STFC follow–on fund support for sub-mm multi-flare angle horns for large format arrays – summary of achievements

J. Leech, G. Yassin, B.K. Tan and R. Roshan

1 Introduction

Here we describe our progress in the development of our smooth–walled horn technology for use in large format focal plane arrays, supported by an STFC follow–on–fund. In summary, over the course of the period supported by the grant, we have successfully,

1. Assembled a new horn test horn system, using a cooled bolometer detector, in a dedicated anechoic chamber, allowing the testing of horns at Oxford Astrophysics to a high dynamic range.
2. Successfully constructed and tested a 2-horn prototype array at 230 GHz. This prototype allowed the cross–coupling between two horns to be measured, an important parameter when using the horns in a focal plane array. We also measured the beam patterns of each these close-packed horns.
3. Constructed a 37 horn prototype array at 230 GHz, as well as an interface block enabling power to be fed to each horn individually. We tested this array using our new horn test system and measured highly uniform beam patterns.
4. Constructed and successfully tested drilled horns at 700 GHz for the first time. The beam patterns were excellent, demonstrating that our technology can readily be extended to higher frequencies.
5. Explored the use of the RF finite element analysis package HFSS to model our horns. Unlike the modal matching technique used so far, this technique is not limited to axisymmetric horns and will enable the exploration of the effect of non-axisymmetric machining errors.
6. Used our parallelised genetic algorithm to produce a series of new horn designs, promising an extended operating bandwidth (20-30%).
7. Improved the efficiency of our design software, enabling us to produce new designs more rapidly.
8. Made good progress towards the commercialisation of our technology in collaboration with ISIS Innovation Ltd, the technology transfer company of the University of Oxford. We have publicised the technology with a press release and have received strong interest in licensing the technology from two microwave component companies.

2 Horn and array fabrication technology

One of the principle aims of the project was the production and testing of horn array prototypes consisting of our our easy–to–machine, smooth–walled horns using our direct drilling fabrication technique. Our horns are smooth-walled, and incorporate one or more flare angle discontinuities near the throat which

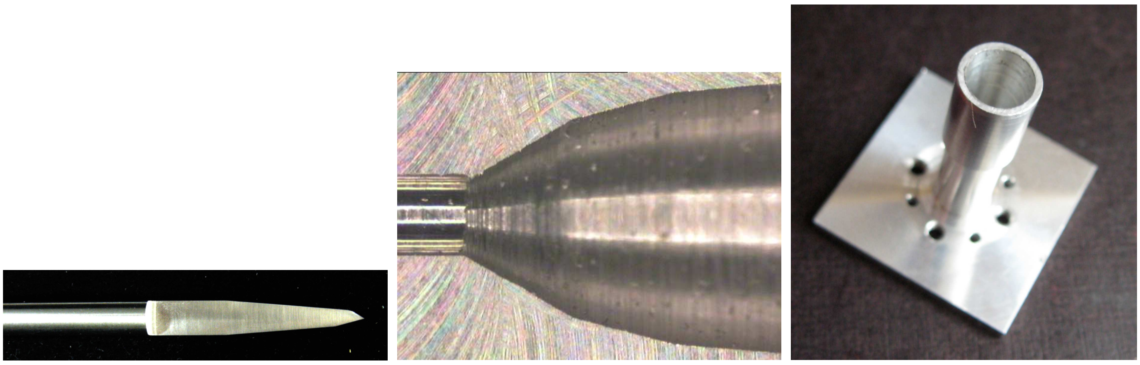

Figure 1: Left – the machine tool used for the fabrication of the drilled horn prototype, centre – the horn throat region and right – the finished single horn.

excite a balance of higher order waveguide modes in order to give high quality beam patterns across a target bandwidth. The position and size of these discontinuities are determined using a software package combining simulation using the modal matching technique and optimisation using a genetic algorithm.

The horns are fabricated by first constructing a machine tool whose cutting edge has the required profile of the horn interior (Figure 1, left). This tool is then used to directly "drill" the horn out of an aluminium block. Our previous development work had shown that the resulting horn follows the profile of the cutting tool very closely, with clean, sharp flare angle discontinuities being achieved (Figure 1, centre). We had successfully tested individual horns (Figure 1, right) with 2-flare angle discontinuities (3 conical sections) fabricated by direct drilling. The attraction of this fabrication technique is that once the cutting tool has been carefully aligned with the aluminium block, many tens or hundreds of horns can be rapidly made by repeated drilling. The technology is thus promising for array receivers, and we expect the cost per horn to be very much lower than conventional corrugated horns made by electroforming. The demonstration of a working array prototype of feed horns made this way is thus a key stage in any attempts to commercialise the technology.

3 A new horn test system

Prior to the award of the follow-on fund grant we had performed all of our experimental horn tests using a Vector Network Analyser (VNA) and anechoic chamber at the Rutherford Appleton Laboratory (RAL). While this facility has performed well for the testing of individual horns, we felt that the large number of beam pattern measurements needed to test an array made it wise to build our own dedicated system at Oxford. Both the limited space available within the RAL anechoic chamber, as well as the mechanical complexity of the VNA test heads meant the RAL system would be poorly suited to testing our 37 horn array prototype. Also, access to our own dedicated horn test facility is highly advantageous for the rapid testing and quality control for any horns which we may supply as part of a commercial contract.

We purchased a complete InP based bolometer detector, together with a pre-amplifier, Winston cone horn and reflective optical filter from QMC Instruments, Cardiff and had it installed into a liquid He test dewar. The frequency range of this detector system, limited by the optical filter passband, is 100 GHz – 1 THz, enabling good coverage of the sub-mm band, particularly above 600 GHz, where the dynamic range achievable with the RAL test system is severely limited ($\sim$ 10 dB). We also constructed an anechoic chamber on a dedicated optical table and assembled the necessary mechanical hardware, a rotary table, control software and electronics. The complete system performs well, and gives a dynamic range of larger than 60 dB across the 210–250 GHz test bandwidth of our array.

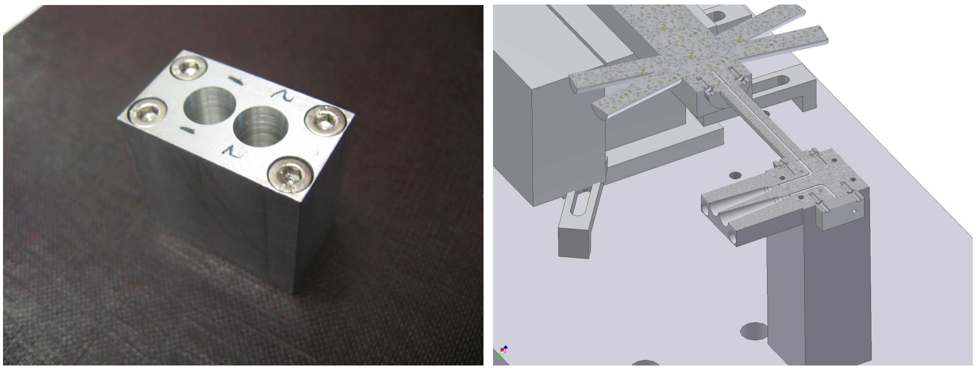

Figure 2: Left – The two horn array prototype, made by repeated drilling into a single block of aluminium. Right – a solid CAD model showing the two horn array and interface waveguide block.

4 A two–horn prototype array

At the beginning of the project, we had successfully tested two horns made by electroforming and two identical horns made using our novel drilling technology. An important next step was demonstrating that the drilled horns would perform well when part of a close-packed focal plane array. To this end, we decided to machine two horns into a single block of aluminium to study the effects of the interaction between two horns packed at a spacing suitable for larger focal plane arrays. This prototype 2-horn array allowed us to measure the cross-coupling between two horns, as well as verify that the quality of the beam patterns from each horn remained high. The prototype 2–horn block and the waveguide interface block enabling power to be delivered to each horn are shown in Figure 2. There was an 8 mm spacing between the horn apertures, which each had an aperture radius of 3.6mm.

Before measuring the cross-coupling and beam patterns for our two–horn array, we investigated modelling the performance of the array using HFSS, a commercial finite element electromagnetic simulation package. Modelling entire feedhorns in HFSS can be challenging because of the large amounts of memory required to construct a fine enough mesh (Figure 3) to capture all of the subtleties of the electromagnetic performance. We compared our HFSS calculated beam patterns with the ones calculated using the modal matching technique, which is known to agree very well with experiment (Figures 4). We found good agreement between the beam patterns simulated using each different technique, demonstrating that HFSS can be used to model our horns with suitable accuracy. Importantly, we could now use HFSS modelling to predict the expected cross-coupling between two of our horns (Figure 5, red curve). Also, since HFSS models do not assume axisymmetry, we will be able model the effect of any non-axisymmetric alignment errors between the horn and waveguide cutting tools.

We next measured the beam patterns for each of the two horns in the array, using the VNA based far–field antenna test range at RAL. The results are shown in Figs. 6–7. The match between the theoretical patterns, calculated using modal matching, and the experimentally measured patterns is seen to be very good. It should be noted that the slight asymmetries found in the patterns are very similar in magnitude for both horns and also that these asymmetries are oriented similarly for both horns. This indicates that they are very likely caused by a small axial misalignment, which would be of similar magnitude and orientation for both horns as they are machined in turn into a single plate.

We also used our two horn array prototype to measure the cross coupling between the two horns. We measured this coupling using the RAL vector network analyser in an anechoic chamber, using an absorbing, carbon loaded plastic cone in front of the two horn array. Our measured cross couplings should thus be viewed as upper limits, since some fraction of the coupling may be due to residual reflection from our

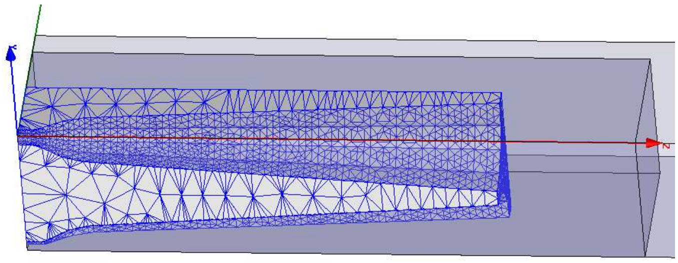

Figure 3: A section of the HFSS model used to calculate the cross coupling between two horns, showing the mesh points used.

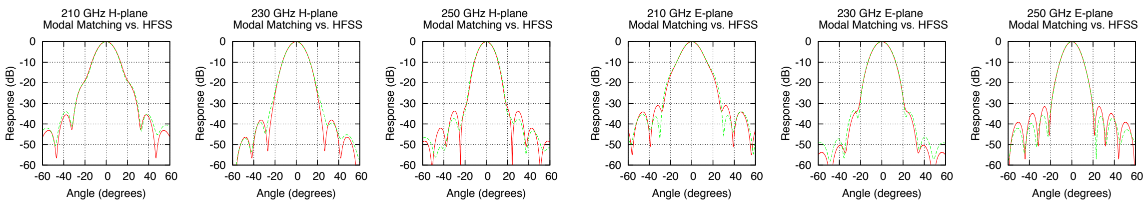

Figure 4: A comparison of HFSS simulated beam patterns (green dashed line) and beam patterns calculated using modal matching (solid red line). The H-planes are shown on the left and the E-planes on the right.

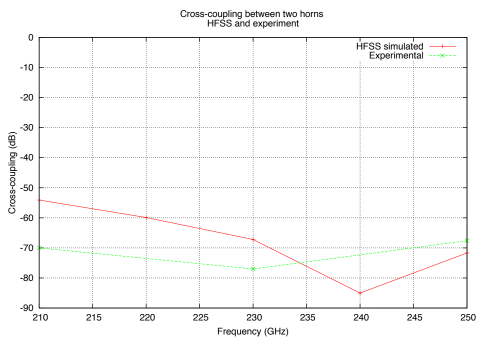

Figure 5: Measured and HFSS simulated cross coupling between the two horns in the 2 horn prototype array.

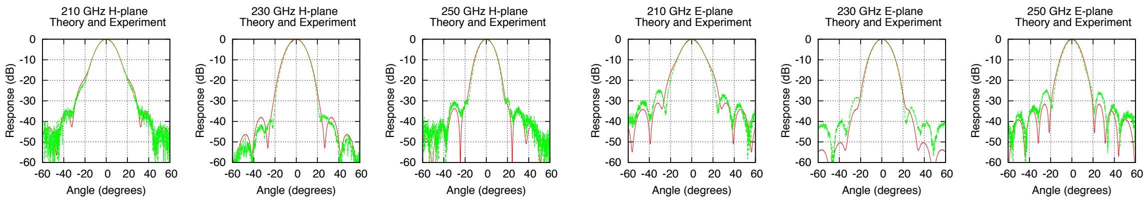

Figure 6: A comparison of the theoretical beam patterns calculated using modal matching and the experimentally measured beam patterns for horn No.1 of the 2 horn block (Left: H-plane, Right E-plane).

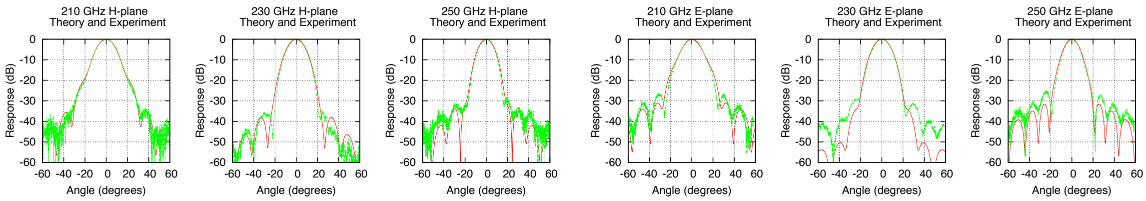

Figure 7: A comparison of the theoretical beam patterns calculated using modal matching and the experimentally measured beam patterns for horn No.2 of the 2 horn block (Left: H-plane, Right E-plane).

absorbing cone. We also calculated the expected cross coupling for our horn array using HFSS. Figure 5 shows the measured and simulated cross coupling for our two horns across the operating bandwidth. The experimentally measured cross coupling is below -70 dB across the band, an excellent result for the successful use of these horns in focal plane arrays.

5 A 37–horn prototype array

The excellent experimental results for the two horn array enabled us to proceed confidently with the construction of a larger array with drilled horns of the same design. We decided to construct a 37 horn, hexagonally close packed array for testing at 230 GHz (Figure 8, left). This array was made as described above, by repeated drilling in a single aluminium plate.

In order to be able to supply RF power to each horn from our 230 GHz local oscillator, it was necessary

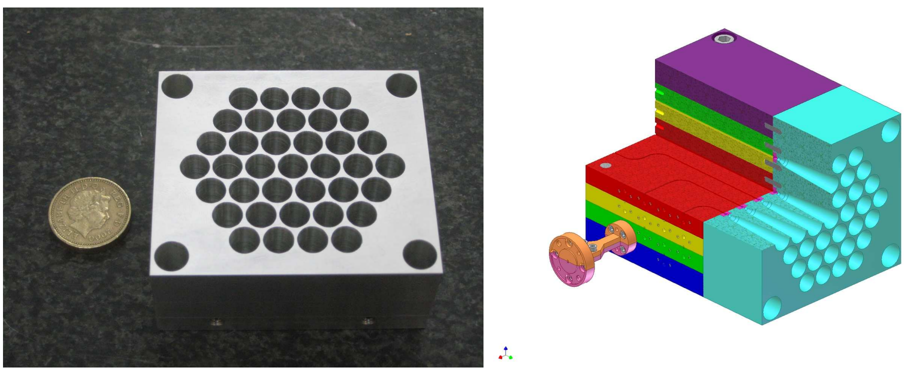

Figure 8: Left – The 37 horn array prototype, made by repeated drilling into a single block of aluminium. Right – the multiplate split block which enables power to be delivered to each of the horns from a split block waveguide at the side.

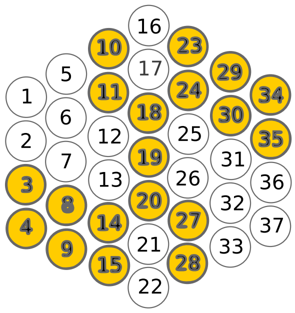

Figure 9: Schematic of the horn array highlighting the sample of horns tested.

to construct an interface block (Figure 8, right). This consisted of waveguide sections, terminated with suitable flange fittings, milled into several layers of a split aluminium block. The outputs of the waveguide were routed to the rear face and two side faces of the interface block, enabling the convenient connection of our local oscillator source to each horn in the array, while enabling the testing of the perpendicular E and H rotation planes of the horns.

After construction of our 37-horn array prototype, interface block and mounting hardware, we began an extensive programme of horn testing, aimed at assessing the performance and uniformity of a sizable sample the horns across the array. For each horn, we measured beam patterns for both H and E-plane polarisations, at three frequencies at the bottom, centre and top of the operating bandwidth. The subset of horns chosen for testing (Figure 9) were spread across the whole array, enabling us to look for any trends in beam pattern behaviour across the array.

The experimentally measured beam patterns for the 19 horns tested are shown in Figures 10 and 11. The measured beam patterns on the whole show excellent beam circularity, low sidelobe levels (below -20 dB) and good agreement with theory across the whole of the array. We found some evidence of E-plane main–beam asymmetry at the extreme end of the measured bandwidth for horn No. 15 and horn No. 27. We are in the process of investigating further both experimentally and using HFSS modelling. Overall, the experimental results show a high degree of beam uniformity across the array, demonstrating the applicability of the direct drilling fabrication technique to large format focal plane array receivers.

6 Extending the technology to 700 GHz

As well as fabricating horn arrays at 230 GHz, we also fabricated three individual horns scaled down for use at 700 GHz. As is readily apparent from Figure 12, the dimensions of the horn become much smaller at 700 GHz (e.g. aperture diameter = 1.2 mm) and thus more challenging to successfully fabricate. Nevertheless, when we tested the first fabrication batch of these horns using our new test range we found that they exhibited excellent beam patterns (Figure 13). This is a very encouraging result, and demonstrates that this horn fabrication technology is effective into the scientifically important high end of the sub-mm wavelength range.

7 Genetic algorithm software optimisation

In parallel with our experimental work, we have been pursuing a program of optimisation of the horn design software, in order to increase the speed of execution to enable the efficient simulation of horns with a higher number of flare angle discontinuities (4 or more). This involved an extensive rewrite of the computationally intensive modal matching part of the software suite, to achieve compatibility of the core

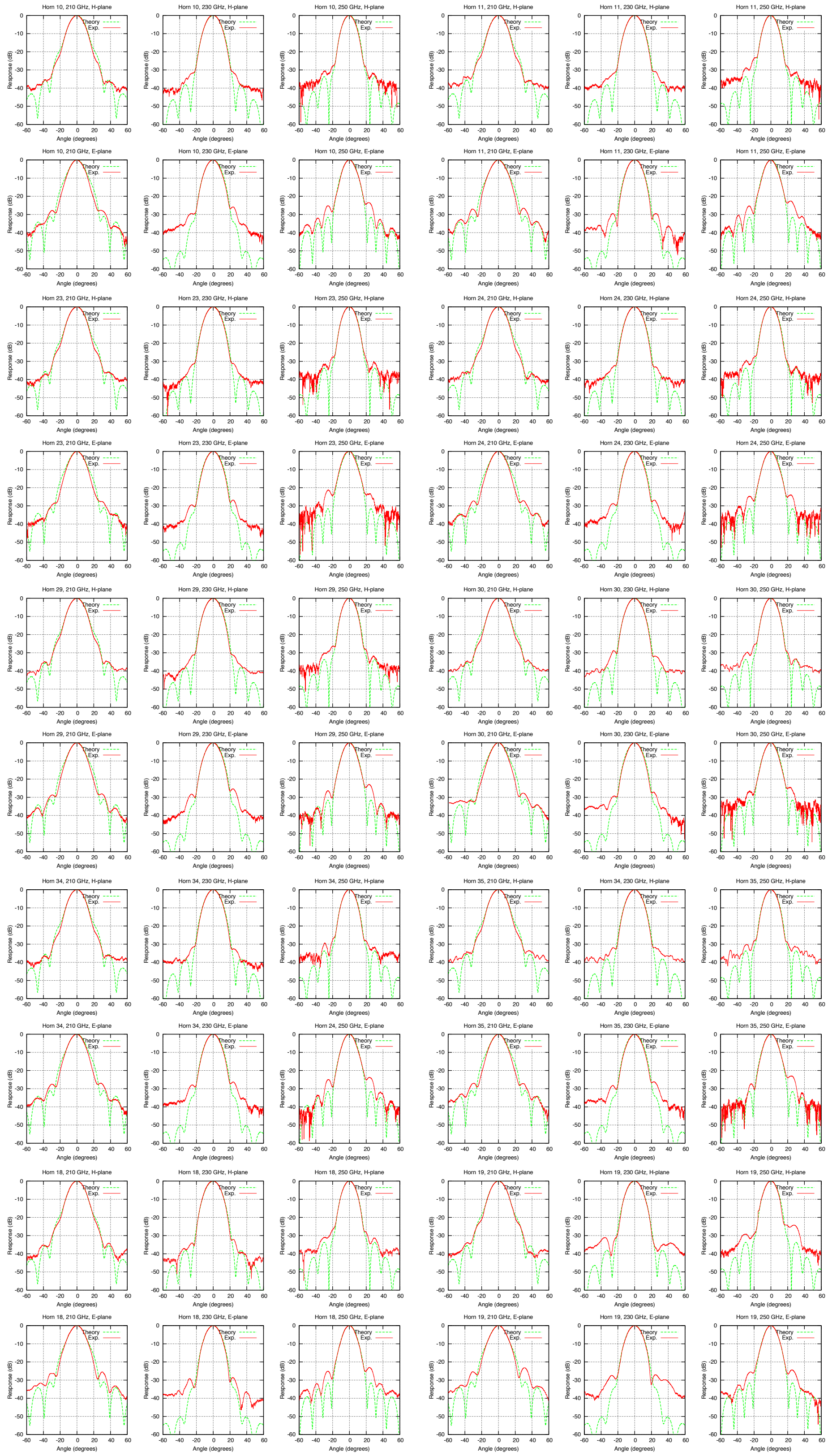

Figure 10: Experimental and theoretical beam patterns for a sample of horns for the upper half of the array (Horn Nos. 10, 11, 23, 24, 29,30, 34, 35, 18 and 19). See Figure 9 for their location within the array.

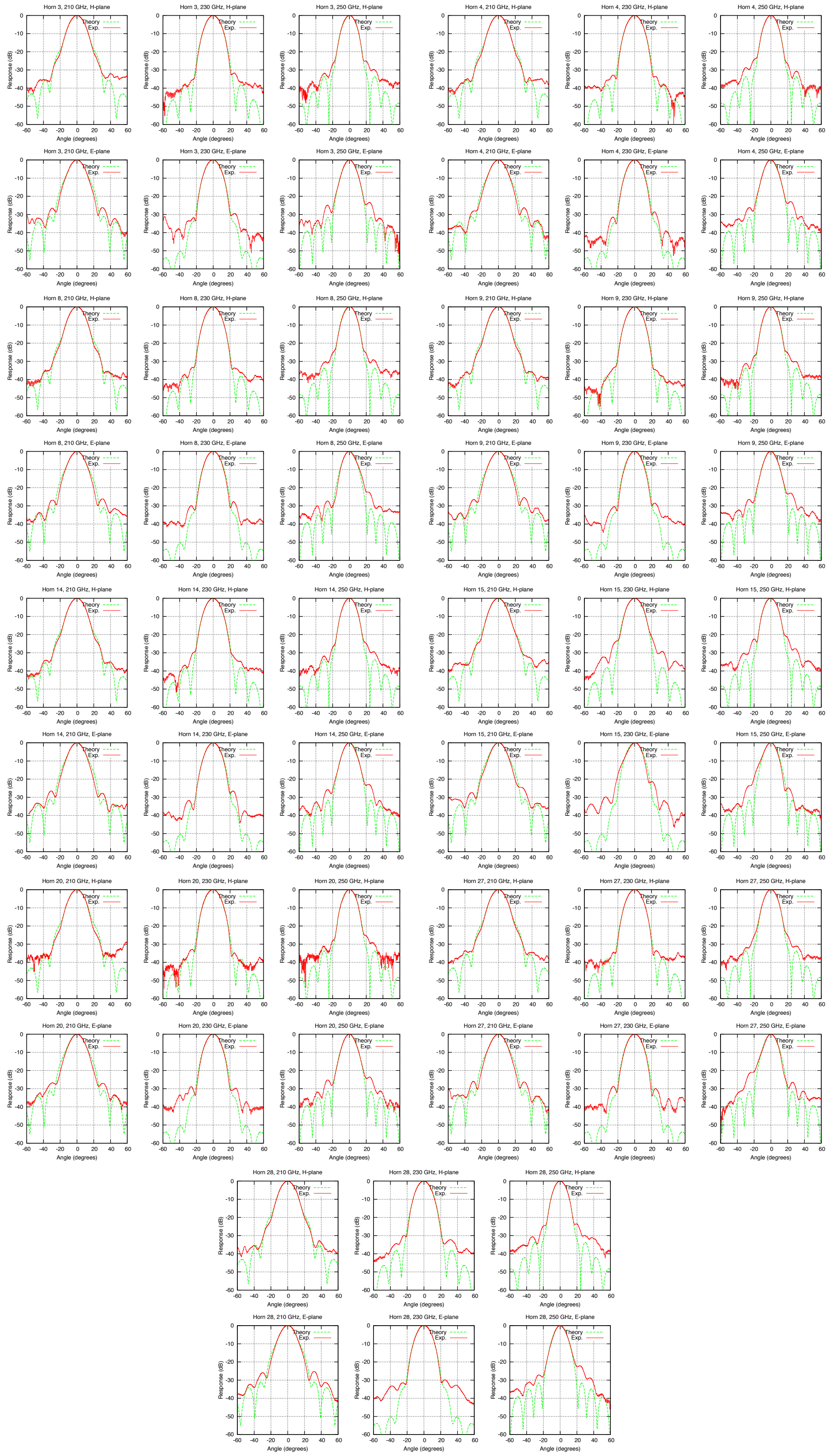

Figure 11: Experimental and theoretical beam patterns for a sample of horns for the lower half of the array (Horn Nos. 3, 4, 8, 9, 14, 15, 20, 27 and 28). See Figure 9 for their location within the array.

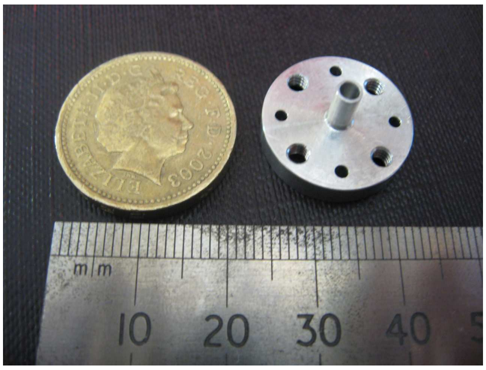

Figure 12: The 700 GHz drilled horn prototype.

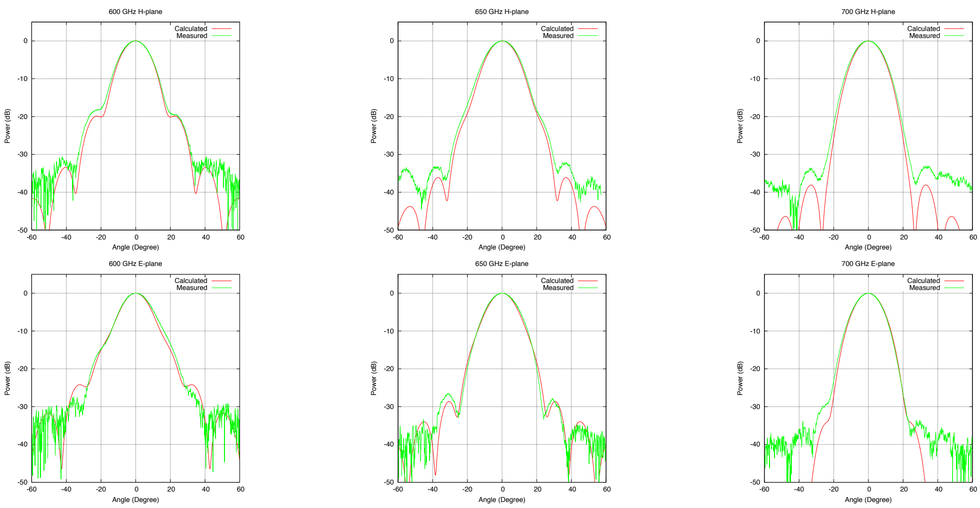

Figure 13: Experimental and theoretical beam patterns for the 700 GHz prototype horn Top: H-plane, Bottom: E-plane.

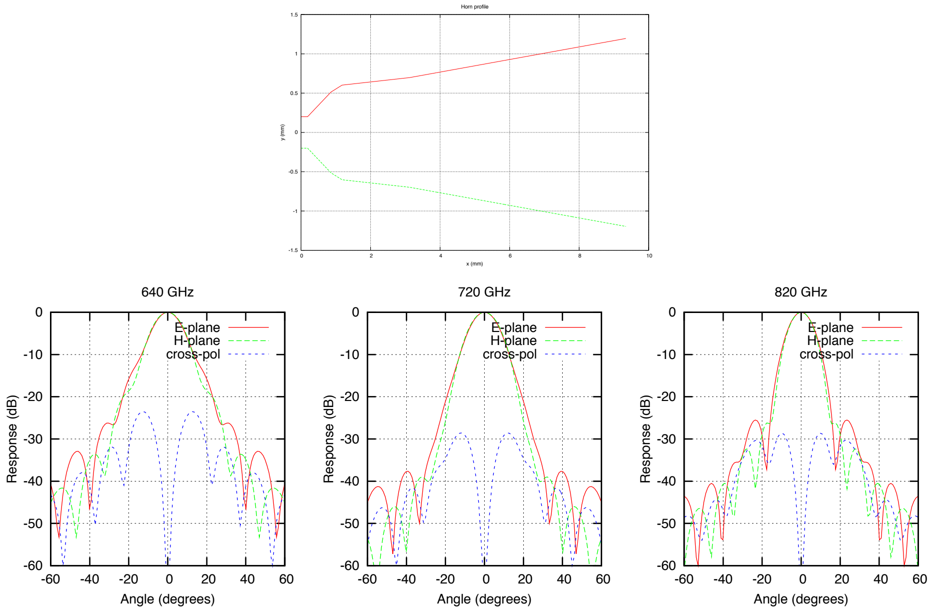

Figure 14: Top: Profile of a new horn design designed with our GA software for extended bandwidth. Bottom: Simulated beam patterns for this horn design. The fractional bandwidth illustrated is 25%.

matrix multiplication and diagonalisation routines with the highly optimised routines which are available as part of the BLAS and LAPACK libraries. Preliminary benchmarking of the software shows speed increases of between a factor of 3–10, depending on the target platform (CPU / operating system / single vs. multiple CPUs).

8 New broadband horn designs

The horns in both the 2–horn and 37–horn arrays described above have 2 flare angle discontinuities near the throat of the horn (i.e. the horn consists of 3 conical sections). The horns perform well over a bandwidth of around 17%. As part of the project, we have been designing, using the genetic algorithm optimisation software, horns with more flare angle discontinuities optimised over a greater target bandwidth. These software simulations have been run using the parallelised version of our horn software on the Oxford e-Science Research (OERC) Beowulf clusters, across 24 parallel processing CPU cores. We have achieved some very encouraging results, including the design illustrated in Figure 14, which has a much improved fractional bandwidth of 25%. We intend to purchase some horn cutting tools with this profile in order to make and test some prototypes of these extended bandwidth horns.

9 Conclusion

The work we have described above, supported by the STFC follow–on fund, places us in a strong position to pursue the further commercialisation of this technology, in collaboration with ISIS Innovation Limited. Our successful construction and testing of prototype horn arrays practically demonstrates the strong suitability of our new technology for commercial applications in both scientific and communication markets.