Experimental Verification of Electromagnetic Simulations of a HIFI Mixer Sub-Assembly

W. Jellema[1], P. R. Wesselius[1], S. Withington[2], G. Yassin[2], J. A. Murphy[3],
C. O'Sullivan[3], N. Trappe[3], T. Peacocke[4] and B. Leone[5]

[1]National Institute for Space Research (SRON), Groningen, the Netherlands
[2]Cavendish Laboratory, Cambridge, UK
[3]National University of Ireland Maynooth (NUIM), Co. Kildare, Ireland
[4]UK Astronomy Technology Centre (UKATC), Edinburgh, UK
[5]European Space Agency (ESA/ESTEC), Noordwijk, the Netherlands

Abstract: In Phase II of the study "Far-Infrared Optics Design & Verification", commissioned by the European Space Agency (ESA), we investigate the ability of several commercial software packages (GRASP, CODEV, GLAD and ASAP) to predict the performance of a representative example of a submillimeter-wave optical system. In this paper, we use the software packages to predict the behaviour of a Mixer Sub-Assembly (MSA) of HIFI, and we compare the simulations with near-field measurements at 480 GHz. In order to be able to distinguish between the predictions of the packages, we move the corrugated horn of the MSA through its nominal focus position. A unique feature of the experimental arrangement is that the measured position of every field point is known absolutely to within fractions of a wavelength. In this paper we present the results of this through-focus experiment, which give a good first-order indication of the agreement between measured and simulated behaviour of a typical submillimeter-wave optical system.

Keywords: ESA-TRP, far-infrared, submillimeter, optics, verification, HIFI

1. INTRODUCTION

The accurate modelling of optical systems in the far-infrared and submillimeter-wave bands is complicated because of the long wavelength character and in many applications necessity for a compact optical layout. The associated diffraction effects inevatibly become important and can no longer be ignored. The unique nature of optical systems in this wavelength band and the lack of dedicated simulation software has lead to the non-ideal use of software packages designed and intended for other wavelengths and based on a variety of underlying physical principles. The adapted use of these software tools for the far-infrared is not reported comprehensively in literature and much uncertainty surrounds the accuracy of these optical simulations.

In order to verify the ability of these commercial packages (GRASP, CODEV, GLAD and ASAP) to predict the performance of submillimeter-wave optical systems, the European Space Agency (ESA) has commissioned the study "Far-Infrared Optics Design & Verification". In Phase I of the study we carefully selected test cases to reveal strengths and weaknesses of the packages in typical submillimeter-wave applications on the basis of the underlying physical principles [1, 2]. In the end of Phase I we carried out first-order simulations of a typical real system case represented by a Mixer Sub-Assembly for HIFI [3, 4]. We observed that the simulated differences in a focussed system were too small to be observed experimentally. In order to distinguish between the packages we therefore proposed a through-focus test revealing differences at a relatively high intensity level relaxing the need for high dynamic range. In Phase II we constructed a near-field facility capable of measuring both amplitude and phase at 480 GHz. The main objective of this work is to address the question to what extent measured and simulated performance of a typical example of a submillimeter-wave system may be expected to agree.

2. SUMMARY OF SIMULATION PACKAGE CAPABILITIES

We have compared the beam predictions of the four different software packages summarized below: **GRASP8, ASAP (v7.1), GLAD (v4.5)** and **CODE V (v9.0 and v9.2)**. The strengths and weaknesses of each package were reported in detail during Phase I of the project [1, 2]

GRASP is a general antenna analysis program package marketed by TICRA. Its theoretical analysis is based on Physical Optics (PO) and the Geometrical Theory of Diffraction (GTD). Physical Optics is based on calculating the induced currents on the reflector surfaces without taking the edge effects into account. This clearly degrades the accuracy of the method predictions at wide angles. In GRASP8 the PO method is supplemented with GTD in order to improve the accuracy of the equivalent current calculation near the edges. GTD approximates the non-uniform current at the reflector edge to the induced current at the edge of a canonical scatterer that conforms to the shape of the reflector in the locality of the edge points. Multiple reflector systems are analyzed in GRASP by calculating the induced current on one reflector and using it as a source illuminating the next reflector. Although not investigated here, cross-polar predictions are also available from GRASP. The model system could be set up in GRASP exactly as it is described in section 3. Throughout Phase I and II of this project we have taken GRASP to be our benchmark software.

ASAP is a package for the analysis of visible / near-IR optical systems. It was originally designed for the analysis of stray light, but was extended for the analysis of diffraction. It is essentially a non-sequential ray tracing package but has an additional diffraction analysis capability. For this it uses a technique called Gaussian beam decomposition. Rays representing a set of Gabor-Gaussian modes are traced through the optical system. These modes can be recombined at any point in the system to calculate the field. ASAP has three forms of decomposition algorithm. In the first, a straightforward spatial sampling is performed. The Gaussian beams have equal sizes, but are spaced out across a grid. In the second algorithm, an angular decomposition is performed. Each Gaussian beam is equal in size but has a different propagation direction, so that the beams are equally spaced in angle in the far field. The third method is a combined spatial / angular decomposition. This last method has only recently been added. The description of the MSA optical system within ASAP was straightforward and very precise.

GLAD was developed to model laser and optical systems where diffraction is expected to play an important role. A beam is represented by its complex amplitude distribution, which need not be a simple function. The primary propagation algorithms in GLAD are based on a plane-wave decomposition with no special symmetry assumed. Light is treated as being strictly monochromatic and therefore perfectly polarized. Optical systems are modelled to the accuracy of small-angle, scalar Fresnel diffraction theory. Conic mirrors can be modelled using exact ray-tracing to compute aberrations. This facility is to be extended to lenses, apertures and obscurations in future versions of GLAD. (In fact tilted apertures have been introduced into the version of GLAD released towards the end of this project. This version has not been used in any of the work presented here.) The mirrors of the model system are set up in GLAD by considering them as sections of larger paraboloids and ellipsoids. Edges cannot be defined for the mirrors themselves, and are therefore approximated by placing apertures in front. This was the only approximation that was made when setting up the system as drawn in Fig. 1. of the next section.

CODE V is an optical analysis and design package for visible / near-IR optical systems. Like ASAP it is primarily a geometrical ray-tracing package, but offers in addition some diffraction analysis capability. CODE V uses a plane wave expansion of fields in its diffraction calculations and allows mirrors and apertures to be de-centered and tilted. In this case, the MSA mirror edges were modelled as tilted elliptical apertures. The field mirror, MAM2 (Fig. 1.) was modelled as a toroid. The greater control of sampling in the latest version of CODE V (v9.2) allowed a technique to be developed to overcome the problems reported throughout the first stages of the project [1].

A more detailed account of setting up the model system in each of the packages is included as Appendix B in the final report of Phase II [5].

3. MODEL SYSTEM DESCRIPTION

In Phase II of the project one of the Mixer Sub-Assemblies of HIFI represents a typical submillimeter-wave optical system. The optics of the selected MSA are designed to operate in the 480-640 GHz frequency range (HIFI band 1). In this paper however, we only consider the lower frequency end of the band, i.e. we only present results in the long-wavelength limit at 480 GHz where diffraction effects are most pronounced.

In Fig. 1. a simplified layout of the optics is shown. The reduced MSA (as shown in Fig. 2.) compromises a conical corrugated horn and three off-axis mirrors. Because of this off-axis geometry we refer to the plane of drawing as the asymmetric plane. When the horn is in its nominal focus position the three mirrors form an image of the horn aperture in the output plane, which is located at 66.25 mm from the parabolic mirror MAM1. At actual wavelengths a frequency independent beam waist is located in this plane with a waist radius of 3.55 mm. The corrugated horn has a slant length of 15.4 mm and an aperture radius of 2.5 mm. The polarisation direction of the corrugated horn is perpendicular to the plane of drawing. We only consider this component of the electric field in the output plane.

Also indicated in Fig. 1. is a set of through-focus positions for the corrugated horn. Apart from the nominal focus position (solid line), the horn can be moved towards the elliptical mirror MAM3 by 5 mm, and away in two steps of 5 mm. Through-focus measurements were simulated for each of these four configurations. As mentioned in the introduction the through-focus test offers a means to systematically study the differences between simulations and experiment by introducing different levels of aberration. The advantage of this model system is that differences which would normally be present at relatively low intensity levels in the far-field, will now show up as main beam distortions in the near-field. We therefore expect that this experimental arrangement will illustrate the differences between the package predictions.

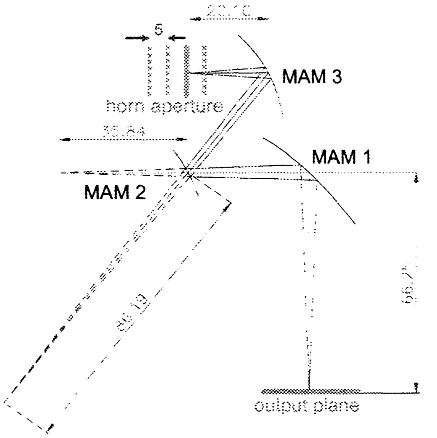

Fig. 1. Layout of model system

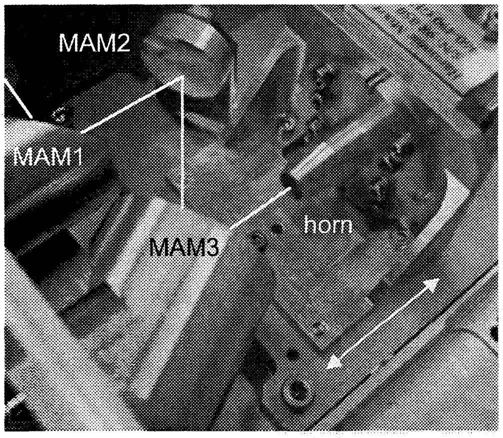

Fig. 2. HIFI Mixer Sub-Assembly.

4. SOFTWARE PACKAGES SIMULATIONS

Initial simulations were done by assuming a Gaussian distribution at the aperture plane of the horn. This aperture field distribution was propagated through the optics to the output plane. These first-order simulations proved to be a useful starting point to define the criteria to be met by the measurement system. Given the differences in the through-focus simulations we found that an experimental system that could detect differences of 3-4 dB at the level of -20 dB would be sufficient to distinguish between the aberrations predicted by the packages. We furthermore found that ASAP had serious difficulties in modelling this compact system with a horn aperture of only eight wavelengths in diameter. We decided to exclude ASAP from the final comparison since we found that its predictions were not sufficiently close to expected behaviour. The intrinsic problem in our particular case appeared to be the decomposition of the source field for which we could not find an independent and consistent procedure for all through-focus positions simultaneously.

We subsequently improved the horn field approximation by assuming an ideal hybrid feed that can be described by a truncated Bessel function with a spherical phase error [6]. Although it is common practise in submillimeter design to substitute the real source field of a corrugated horn by a fundamental mode Gaussian beam, we found that differences might not be negligible. We found that using a Gaussian beam to approximate the horn field did not predict either the sidelobe level or the amount of main-beam distortion. An example that illustrates this point is shown in Fig. 3. which shows the GRASP prediction (dotted) assuming a Gaussian approximation in comparison to the GRASP and GLAD predictions (solid) assuming an ideal hybrid feed for -5 mm defocus (away from the first mirror). It is clear that the Gaussian approximation fails to predict the main beam distortion leading to significant errors already at the -10 dB level. The differences in phase predictions were also significant and measurable given the demonstrated measurement performance at this stage. The narrowest spatial features in the predictions could be resolved by the measurement system and based on this set of simulation results we were able to define the final test criteria.

Finally the field from the actual corrugated horn was calculated using the mode-matching technique and this was taken as the input to the model system. For these last simulations the new CODE V version was available and its results were a significant improvement on those reported earlier [1]. In order to compare the differences between an ideal and real horn field, we used GRASP to predict the output beam when the horn is moved 10 mm away from the first mirror. The result is shown in Fig. 4. It can clearly be seen that the two patterns are indistinguishable. The remarkable similarity between the two patterns results from a good horn design in which the ideal and real field distributions are almost identical in the upper 30 dB, and due to the finite throughput of the optical system (spatial filtering).

The final set of simulation results is partly shown in section 6 together with the experimental results. The full set of simulation and measurement results can be found in the final report of Phase II of this project [5].

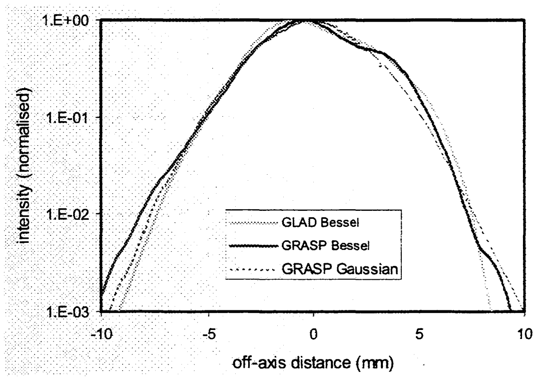

Fig 3. Asymmetric cut for an ideal and real horn field for a -5 mm defocus.

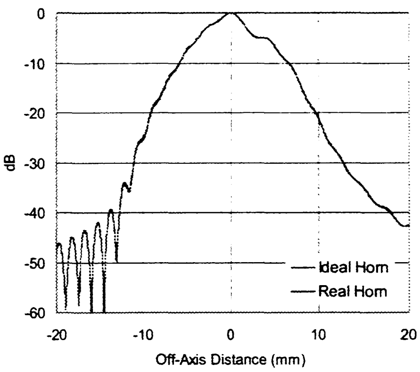

Fig. 4. GRASP simulation comparing ideal and real horn fields.

5. EXPERIMENTAL SETUP AND RESULTS

A substantial task in Phase II of the project was the development of a near-field facility capable of measuring both amplitude and phase at 480 GHz. In this paper we only briefly summarize some characteristics of the facility which is fully described in the final report [5].

The schematic diagram of the detection system is shown in Fig. 5 and is quite similar to other systems reported in literature [7, 8, 9]. In the upper-left corner of the diagram the Phase-Lock Loop (PLL) is shown. An InP Gunn oscillator is phase-locked at 80 GHz. A second directional coupler and waveguide harmonic mixer provide an independent reference signal. Because this signal is taken before multiplication to 480 GHz, the Intermediate Frequency (IF) of the waveguide harmonic mixer is multiplied by a factor of six, i.e. N = 6 in the diagram. The actual detector in the MSA is a subharmonically pumped Schottky mixer pumped by the same Local Oscillator (LO) as the reference mixer. We use a compensating pair of mixers to remove any correlated phase variations present in both the reference and detected signal. This allows a very narrow-band detection increasing system sensitivity. We finally use a Vector Network Analyzer (VNA) in the S21 mode to detect the relative field coupling between the test source and the detector. A signal-to-noise calculation shows that the dynamic range can be as high as 60 dB when detecting in a 100 Hz IF bandwidth and integrating in 10 ms. More details on performance can be found in [10].

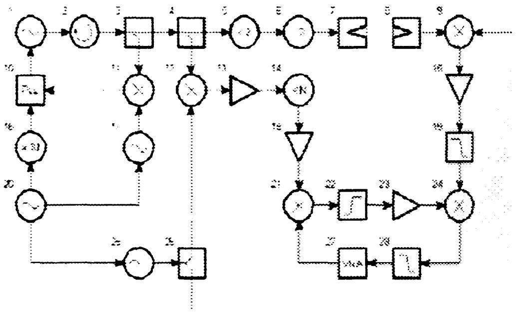

Fig. 5. Detection system diagram

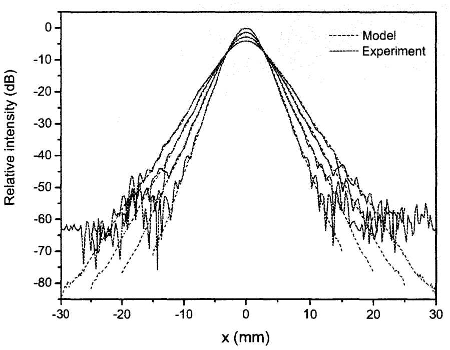

Fig. 6. Near-field horn measurements

In addition to the detection system several other system components were designed. We designed and modelled a modified version of the HIFI corrugated horn to shift the centre frequency to 480 GHz. In order to resolve the spatial structures present in the simulated beam patterns a flared-waveguide probe was designed that could resolve spatial frequencies of ½ mm^{-1}. Special mechanical flanges for the horn and probe were designed to fix the horn axis and aperture position with tight mechanical tolerances.

A three-dimensional scanner system was used to scan the test source with probe in the output plane of the MSA. A special support frame for the source and MSA was designed that also contained alignment devices. In the frame of the source we mounted two alignment windows with well-established relations to the probe coordinate system. We placed two alignment mirrors on the MSA support frame. Using an optical theodolite we were able to accurately align the scanner system with respect to the MSA. We achieved a lateral alignment accuracy of 25 - 50 μm, an axial accuracy of 0.1 - 0.2 mm, a tilt accuracy of a few arcmin and a polarisation alignment of 0.5 deg. A unique feature of the facility is therefore that the absolute coordinates of the measured fields points are known within fractions of a wavelength.

A detailed performance characterisation and error analysis was performed in which we identified and quantified the sources of error [5, 10]. We furthermore developed first-order error correction methods to reduce errors due to multiple reflections and long-term drift [5, 10]. To verify the performance, near-field measurements of the corrugated horn were taken at distances of 15, 20, 25 and 30 mm respectively at 480 GHz. The results and simulations are shown in Fig. 6. Both the level of agreement and the observed sensitivity clearly illustrate that we realised an accurate near-field system with known, and well understood, errors.

We finally mounted the corrugated horn and harmonic mixer in the MSA (Fig. 2.) and took co-polar measurements at 480 GHz in the output plane in both the asymmetric as well as the symmetric direction for each of the through-focus positions. The individual amplitude and phase plots can be found in chapter 5 of the final report [5] and some of the results will be presented in the next section of this paper.

6. COMPARISON SIMULATIONS AND EXPERIMENTAL RESULTS

Before we start comparing the simulations and experimental results, we would like to note that the comparison of one particular field component, and in particular its phase, is not straightforward at all. Apart from GRASP, the packages produce a scalar quantity that represents the field, i.e. the vector-nature of the field is completely ignored. A comparison is therefore only reasonable in the limit that the cross-polar component is very small. Using GRASP we found that the cross-polar level is indeed sufficiently low. The comparison between GRASP and experiment is however sound, since the detection system is sensitive to only one field component (polarised probe).

In general we observed good agreement in amplitude between the predictions and experiment in the main beam. In particular, GRASP and CODE V agreed exceptionally well (see Fig. 7.). Below the -40 dB level there were only small differences which could be easily attributed to sampling and systematic errors of the facility. It is not clear whether experiment or simulations get wrong at this level. More experimental and simulation work is therefore required to draw firm conclusions below the -40 dB level. In several cases GLAD failed to agree with experimental results. In particular in the asymmetric cases where the horn was moved 5 mm towards respectively 10 mm away from the mirror, GLAD failed to predict the sidelobe structure and distortion (see Fig. 8.). Considering that GLAD integrates over a projected aperture rather than over the physical mirror aperture, we indeed expect the sidelobe level for the asymmetric patterns to be inaccurate.

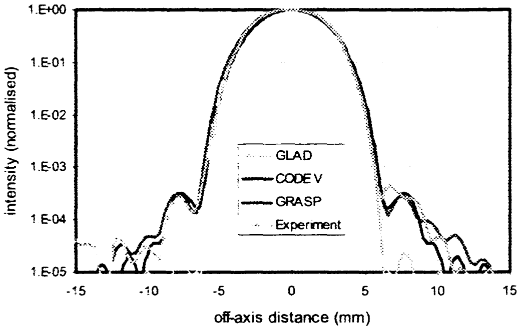

Fig. 7. Measured and simulated amplitude at nominal focus (symmetric cut).

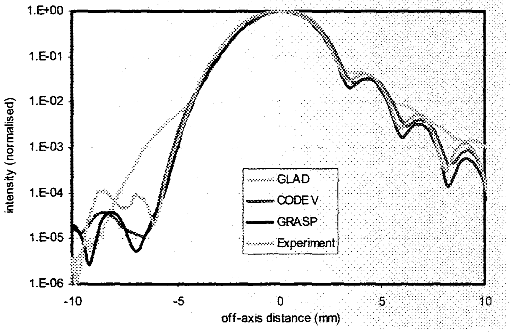

Fig. 8. Asymmetric cut at +5 mm defocus (towards mirror MAM3).

Regarding the phase simulations and measurement we found that phase information indeed provided additional useful information in assessing the performance of the packages. It is remarkable that GLAD, which predicted amplitude relatively well in many test cases, failed completely to predict phases correctly. In Fig. 9. for example the phase predicted by GLAD is in complete disagreement even in the symmetric plane. In the asymmetric cuts we observed substantial differences with experiment especially for positive off-axis distances (Fig. 10.). This again might be due to integrating over a projected aperture rather than the physical one. CODE V showed in general good agreement with the experimental results. The agreement is however best in the main beam region and starts to deviate at lower intensity levels. The GRASP simulations showed best agreement with the measured curves and predicted the observed phase structure most accurately. An example of an asymmetric pattern is given in Fig. 10. Although the differences might appear significant one should realize that the absolute deviations in phase between GRASP, CODE V and experiment are all below $\lambda / 20$ at 480 GHz once again illustrating the accuracy of our work.

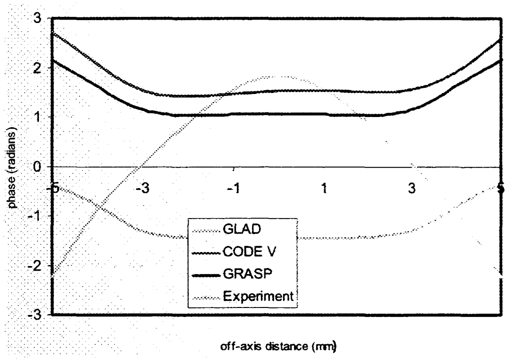

Fig. 9. Phase distributions (symmetric cut) for +5 mm defocus (towards mirror).

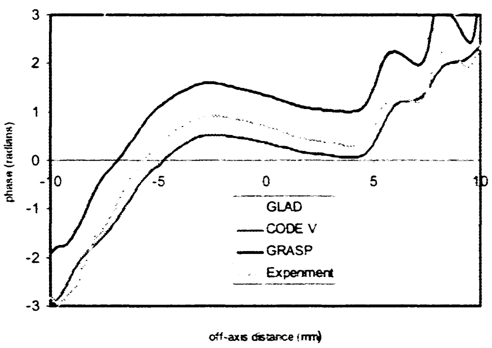

Fig. 10. Phase distributions at nominal focus position (asymmetric cut).

7. SUMMARY AND CONCLUSIONS

In Phase II of the study "Far-Infrared Optics Design & Verification" we investigated the ability of several commercial software packages (GRASP, CODEV and GLAD) to predict the performance of a representative example of a submillimeter-wave optical system. We did not attempt to compare the different packages in a competitive way. We were only interested in assessing the ability of each package to carry out a predetermined task. In this part of the study a modified version of one of the Mixer Sub-Assemblies for HIFI was taken as a model system. The optical layout is believed to be typical of a high performance submillimeter-wave system. The key question we beared in mind is to what extent simulated and measured performance may be expected to agree. To address this question we selected a strategy of through-focus near-field phase and amplitude measurements revealing the differences between the packages. In this through-focus test the differences were shifted from the far-out sidelobes into the main beam relaxing dynamic range requirements for the measurement system. We developed a near-field facility and demonstrated a dynamic range of at least 50 dB. A unique feature of the experimental system is that geometry is controlled within fractions of a wavelength. Therefore the theoretically derived and experimentally measured field patterns were determined by reference to one single absolute position and overlaid without any adjustment. We finally constructed a full error model of the measurement system and experimentally verified the system on a corrugated horn. Both the level of agreement and the observed sensitivity clearly illustrated that we realised an accurate near-field system with known, and well understood, errors.

After initial investigations we excluded the simulation results of ASAP as we found that its predictions were not sufficiently close to expected behaviour in this particular case. In contrary to what we found in early stages, CODE V now showed good performance whereas we initially had severe problems in getting meaningful results. Based on the out-of-focus measurements we conclude that GLAD is only accurate above the -20 dB level. Phase measurements furthermore revealed that GLAD can make substantial errors when simulating phase. The principle limitation seems to originate from the definition of the rim of mirrors which are represented as projected apertures perpendicular to the chief ray. This limitation has been addressed however in the version that has become available since. Both GRASP and CODE V simulation results agree very well with experiment down to -40 dB. GRASP was even capable of tracing the sidelobe structure down to -45 dB. Below this level it is not clear whether simulations or measurements become inaccurate. Finally we observed that the phase distributions predicted by GRASP and CODE V are generally in agreement with measurement. In particular the agreement between GRASP and experiment was excellent with the exception of one single case. In general the overall agreement between simulation and experimental results is best for GRASP. The advantages of its full electromagnetic approach are evident. For design purposes however the awkwardness of setting up models might limit the flexibility to explore different layouts. We therefore feel that an excellent approach would be to combine GRASP with a first-order pre-processing and design package before verifying an optical system using rigorous electromagnetic calculations.

8. ACKNOWLEDGEMENTS

The authors would like to acknowledge Peter de Maagt and Maurice Paquay from ESA / ESTEC for their useful comments. The authors are grateful for design support by Edward Tong from Harvard-Smithsonian, Matt Carter from IRAM and Andrey Baryshev from SRON / RuG. We finally acknowledge Lenze Meinsma and Geert Keizer from SRON as well as Jan Idserda from ASTRON for their mechanical design efforts. This work was carried out in Phase II of the ESA TRP Study "Far-Infrared Optics Design and Verification Tools", ESTEC/Contract No. 13043/98/NL/PB.

9. REFERENCES

[1] Atad-Ettedgui E., Duncan W., Henry D., Jellema W., Murphy J. A., Trappe N., van de Stadt H., Withington S. and Yassin G., "Far-IR Optics Design and Verification Tools", *Final Report Phase I ESA TRP Study 13043/98/NL/NB*, December 2000, ESA.

[2] O'Sullivan C., Atad-Ettedgui E., Duncan W., Henry D., Jellema W., Murphy J.A., Trappe N., van de Stadt H., Withington S. and Yassin G., "Far-IR Optics Design and Verification", *International Journal of Infrared & Millimeter Waves*, pp. 1029-1045, Vol. 23, No. 7, July 2002.

[3] T. de Graauw, F. P. Helmich, "Herschel-HIFI: The Heterodyne Instrument for the Far-Infrared", in *The Promise of the Herschel Space Observatory*, edited by G. L. Pilbratt et al., ESA SP-460, pp. 45-51, 2001.

[4] B. D. Jackson, K. J. Wildeman, N. D. Whyborn on behalf of the HIFI Focal Plane Consortium, "The HIFI Focal Plane Unit", *Proc. 13th International Symposium on Space Terahertz Technology*, pp. 339-348, 26-28 March 2002, Harvard University, Cambridge, Massachusetts, USA.

[5] P. R. Wesselius et al, " Far-Infrared Optics Design and Verification Tools", *Final Report Phase II ESA TRP Study 13043/98/NL/PB*, March 2003, to be made available by ESA.

[6] P. F. Goldsmith, *Quasioptical Systems: Gaussian Beam Quasioptical Propagation and Applications*, IEEE Press: New York, Chapter 4 and 7, 1997.

[7] P. Goy, M. Gross, "Vector Transceiver for mmWave Antennas", *Proc. 20th ESTEC Antenna Wokshop on Millimetre Wave Antenna Technology and Antenna Measurement*, pp. 289-294, 18-20 June 1997, ESTEC, Noordwijk, The Netherlands.

[8] N. Erickson, V. Tolls, "Near-Field Measurements of the Submillimeter Wave Astronomy Satellite Antenna", *Proc. 20th ESTEC Antenna Wokshop on Millimetre Wave Antenna Technology and Antenna Measurement*, pp. 313-319, 18-20 June 1997, ESTEC, Noordwijk, The Netherlands.

[9] C. E. Tong, S. Paine, R. Blundell, "Near-Field Characterization of 2-D Beam Patterns of Submillimeter Superconducting Receivers", *Proc. 5th International Symposium on Space Terahertz Technology*, pp. 660-673, 1994.

[10] W. Jellema, S. J. Wijnholds, P. R. Wesselius, S. Withington, G. Yassin, J. A. Murphy, C. O'Sullivan, N. Trappe, T. Peacocke, B. Leone, "Performance Characterisation and Measurement Results of a Submillimeter-Wave Near-Field Facility for the Heterodyne Instrument for the Far-Infrared", *Proc. 3rd ESA Workshop on Millimeter-Wave Technology and Applications*, Millilab, Espoo, Finland, May 2003.