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The optimisation, design and verification of feed horn structures for future Cosmic Microwave Background missions

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HIGHLIGHTS

- Efficient mode-matching based optimisation process for feed horns is presented.
- Allows design of high performance smooth-walled feed horns using desktop computers.
- Horn designed for future CMB missions with rigorous performance requirements.
- Horn meets all requirements across the band, only taking 6.5 h to design.
- Horn was manufactured and measurements agreed excellently with simulations.

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ABSTRACT

In order to investigate the origins of the Universe, it is necessary to carry out full sky surveys of the temperature and polarisation of the Cosmic Microwave Background (CMB) radiation, the remnant of the Big Bang. Missions such as COBE and Planck have previously mapped the CMB temperature, however in order to further constrain evolutionary and inflationary models, it is necessary to measure the polarisation of the CMB with greater accuracy and sensitivity than before.

Missions undertaking such observations require large arrays of feed horn antennas to feed the detector arrays. Corrugated horns provide the best performance, however owing to the large number required (circa 5000 in the case of the proposed COrE+ mission), such horns are prohibitive in terms of thermal, mechanical and cost limitations.

In this paper we consider the optimisation of an alternative smooth-walled piecewise conical profiled horn, using the mode-matching technique alongside a genetic algorithm. The technique is optimised to return a suitable design using efficient modelling software and standard desktop computing power. A design is presented showing a directional beam pattern and low levels of return loss, cross-polar power and sidelobes, as required by future CMB missions. This design is manufactured and the measured results compared with simulation, showing excellent agreement and meeting the required performance criteria.

The optimisation process described here is robust and can be applied to many other applications where specific performance characteristics are required, with the user simply defining the beam requirements.

1. Introduction

The measurement of full sky maps of the Cosmic Microwave Background (CMB) radiation, the remnant of the Big Bang, is critical in the fields of astrophysics and cosmology. Polarisation sensitive measurements of this radiation allow for the detailed study of the origins of the Universe and the structures contained within it, allowing further constraints to be placed on the various inflationary and evolutionary models that currently exist. Many missions have recorded such full sky maps, for example COBE [1], WMAP [2] and more recently Planck [3]. In order to continue progressing in these areas, it is necessary to design instruments which are polarisation sensitive as this will allow the measurement of the CMB E- and B-modes, revealing additional information centred around 100–150 GHz, about the various inflationary models.

Such high performance polarisation sensitive instruments can potentially make use of several array formats, including horns, bare

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arrays and lens arrays. Horn arrays are popular as they are proven technology, have low stray light coupling and do not require the use of a cold stop to truncate sidelobe structure or even define the beam. Such arrays typically make use of corrugated feed horn antennas to feed the detector array. In order to increase the sensitivity, it is necessary to increase the number of pixels on the focal plane, and so this makes the use of traditional corrugated horns prohibitive due to more complex cryogenics and manufacturing processes and associated cost implications. A suitable alternative to the use of corrugated horns would be the use of a smooth walled horn which is optimised to retain the high performance of a corrugated horn in terms of the figures of merit which are of interest for CMB missions, at the expense of those which are less critical. For example, a typical requirement for a CMB mission to measure polarisation would be low cross-polar power, high beam symmetry and low return loss in order to maximise the throughput of the measured signal, so these performance metrics could be optimised.

Additionally, it is necessary to be flexible in the design process of such horns, being able to change the horn geometry to meet any new requirements that arise from constraints associated with the optics or the focal plane. A lengthy optimisation would hinder this process, as would the need to be able to access a supercomputer at short notice. To this end, it is desirable that the optimisation process be capable of completion within a reasonable timeframe and using only the standard desktop computing power which is typically available. Rapid horn optimisation also helps in providing a robust and efficient optics design process. Although future CMB missions were chosen as the example with which to demonstrate the optimisation process, it can be applied to any application whose performance requirements are known, including multi-mode systems.

The optimisation of feed horn antennas is a problem which has received considerable attention [4–7]. A particular aim of the investigation presented in this paper is to maximise the efficiency of the optimisation process, using only standard desktop computing power to achieve the particular design criteria for the system in question. This allows a simple horn geometry to be realised quickly and efficiently when compared to some other optimisation techniques where large supercomputers are required. In order to achieve this goal, it was necessary to adapt a more efficient approach in terms of the complexity of the optimisation process relative to those presented in the references above, and to see how well a horn resulting from this simple process could approach the required high levels of performance in terms of the performance metrics of interest, in this case those required by future CMB missions. In this approach, the horn geometry is defined in terms of *N* segments, where *N* is a relatively small number in order to reduce the computational effort required during the optimisation process but allowing sufficient degrees of freedom to achieve good performance.

Unlike in the investigations undertaken by other groups where these segments are profiled by interpolation using a spline that represents some function, such as $\sin^2$ for example, here the segments are linearly interpolated. This reduces the computational complexity of the problem, however as the profile is now less smooth it becomes more difficult to achieve the required level of performance, and so it is of interest to investigate whether the required performance (high beam symmetry, low levels of cross-polarisation power return loss and sidelobe levels) can be realised using this simpler design. We refer to this type of horn geometry as a piecewise conical profile horn (PCPH), a design envisaged to have sufficient degrees of freedom to achieve the required performance. This type of feed horn geometry is outlined in [8], along with an analysis of the impact of using the geometry along with various figures of merit and constraints in the optimisation process.

2. Optimisation process

In this section the optimisation process is described, including a description of the mode-matching technique which is used to simulate waveguide structures. The modifications necessary to make the mode-matching technique more efficient in order to allow the overarching optimisation process to converge are also described, in addition to a description of the integration of the mode-matching technique with the optimisation algorithm and the resulting horn design.

2.1. The mode-matching technique

To simulate the performance of a waveguide horn antenna, code developed in-house known as SCATTER [9], based on the mode-matching technique as applied to a two port system [10], is used. SCATTER allows the calculation of the transmission and reflection scattering matrices (S matrices) which govern the bulk behaviour of the antenna, giving a full vector description of its performance. Results predicted using SCATTER have been extensively verified against experimental results for both single and multi-mode systems and so it can be applied to the analysis of waveguide structures with confidence.

In the mode-matching technique, the field in the waveguide structure is represented by a combination of transverse electric (TE) and transverse magnetic (TM) modes, with the scattering matrices that result from the analysis representing the complex coefficients of these modes in reflection and transmission. Using these scattering matrices the field patterns of the horn (co-polar, cross-polar and unpolarised) can be calculated at the aperture or in the far field, along with many associated figures of merit such as reflected and cross-polar power, and beam symmetry.

In any iterative optimisation process that uses the mode-matching technique to calculate the figure of merit, it is necessary to execute SCATTER a large number of times. It is therefore necessary to make SCATTER as computationally efficient as is possible in order to minimise the computational time and resources required for the optimisation process. By using only the required number of modes at each junction the scattering matrix calculation step is already very efficient, however the field pattern calculation can be time consuming. This is an issue, as the field pattern must be accurately calculated in order to determine many figures of merit in terms of the performance of the horn. The modification made to the calculation in order to improve the speed of this step will now be described.

Often, when the transmission matrix at the aperture of the horn is analysed (the S_{21} matrix in the convention used in SCATTER), many of the modes are found to not contribute significantly to the field. For example in a single-mode horn, as is being considered here, there will only be one channel of power supported by the horn. The unsupported modes are still included in the calculation, resulting in an increase in computational time. It is not advisable to simply ignore these modes as their contribution, however small, is real. It is possible however to reduce the execution time by expressing the output basis set of the horn in a more efficient manner by using the mathematical technique of singular value decomposition (SVD) [11].

If $\mathbf{S}$ is an $m \times n$ matrix representing the S_{21} matrix, then the SVD of $\mathbf{S}$ is defined as

$$\mathbf{S} = \mathbf{U} \cdot \boldsymbol{\Sigma} \cdot \mathbf{V}^{\dagger}, \tag{1}$$

where $\mathbf{U}$ is an $m \times m$ unitary matrix, $\boldsymbol{\Sigma}$ is an $m \times n$ rectangular matrix containing non-negative real numbers on the diagonal, and zeros elsewhere, and $\mathbf{V}^{\dagger}$, the complex transpose of $\mathbf{V}$, is an $n \times n$