*Irish Astr. J.*, **26(2), 109-114, (1999)**

# OPTICAL MODELLING OF THE HFI INSTRUMENT ON BOARD THE PLANCK SURVEYOR

D. COBURN & J. A. MURPHY

Dept. of Experimental Physics, National University of Ireland, Maynooth, Co. Kildare, Eire

**ABSTRACT.** The PLANCK SURVEYOR is a European Space Agency satellite mission to image the very faint anisotropies in the temperature of the Cosmic Microwave Background (CMB) radiation. Maynooth is actively participating in an international collaboration of scientists involved with the optical design of the High Frequency Instrument (HFI). This paper outlines research which has been undertaken in Maynooth concerned with numerical modelling of the optical characteristics of the multi-frequency array of detectors making up the HFI instrument. In the study the commercial software package ZEMAX was used to model the coupling of the focal plane HFI detectors to the PLANCK telescope. This package is particularly useful in the optical design of PLANCK because of the powerful optimisation features of the software. It is thus possible to readily determine the optimum positioning of the detectors in the focal plane of the telescope. Although the package is based on a numerical ray tracing approach, diffraction effects can be included making it possible to model the beam patterns for the HFI array on the sky. As a method of validating this approach the results of the ZEMAX model of the system were compared with that of a more rigorous physical optics simulation. It was concluded from the study that the level of agreement between the two approaches support the proposed use of ZEMAX. Once the detector positions were optimised using ZEMAX the physical optics approach was used to determine a more accurate set of beam patterns for the array.

## 1. INTRODUCTION

The PLANCK SURVEYOR is a space telescope designed to sense radiation in the mircowave - sub-millimetre wavelength range over the frequencies 30 - 857GHz. This instrument will map the anisotropies in the cosmic microwave background (CMB) with the aim of retrieving data relating to the development of the early universe which is encoded in the temperature signal. It is hoped that the surveyor will map the temperature fluctuations in the CMB with a precision of 2 parts per million and an angular resolution of 10 arc-minutes. Detailed computational models of the CMB anisotropies predict that most of the cosmological information in the sky map is contained on the angular scales which PLANCK is designed to cover. The PLANCK SURVEYOR will represent a very significant advance over previous CMB observations such as the data produced by the famous COBE observer (Smoot *et al.* 1992), as well as balloon and earth bound measurement (O'Sullivan *et al.* 1995). This relates to improved angular resolution and sensitivity of the measurements resulting from improvements in detector technology (Holland *et al.* 1999). These advances will enable PLANCK to place fundamental constraints on the models of the evolution of large-scale structure in the universe. The results will make it possible to test competing theories of the early universe and will provided unprecedented accuracy in the measurement of cosmological parameters. In addition to the CMB data, PLANCK will also provide a near-all sky map of all the major microwave emissions. Additional details of the scientific objective of PLANCK are provided at the official PLANCK website http://astro.estec.esa.nl/planck/. The significance of CMB measurement in establishing parameters in the cosmological model of the early universe are outlined in brief by Van der Veen *et al.* (1998) and Heavens (1998) in two recent review articles on the subject.

Maynooth is involved with the development of PLANCK as part of an international consortium of scientists concerned with the optical design of the front-end detector array of the high frequency instrument (HFI) onboard the satellite. This collaboration includes research groups from Queen Mary and Westfield College, University of London, the Institut d'Astrophysique Spatiale (IAS), Paris, the California Institute of Technology and Stanford University, California. Research at Maynooth is concerned with two key areas of interest in the HFI design - (a) the modelling of the optical characteristics of the HFI detector feed horns and (b) understanding coupling of the sky signal to the focal plane of the PLANCK telescope. This paper will focus on work being performed on modelling the telescope optics and the coupling of the sky signal to the focal plane.

## 2. OPTICAL DESIGN OF THE PLANCK TELESCOPE

The main optical components onboard the PLANCK surveyor are shown in Figure 1. In orbit this satellite will be located about the Earth - Sun L2 point with the earth positioned behind the optical platform. In this orbit the telescope will track the motion of the earth about the sun with the orientation of the bottom shield of the satellite shadowing the detectors from the direct radiation from both bodies. This will provide an environment suitably free of radio and infrared interference to avoid degradation of the CMB data. In operation the satellite will rotate about the spin axis shown in the figure as it collects data, thus enabling the surveyor to map the CMB during its orbit about the sun.

The current telescope design is based on an off-axis Gregorian geometry, which is particularly suited to the mircowave - millimetre wavelengths, as it avoids the effect of scattering caused by support struts in the path of the telescope beam.

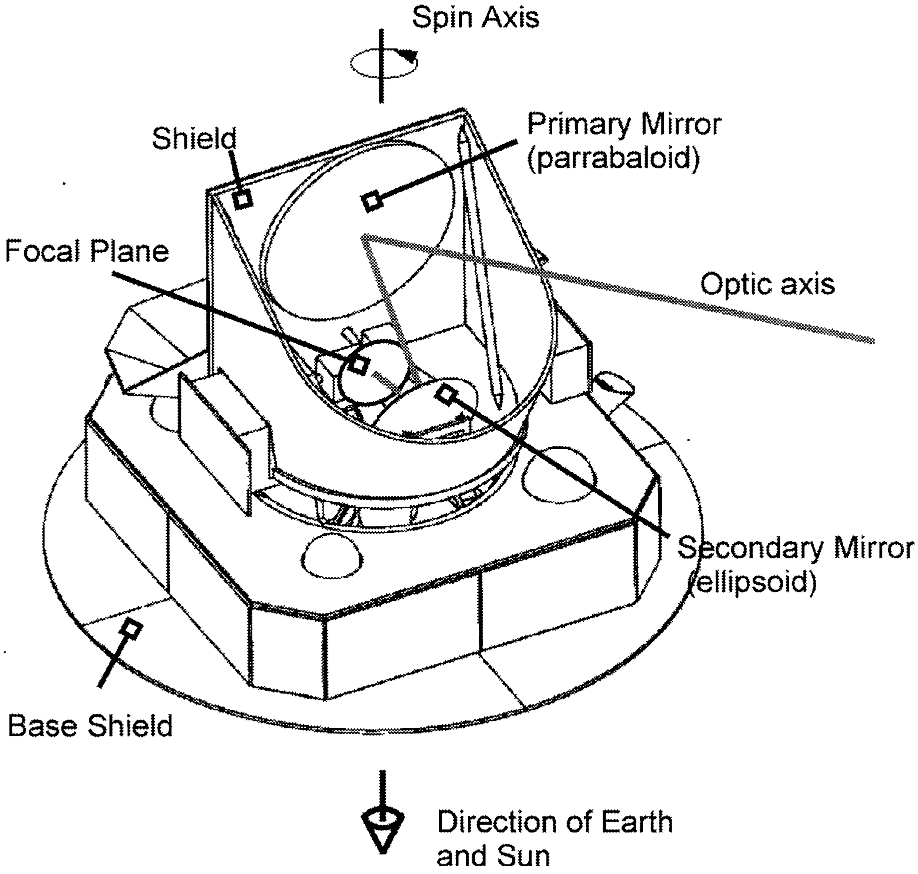

**Fig. 1.** A diagram of the PLANCK surveyor showing the main optical components in the telescope.

Such diffraction would be unacceptable in the PLANCK telescope as it could give rise to scattering of unwanted radiation into the detectors from strong sources positioned well off-axis. In the PLANCK design the eccentricity and tilt angle of the secondary mirror has been chosen to adhere to the Mizuguchi-Dragone condition (Bersanelli *et al.* 1996), which results in a minimisation of possible cross polarisation effects in the imaging process. Thus, small changes in the polarisation direction of the CMB can in principle be measured at the telescope focal plane. The polarisation characteristics of the microwave signal provides additional data of scientific interest in mapping the anisotropies in the CMB radiation.

There are two instruments in the focal plane of the system, the high frequency instrument (HFI), with which we are principally concerned, and the low frequency instrument (the LFI). The HFI consists of a total of 48 detectors located around the central region of the focal plane. These detectors cover a series of bands over the frequency range between 100 and 857GHz. The HFI detector technology is based on state of the art, low temperature spider-web bolometers, which in operation are actively cooled to a temperature of 0.1°K. The focal plane signal is coupled to the bolometers via a complex corrugated conical horn and waveguide structure (HFI Consortium 1998). In the HFI design the detector feeds for the lower frequency pixels are single moded corrugated horns (Holland *et al.* 1999) with the two higher frequency channels operating using multimoded horns (Murphy & Padman 1991). This feed horn design coupled together with the telescope imaging geometry provide a maximum angular resolution of the microwave sky of 5 arcminutes. The best temperature sensitivity of the detectors is 5 $\mu$K.

The low frequency instrument is made up of an array of 56 tuned radio receivers located in a ring around the HFI. This detector set is sensitive to the frequencies in the range 30 - 100GHz and provides a highest angular resolution of 12 arcminutes. The wide frequency coverage of the HFI and LFI is chosen to enable the removal of foreground contamination of the CMB signal, caused by sources such as galactic dust emissions. This relies on identifying the various spectral signatures of the contaminating sources and removing these components from the microwave signal (Bersanelli *et al.* 1996; HFI Consortium 1998).

In PLANCK the telescope optics are such that the sensitivity of the detectors is weighted to receive light mainly from the central portion of the primary mirror with a significant rejection of radiation from the edge region of the mirror. One method commonly used to characterise the level of sensitivity of the detector to signals from different regions of the telescope is to propagate the field accepted by the aperture of the detector back through the telescope. Using this approach the power of the radiation at the edges of the primary are of the order of -30 dB relative to the centre. This low signal level is a design measure intended to address the stray light sensitivity of the detectors. In this way the detector is significantly less sensitive to stray light scattered by the edges of the primary than the CMB signal imaged by the centre of the mirror. In addition the dimensions of secondary mirror have been oversized relative to the detector beam in order to minimise the sensitivity of the HFI pixels to light scattered by the edges. A more detailed review of the design issues associated with PLANCK are addressed in the HFI proposal (HFI Consortium 1998) and the Phase A report on the mission (Bersanelli *et al.* 1996) which is available under the public documents page of the http://astro.estec.esa.nl/ website.

The current paper focuses on a number of key design issues relating to the coupling of the field through the telescope onto the focal plane detectors. Of primary importance in the design is the need to understand the position and shape of the forward beam on the sky. This information is vital to investigating the ability of the PLANCK instrument to recover the CMB data with the required level of sensitivity from the detected signal. To study this the modelled optical response of the telescope is used together with simulated data based on models for the CMB anisotropies to computationally assess whether the required level of sensitivity has been achieved in the design.

In addition to the above consideration there is also a need to determine the optimum horn positions in the focal plane. In the design of PLANCK the detectors are spread over quite a large field of view (± 5°) on the focal plane and are therefore subject to significant off-axis aberration effects, including beam distortion and a warped Petzval surface. Another important component in the body of data that PLANCK is designed to establish is the polarisation characterisation of the sky signal. The optical modelling is also required to characterise the polarisation state of the sky signal imaged off-axis across the focal plane. The Mitsugushi-Dragone condition only ensures immunity of the on-axis pixel to cross polarisation effects.

### *2.1. Modelling of the PLANCK Telescope*

The optical system in PLANCK lies in what is termed the quasi-optics regime. This is in between the wavelength range for which RF analysis techniques (which are computationally intensive, time consuming procedures particularly at the higher frequencies) and standard optical modelling techniques work well. The principal difference between telescope systems at sub-millimetre and optical wavelengths relates to the typical aperture sizes in such systems. In a quasi-optical system the diameters of optical components are in general only 10 - 100 wavelengths across and the propagating fields are usually considered to be coherent. This is compared to the size of components in optical telescopes, which may be many thousands of wavelengths across and in which the detector is usually multimoded (spatially incoherent). Therefore, as well as accounting for aberrations in the system diffraction of the beam is considerable importance in optical modelling of the sub-millimetre systems. This is particularly true at the mouth of the single moded feed horns in the PLANCK detector array, which are only a few wavelengths in width. In addition the F-number of beams in a millimetre telescopes such as PLANCK are quite small (between the primary and secondary mirrors, for example). Thus, computing the beam diffraction based on scalar field models can be rather approximate compared to full vector field diffraction calculation.

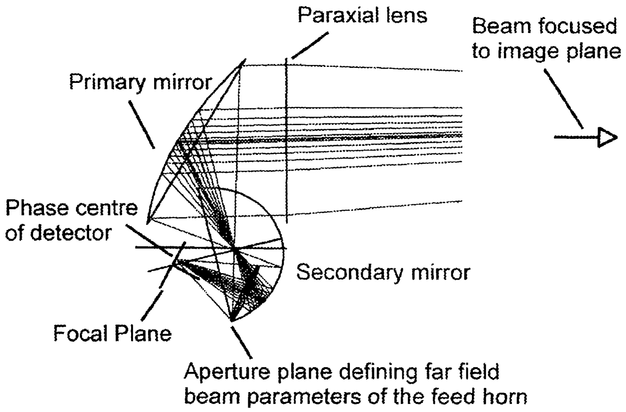

**Fig. 2.** Geometrical ray trace of a detector beam generated using the modified IAS model of the PLANCK Telescope. The entrance pupil used to specify the far field parameters of the Gaussian beam from the feed horn is also indicated in the figure.

In the study two software models have been adopted one which establishes beam propagation based on a Physical Optics (PO) modelling approach and one which analyses the beam diffraction in terms of a scalar diffraction theory using optical path difference calculations. These two models are related to the RF and optical wavelength regimes respectively.

### *2.2. The ZEMAX Model of the Telescope*

The first of the optical modelling techniques employed made use of a commercial optical modelling package called ZEMAX (ZEMAX-EE 7 supplied by Focus software Inc., Tucson Arizona). This package, which was designed for use at the optical wavelength region, has a number of features of interest to the PLANCK model, principally the ability to optimise an optical system at high speed. The work detailed here was carried out along with the IAS in Orsay, Paris and corresponds to a development of an earlier model generated by the IAS.

At its most basic level the package enables geometrical ray tracing from the detector location through the telescope thus showing the changes in the envelope of the beam through the system. In order to understand the location of the resulting beam on the sky an idealised thin lens has been incorporated into the system near the telescope aperture to image the beam from detector horn, thus simulating the beam on the sky. This ideal lens is called a paraxial lens and is used in ZEMAX to focus a beam without introducing aberrations into the geometrical ray propagation calculations. A figure showing the basic arrangement of the system is illustrated in Figure 2. This diagram shows a geometrical ray trace through the system for an off-axis source placed in the focal plane of the PLANCK model. Outside of its use in understanding the basic geometries of the telescope this ray tracing approach is also useful in calculating the required tilts on feed horns to centre the beams on the primary mirror (the secondary is oversized and so contributes less to vignetting effects). This is particularly useful in the more accurate PO approach as it enables the user to establish the required input parameters to locate the beams at the correct location on the primary.

In calculating the beam pattern of the detector on the sky it is important to include diffraction effects caused by apertures in the system. The diffraction calculation performed by ZEMAX is a scalar field model in which the beam profiles for a particular object point is established by determining the optical path length of rays traced through the system. These rays are propagated between the optical components as they fan out from the object point in the focal plane of the telescope. The path length along the various rays is used to calculate the optical path length difference (OPD) across the width of the exit aperture of the system. A Fourier transform of the OPD and wavefront amplitude data is then used to perform the diffraction calculation between this pupil and the image plane. In the ZEMAX approach it is necessary to focus the beam (using a paraxial lens) and examine the diffracted focal spot computed via a Fourier Transformation of the field at the lens. This spot is effectively an image of the far field pattern of the telescope beam on the sky.

An important limitation in the ZEMAX simulation is that it models diffraction in terms of the wavefront emanating from a point source. However the field from the mouth of the horn is not that of a point source but instead has a field distribution that changes in amplitude and phase across the feed aperture. To a good approximation the beams from the circular corrugated horns used in the single moded HFI detectors couple power to a single free space Gaussian mode (Lesurf 1990). As the name suggests these beam modes have a Gaussian intensity distribution across their width and maintain this characteristic field pattern along the path of the beam (Kogelnik & Li 1966). For the detector feed horn the centre of phase curvature of the Gaussian mode changes position for different locations in the near field of the horn. However, in the far field region the phase front is spherical and appears to originate from a point source located at a fixed point (Lesurf 1990) (known as the phase centre of the horn). The first optical component which the horn beams encounter is in the far field region and therefore it should be possible to model field propagation using Gaussian weighted rays emanating from the horn phase centre. ZEMAX allows the user to define a beam in terms of a point source which acts as the phase centre and an aperture weighting which is used to define the Gaussian beam size at a point in the far field region of the horn. This aperture plane is indicated in Figure 2.

A typical example of the beam pattern on the sky produced using the ZEMAX model is shown in Figure 3(a). This shows a contour plot of the beam intensity in dBs for the 100GHz-1 pixel in the HFI (wavelength 3mm). This detector is located in the focal plane at an off-axis position of 42.92mm, 40.58mm. The co-ordinates used to represent the contour map correspond to the x and y angular tilts with which the $k$ vector is oriented with respect to the principal optical axis of the system. As shown the asymmetry in the beam pattern due to the aberration are only significant at a level of the order of -30dB. The full width at half maximum for the beam is 0.178° which is in excellent agreement with the expected beam shape for this pixel (0.18°).

As detailed a useful feature with the ZEMAX package is the capability it offers to optimise the performance of the optical system by changing parameters such a component separation, focal lengths, etc. In this process the optical design is optimised by setting parameters of the geometry as variable in the program code and maximising the optical performance of the system using the ZEMAX optimisation process. Of primary interest in the current study is the ability to optimise the system based on an optical path difference (OPD) calculation thus minimising the wavefront error in the image space. In such an analysis the optimised OPD procedure calculates the system which has the best diffraction limited performance. By setting the phase centre location as a variable the optimisation procedure can be used to determine the best location for the phase centre of a particular HFI pixel. This allows the non-planar focal surface for the telescope to be established over the field of view of the detectors. Clearly the use of such an approach relies on the OPD calculated by the ZEMAX procedure providing a realistic representation of the wavefront error of the system. It should be noted that in the ZEMAX model the OPD calculation does not include the effect that diffraction of the beam by the secondary mirror has on the phase of the wavefront at the primary.

### *2.3. The Physical Optics Model*

In this paper the use of the term physical optics complies with the accepted use in antenna engineering where the diffraction calculations encode the vector nature of the field (this is the common usage of the term at microwave and RF frequencies). This definition is distinct from that normally used in the optical wavelength regime where it refers to a scalar diffraction theory. In the model the beam propagation is calculated using integral solutions of the time harmonic electromagnetic wave equation through what is termed the dyadic Green's functions (Diaz & Milligan 1996). These integral solutions are closely related to the retarded potential formalism of electromagnetic wave theory and relate the radiated field to the distribution of current over the source and the field position (Harrington 1861; Balanis 1989). In the PO approach the field radiated from the feed horns is determined by calculating the field produced by the equivalent source currents at the mouth of the horn. For numerical purposes the field integral is replaced by a finite sum of source terms. In this calculation the sampling of the distribution is made sufficiently dense to ensure that the changes in the phase and amplitude are correctly represented in the sum. Following this approach the currents induced on the secondary reflector are first established over the surface of the mirror. These currents are then re-radiated and the process repeated to establish the current distribution over the primary mirror. Using this data the far field pattern radiated by the telescope can be calculated. In the model the effects of blockages and finite aperture sizes on diffraction of the beam is characterised by the truncation of the current distribution. The numerical model used in the study was based on a toolkit of software procedures supplied as part of a physical optics textbook produced by Diaz & Milligan (1996). In the model development this series of procedures, which took the form of a number of MATLAB script files, were adapted for use with the off-axis Gregorian design of PLANCK.

The beam pattern on the sky for the 100GHz-1 horn determined using the PO model is shown in Figure 3(b). These data show a contour plot of the beam intensity in dB for the case

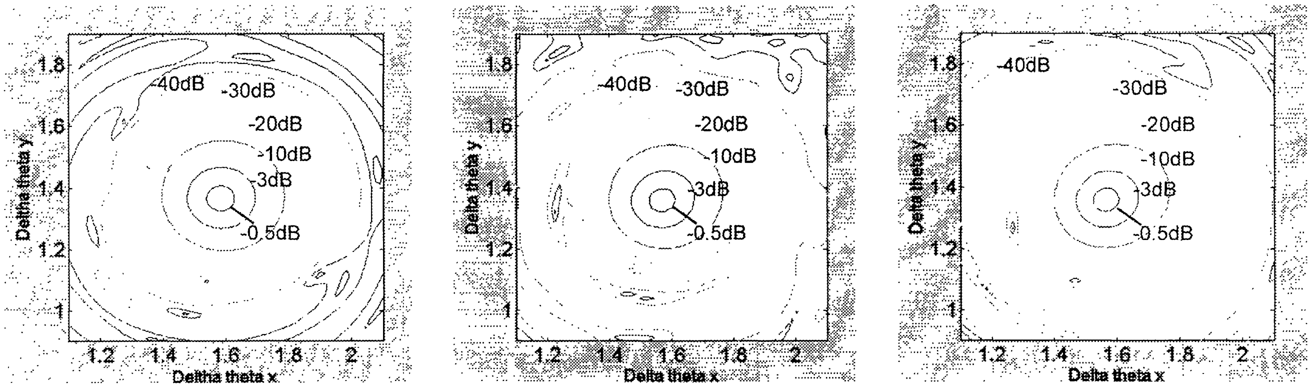

**Fig. 3.** Figure 3(a) (right) shows the projected beam pattern on the sky for the HFI feed horn 100GHz-1 as calculated using the ZEMAX model. This contour map represents a decibel plot of the beam intensity with the x and y co-ordinates indicating the angular position with respect to the principal optical axis of the system. Figure 3(b) (centre) and (c) (left) shows similar contour plots for the 100GHz-1 detector as calculated using the Physical Optics model based on Figure (b) a Gaussian model and (c) a Bessel function model of the field at mouth of the feed horn.

of a Gaussian beam model of the field at the feed as consistent with the ZEMAX model discussed previously. The co-ordinates used to represent the contour map are in keeping with those used in Figure 3(a). As shown the location of the beam centre and asymmetry in the beam pattern is in close agreement with the pattern generated using the ZEMAX calculation (down to a level of -20dB). Again the full width at half maximum for the beam is 0.18° which is in good agreement with the expected beam shape for this pixel. This indicates that the ZEMAX model generates a relatively good representation of the beam propagation for the single moded horns (HFI detector frequencies 100 - 353GHz).

As a further improvement in the accuracy of the PO model for PLANCK the field at the mouth of the feed horns can be represented in terms of a Bessel function distribution with the width and spherical phase curvature of the beam determined by the horn geometry (Lesurf 1990). This distribution constitutes a more accurate representation of the field at the feed horn compared to the Gaussian beam model. However, as shown in the data given in Figure 3(c) the beam on the sky for this Bessel function differs little from the Gaussian model (difference are apparent only at a level of $\sim$ -30dB). A similar approach can be used to represent field distributions associated with other feed horn types.

As detailed the PO approach represents a more rigorous method of investigating the effects of diffraction at the secondary mirror on the beam propagation. However, this is achieved at the cost of a significantly lower running speed for the model compared to ZEMAX. This reflects the high sampling requirements needed in calculating the field sum when propagating the field through the telescope. This is particularly true in the case of the near field propagation of the field between the secondary and the primary mirror. In this case it is necessary to determine the field at a sample spacing of the order of the wavelength of the field. Using the MATLAB version of the physical optics model a calculation for the beam pattern on the sky for the 147 GHz horns takes approximately 8 hours on a 300MHz Pentium PC. This can be estimated to be of the order of 100 times faster than the runtime one might expect for an 857GHz horn. Clearly these sampling requirements are a concern in terms of the resulting effect on the runtime of the PO model and make this approach an unrealistic method of optimisation the system. This highlights the importance of optimisation approaches such as that provided by ZEMAX which take only a matter of seconds. At the moment a study is being performed to investigate methods of speeding up the physical optics model.

In addition to the use of the physical optics simulation in determining the beam shape on the sky the model also offers the possibility of determining the polarisation properties of the field imaged by the telescope. This enables the effect of cross polarisation of the field to be investigated. An added benefit of the physical optics calculation is that in principal it should be possible to determine the pattern of the multimoded HFI detectors on the sky for the HFI. Such modelling would be based on an understanding of the field distribution over the mouth of the multimoded feed horns.

To date the PO model has been used to characterise the bandwidth response of the 100GHz and 147GHz HFI pixels following the Bessel function approach described. In this work the phase centre positions for the various feed horns have been optimised using the ZEMAX model.

## 3. CONCLUSION

This paper has focused on research at the Experimental Physics Department, NUI Maynooth into modelling the optical characteristics of the HFI instrument on board the PLANCK surveyor. The advantages and disadvantages associated with the two techniques investigated in the study (the ZEMAX and physical optics model) have been discussed both in terms of system optimisation and in relation to rigorous modelling of the telescope. The results of this study have shown the sky pattern of the single moded feed horns generated using the

ZEMAX model of PLANCK to be in reasonable agreement with the data generated by the more accurate physical optics approach. This supports the use of the ZEMAX model in optimising the phase centre locations of the horns in the single moded HFI set. Clearly, despite the usefulness of the ZEMAX package in optimising the design of the PLANCK telescope, the Physical Optics approach is necessary in establishing an accurate description of the beam patterns of the horns on the sky. The PO model also offers the possibility of modelling the beam patterns generated by the high frequency multimoded horns in the HFI. In addition, the PO technique provides a useful tool when studying the polarisation properties of the system. At the present moment a concern in the use of the PO approach is the significant numerical processing load associated with the technique. We are currently looking at methods of improving the runtime of these simulations by examining the sampling issues related to the PO model.

## Acknowledgements

We wish to acknowledge the financial support of Forbairt and Enterprise Ireland for this research. We would also like to thank Yuying Longval and Jean-Michel Lamarre from the IAS, Orsay Paris for their help in relation to the development of the code for the ZEMAX model.

## References

Balanis C. A., 1989, *Advanced Engineering Electromagnetism*, John Wiley & Sons.

Bersanelli M. *et al.*, 1996, *The Planck Phase A Report - A Mission Dedicated to Imaging the Anisotropies in the Cosmic Microwave Background.*

Diaz L., Milligan T., 1996, *Antenna Engineering Using Physical Optics - Practical CAD Techniques and Software*, Artech House.

Harrington R. F., 1961, *Time-Harmonic Electromagnetic Fields*, McGraw-Hill.

Heavens A., 1998, *Astronomy & Geophysics*, 39, 5.14

HFI Consortium, 1998, *HFI: High Frequency Instrument for the PLANCK Mission*, Response to ESA Announcement of Opportunity.

Holland W. S. *et al.*, 1999, MNRAS, 303, 659.

Kogelnik H., Li T., 1966, *Proc. IEEE*, 54, No. 10, 1312.

Lesurf J., 1990, *Millimetre-Wave Optics, Devices and Systems*, Adam Hilger.

Murphy J. A., Padman R., 1991, *Infrared Physics*, 31, 291.

O'Sullivan C. *et al.*, 1995, MNRAS, 274, 861.

Smoot G. *et al.*, 1992, ApJ, 396, L1.

Van der Veen J., *et al.*, 1998, *The Physics Teacher*, 36, 529.