers – instrumentation: spectrographs – instrumentation: polarimeters – submillimeter: general – cosmic background radiation

1. Introduction
1.1. Astronomical motivation

Bolometric and heterodyne detectors are now approaching the background and quantum limits in sensitivity at sub-mm wavelengths and further gains in single dish telescope mapping speed therefore requires the integration of large numbers of detectors into the telescope focal plane. Such instruments, with many hundreds of detectors, are forming the next generation of both general purpose sub-mm instruments and cosmic microwave background mapping experiments. While “CCD-style” filled-aperture bolometer arrays, such as SCUBA-2 (Holland et al. 2006), are suitable for some mapping applications, heterodyne receivers (e.g., HARP-B Smith et al. 2008) and TES bolometer focal plane arrays for CMB mapping (e.g., Clover, North et al. 2008) continue to consist of close packed arrays of feed horns. Such feedhorn arrays are popular since they offer the high aperture efficiencies, low sidelobes, low stray light sensitivities and low cross-polarisations required for many astronomical applications. The problem of rapidly fabricating large numbers of high quality feeds at an acceptable cost is becoming increasingly difficult, and the cost of horn array fabrication is becoming a large fraction of the total instrument cost.

Table 1 describes some current and proposed mm and sub-mm wavelength focal plane arrays. Feedhorn arrays rather than filled-aperture bolometer arrays are seen to dominate both heterodyne receivers and CMB mapping experiments. For heterodyne receivers, arrays of feed horns are currently the only way to couple the astronomical and local oscillator signals efficiently into a waveguide and then to an SIS (superconductor-insulator-superconductor) or HEB (hot-electron-bolometer) mixer chip. For CMB mapping experiments, arrays of feed horns provide both the low sidelobe and low cross-polarisation levels that are essential scientific requirements. While filled-aperture bolometer arrays can provide higher mapping speeds with simpler observing modes, they are less sensitive for pointed observations and require more detectors in the focal plane to cover the same area of sky (Griffin et al. 2002). They are also much more
vulnerable to stray radiation within the detector cryostat and so must be used with a very carefully designed optical system, typically consisting of a series of cooled aperture stops.

Common user submillimetre telescopes are increasingly falling into two scientifically complementary categories: (i) large aperture single dish telescopes equipped with focal plane array receivers that can rapidly map large areas of the sky, and (ii) interferometers that are best suited to mapping small areas of the sky with very high angular resolution. Typically, large area interferometers that are best suited to mapping small areas of the sky, and (ii) aperture single dish telescopes equipped with focal plane array receivers that can rapidly map large areas of the sky, and (ii)

<table>
<thead>
<tr>
<th>Name (telescope)</th>
<th>Band(s)</th>
<th>No. of pixels</th>
<th>Detector type</th>
<th>Array type</th>
<th>Horn type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCUBA (JCMT)$^a$</td>
<td>850, 450 μm</td>
<td>37, 91</td>
<td>Bolometer (Ge)</td>
<td>Horn</td>
<td>Conical</td>
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<tr>
<td>HARP-B (JCMT)$^b$</td>
<td>350 GHz</td>
<td>16</td>
<td>Heterodyne (SIS)</td>
<td>Horn-reflector</td>
<td>Filled</td>
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<tr>
<td>SCUBA-2 (JCMT)$^c$</td>
<td>850, 450 μm</td>
<td>5120, 5120</td>
<td>Bolometer (TES)</td>
<td>Filled</td>
<td>-</td>
</tr>
<tr>
<td>BOLOCAM (CSO)$^d$</td>
<td>2.1, 1.4, 1.1 mm</td>
<td>144</td>
<td>Bolometer (Ge)</td>
<td>Horn</td>
<td>Conical</td>
</tr>
<tr>
<td>Supercam (HHT)$^e$</td>
<td>350 GHz</td>
<td>64</td>
<td>Heterodyne (SIS)</td>
<td>Horn</td>
<td>Diagonal</td>
</tr>
<tr>
<td>SHARC-2 (CSO)$^f$</td>
<td>350, 450 μm</td>
<td>384</td>
<td>Bolometer (Si)</td>
<td>Filled</td>
<td>-</td>
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<tr>
<td>SPIRE (Herschel)$^g$</td>
<td>250, 350, 500 μm</td>
<td>139, 88, 43</td>
<td>Bolometer (Ge)</td>
<td>Horn</td>
<td>Conical</td>
</tr>
<tr>
<td>SEQUOIA (LMT)$^h$</td>
<td>85–116 GHz</td>
<td>32</td>
<td>Heterodyne (MMIC)</td>
<td>Horn</td>
<td>Diagonal</td>
</tr>
<tr>
<td>AzTEC (LMT)$^i$</td>
<td>2.1 mm, 1.1 mm</td>
<td>144</td>
<td>Bolometer (Ge)</td>
<td>Horn</td>
<td>Conical</td>
</tr>
<tr>
<td>GIMO (IRAM)$^j$</td>
<td>2 mm</td>
<td>128</td>
<td>Bolometer (TES)</td>
<td>Filled</td>
<td>-</td>
</tr>
<tr>
<td>LABOCA (APEX)$^k$</td>
<td>87 μm</td>
<td>295</td>
<td>Bolometer (Ge)</td>
<td>Horn</td>
<td>Conical</td>
</tr>
</tbody>
</table>

### References

(a) Holland et al. (1999); (b) Smith et al. (2008); (c) Holland et al. (2006); (d) Mauskopf et al. (2000); (e) Grenier et al. (2003); (f) Griffin et al. (2003); (g) Narayan et al. (2004); (h) Wilson et al. (2008); (i) Staguhn et al. (2008); (j) Siringo et al. (2009); (k) Niemack et al. (2008); (l) Grimes et al. (2009); (m) Yoon et al. (2006); (n) Crill et al. (2003); (o) Reichborn-Kjennerud et al. (2010); (p) Arnold et al. (2010); (q) Cahill et al. (2004); (r) Ade et al. (2010); (s) Ruhl et al. (2004); (t) De Bernardis et al. (2008); (u) Runyan et al. (2010).

### 1.2. Submillimetre feed horns

Corrugated horns (Clarricoats 1984) are often used as sub-mm astronomical feeds, and have been used successfully in focal plane array receivers. These horns have azimuthal corrugations in their interior that present isotropic surface boundary conditions to the electric and magnetic fields resulting in the propagation of a so-called hybrid HE$_{11}$ mode (Olver et al. 1994). Corrugated horns require several corrugations per wavelength, and each corrugation is close to a quarter wavelength deep away from the throat of the horn. While the radiation properties of these horns can be excellent over a wide bandwidth, they can be difficult and expensive to manufacture, particularly as the wavelength decreases into the THz regime. Typical fabrication methods include either electroforming or direct machining into a split block. For electroforming, an aluminium mandrel that is the shape of the required horn interior is turned on a lathe and then electroplated with a suitable metal (e.g., copper). The mandrel is then dissolved chemically to leave the finished horn. In split-block machining, the corrugated horn is fabricated directly in each half of a block of metal using a high precision milling machine. For either technique, a typical corrugated horn for wavelengths of around 1 mm will cost between 1000 and 2000 US dollars.

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2. Feed horn design using a genetic algorithm

The horns described in this paper were obtained using a genetic algorithm, the details of which have been previously reported by Kittara et al. (2007) and hence will be only briefly described here. Genetic algorithms employ a natural selection process similar to biological evolution to solve optimization problems (Haupt & Haupt 1998). We begin by encoding each of the parameters describing the geometry of a horn (i.e. \( R_0, R_1, R_2, R_3, L_1, L_2, L_3 \) in Fig. 1b) to form a binary string known as a chromosome. Here the continuous numerical value of each parameter is represented by a binary integer, which is then further encoded using a Gray code, to ensure that each successive integer value differs only by a single bit. The collection of chromosomes, describing one particular horn geometry, is known as an individual. An initial population of individuals is formed where the parameters are chosen randomly between sensible upper and lower constraints e.g., such that \( R_{1\text{min}} < R_1 < R_{1\text{max}} \). In our case, these constraints are chosen such that the first two discontinuities are near the throat and are followed by a long, smooth phasing section. The fitness of each individual is now found by the evaluation of a cost function (described in detail below) that measures the quality of the individual’s far-field beam pattern. These beam patterns are calculated for each individual using the modal matching technique.

Once the cost function has been calculated, the individual horn designs with a high fitness (low cost function) are selected to form the parents that produce the next generation of individuals via a mating process. This mating process uses crossover and mutation to provide genetic diversity in the offspring population. In crossover, each parent chromosome is divided at the same random point along its length, and then the two offspring chromosomes are formed by swapping over each end of the two parent chromosomes and joining them back together. The Gray code encoding of the chromosomes described above ensures that this crossover will produce offspring chromosomes that are not too numerically dissimilar to the parent chromosomes. After the offspring are formed by crossover, the individual bits of each offspring chromosome may be flipped with some small probability, thus mimicking the random mutation in biological natural selection.

After the new population of horn designs has been formed, the cost function for each individual design is re-evaluated, and the mating process is repeated to form a new generation. Thus
the average fitness of the population of horns will tend to increase as the number of generations increases. After a sufficient number of generations the fittest individual horn design is selected, and further optimised using a Simplex minimisation technique.

Any optimisation algorithm requires a careful choice for the cost function that is to be minimised. We have chosen a cost function that maximises the far-field beam circularity and minimises the peak cross-polar level. Horns that exhibit good beam circularity and low cross-polarisation will also tend to exhibit low sidelobe levels and high beam efficiency, so we have not included the latter parameters explicitly in the cost function. Similarly, Potter horns tend to exhibit low return loss, so we have included the latter parameters explicitly in the cost function.

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In this section we describe a particular 3-section horn design, and further optimised using a Simplex minimisation technique.

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the optimised horn is given in Table 2. The initial waveguide radius was fixed to 0.62 mm and the aperture radius was fixed to 3.652 mm to give a convenient FWHM beamwidth of around 14.6 degrees. The other 5 parameters of the horn design were left as variables to be determined using our GA software package.

Figure 2 shows the expected far-field beam patterns for this horn design. The patterns exhibit good beam circularity, low sidelobes and low cross-polarisation across a bandwidth of 20%. In order to verify experimentally the expected performance of our horn design, we had two prototype horns manufactured using conventional electroforming. Electroforming delivered a precise realisation of the horn geometry that enabled us to experimentally verify our design technique in the absence of significant manufacturing errors. This also enabled a useful comparison to be made with horns manufactured using the new direct drilling method described in Sect. 5.

### Table 2. Geometrical parameters for the 3-section 230 GHz horn design.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_0$</td>
<td>0.62</td>
</tr>
<tr>
<td>$R_1$</td>
<td>1.486</td>
</tr>
<tr>
<td>$R_2$</td>
<td>1.812</td>
</tr>
<tr>
<td>$R_3$</td>
<td>3.652</td>
</tr>
<tr>
<td>$L_1$</td>
<td>1.479</td>
</tr>
<tr>
<td>$L_2$</td>
<td>1.212</td>
</tr>
<tr>
<td>$L_3$</td>
<td>24.0</td>
</tr>
</tbody>
</table>

4. Radiation patterns for electroformed prototype horns

The far-field radiation patterns of the prototype horns were measured directly in an anechoic chamber at the Rutherford Appleton Laboratory. We used an ABmm vector network analyzer (VNA) and a rotary scanner in an anechoic chamber to make a direct far-field measurement of the beam patterns of the prototype horns. Two identical prototype horns were used for transmission and reception, separated by 350 mm (~9 $D^2/4$), where $D$ is the horn aperture diameter. The transmitter horn was rotated around its aperture using a stepper motor driven rotary table, under computer control. By using the VNA as a simple total power detector, we were able to achieve a measurement dynamic range of 60 dB. We removed the effect of stray reflections and standing waves by the careful positioning of Eccosorb RF absorber around the horns and their mounting brackets. The uniformity of our measured beam patterns show that this arrangement was successful in eliminating stray power pickup across the band centred at 230 GHz.

Figure 3 compares the theoretical H-plane and E-plane beam patterns calculated using modal matching and those obtained.
5. Horn fabrication by drilling

The simple shape of the interiors of our smooth-walled horns is an attractive feature and lends itself well to fabrication techniques that are simpler and faster than electroforming. One technique that we have investigated is the fabrication of horns by direct machining using shaped drill bits (Leech et al. 2009, 2010). First we have manufactured a high speed steel machine tool whose cutting edge has the required shape of the interior of the horn (Fig. 5). We then use this cutting tool to drill the feed horn directly in a block of aluminium. The circular waveguide that feeds the horn is also manufactured by direct drilling. The process is very rapid and does not require the time consuming electroplating and dissolving stages used in electroforming. Once the machine tool and working metal plate have been properly aligned, one can quickly fabricate many feed horns by simply repeating the drilling process many times.

In order to test our new manufacturing technique, we fabricated three 230 GHz feed horns (Fig. 6), each with an identical design to the one described in Sect. 3. We split one of the horns using a milling machine to examine the machining quality along its interior (Fig. 7). The interior surface of both the horn and the input waveguide are seen to be very smooth, with a roughness of a few μm. We can also use Fig. 7 to estimate the accuracy of the alignment of the axes of the drilling tools used to cut the horn and the input waveguide. The overall accuracy of the alignment is seen to be good, although a close examination reveals a slight translational offset of around 50 μm. In order to excite the correct balance of higher order modes, it is important that the discontinuities near the throat have a high degree of sharpness. Figure 7 shows that the interior of the horn has taken the shape of the cutting tool very well and the machined discontinuities are very sharp, as desired.
Fig. 8. A comparison of the theoretical beam patterns calculated using modal matching and the experimentally measured beam patterns, for the drilled horn, prototype No. 1.

Fig. 9. A comparison of the theoretical beam patterns calculated using modal matching and the experimentally measured beam patterns, for the drilled horn, prototype No. 2.

Fig. 10. Experimental co-polar and cross-polar beam patterns, measured for the drilled horn prototype No. 1.

Fig. 11. A drilled 2-horn array prototype.

Fig. 12. A comparison of the theoretical beam patterns calculated using modal matching and the experimentally measured beam patterns for horn No. 1 of the 2-horn block.

6. Radiation patterns for drilled prototype horns

The measured beam patterns for two drilled feed horns are shown in Figs. 8–10. The beam circularity is high and the sidelobe levels are low (below –25 dB across the band). One can also see that the measured patterns for each of the horns are virtually identical, showing that the horns made by drilling are highly repeatable—an important result for the fabrication of large arrays of many horns using this technique. There is a slight asymmetry in the sidelobe levels for each horn in the H-plane at 250 GHz. This may be caused by the small alignment mismatch of the horn throat and the input waveguide discussed above. Nevertheless, such machining imperfections do not have a significant effect on the overall quality of the patterns. The measured cross-polarisation of the horn (Fig. 10) remains low, at –20 dB or lower, across the band.

7. A 2-horn drilled array prototype

In order to investigate the suitability of our drilling technique for the manufacture of arrays of horns, we constructed a simple 2-horn array by drilling into a single block of aluminium (Fig. 11). The centres of the horns were separated by 8 mm, a packing density appropriate for large format focal plane arrays. We measured the beam patterns for each horn (Figs. 12, 13), and again found good agreement with the theoretical patterns calculated using modal matching. It should also be noted that the patterns measured for each horn are very similar to each other, again showing the reproducibility and consistency of the manufacturing technique.

We also used our 2-horn array to investigate the cross-coupling between two close packed horns. A low cross-coupling
between horns is important for any horn design intended for use in close packed focal plane arrays. Historically, a variety of analytical and numerical approaches have been used to calculate the expected cross coupling between two horns (Olver et al. 1994), but we chose to perform the calculation using Ansoft’s HFSS, a full wave, finite element 3D electromagnetic simulation package. Such software packages are not generally used to design corrugated horns, since such horns depend on large numbers of corrugations per wavelength and thus require a very large amount of computer memory to mesh with sufficient accuracy. For the horns described here, which consist of a small number of flare angle discontinuities and long phasing sections, HFSS models can be sufficiently finely meshed with a moderate amounts of RAM (∼8−16 GB). Figure 14 shows, for the 3-section horn described above, the good agreement between the beam patterns calculated using HFSS and the beam patterns calculated using traditional modal matching. While HFSS modelling requires much more memory and computing time than modal matching, it does not assume axial symmetry and hence will be useful in studying the effect of non-axisymmetric machining errors on horn performance.

We used HFSS to calculate the expected cross-coupling between our two horns and the experimentally measured the cross-coupling of the horns using a vector network analyser. The measurements were performed in an anechoic chamber, with a carbon loaded epoxy cone positioned in front of the two horn array as an absorber. Figure 15 shows the simulated and measured cross-coupling between the two horns across the 210−250 GHz operating bandwidth of the horns. The measured cross-coupling is seen to be below −68 dB across the band, demonstrating that cross-coupling will not present a problem when these horns are close packed to form large format focal plane arrays. One should note that these experimentally determined cross-coupling measurements are in fact upper limits, due to the fact that there may be some residual reflection from our absorbing cone.

8. Conclusions and further work

We have developed a new technique for the design of smooth-walled multi-flare angle horns based on a genetic algorithm. These horns are much cheaper and easier to fabricate than corrugated horns and thus lend themselves more readily to the next generation of focal plane array sub-mm astronomical receivers. Our experimental results demonstrate the good agreement of our new designs with theoretical expectations obtained from modal matching, as well as the effectiveness of our new manufacturing technique using simple direct drilling. The measured beam patterns and cross-coupling from the horn prototype array show that these new horns will perform well in close packed large format focal plane arrays.

In order to further demonstrate the technology, we are currently constructing and testing a larger, 37 horn close packed focal plane prototype array. We have also made promising preliminary measurements for drilled horns designed for 700 GHz, demonstrating that we can routinely achieve the machining tolerances required to construct the much smaller horns required for wavelengths below ∼1 mm.

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