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Millimetre-Wave Optics Design & Verification

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Abstract. Microwave background astronomy requires very high performance millimetre-wave optical systems. However, compact quasi-optics are difficult to design with any confidence using techniques developed for visible wavelengths. In this paper we investigate the performance of existing software design tools (ASAP, CODE V, GLAD) as well as a Gaussian beam mode analysis technique not yet available as commercial software. We have devised a set of test cases and used these to study the underlying methodologies and physics of these packages and we look at their ability to analyse millimetre systems and components. We have used GRASP as our benchmark software.

INTRODUCTION

In this paper we investigate the performance of a range of commercial optical design software packages (GLAD, ASAP and CODE V) in analysing the behaviour of millimetre-wave optical systems. These packages are not specifically intended for use at millimetre wavelengths but they represent the only types of optical design tools available. We investigate approximations that are inherent in the theoretical method on which the software analysis is based, and how these impact on long-wavelength predictions.

Several test examples have been chosen that highlight some of the discrepancies that can arise between field predictions from the different software packages when applied to the millimetre-wave regime. We have taken the physical optics package, GRASP, a software tool for reflector antenna design and analysis, as our benchmark software against which the results of the other packages are compared. It should be noted that because of its complexity and computational intensity, GRASP is more suited to design verification rather than initial instrument design. Future work will involve an experimental verification of some GRASP results.

ANALYSIS TECHNIQUES

At optical wavelengths, away from any abrupt changes in intensity distribution, energy can be considered to be transported along light rays obeying certain geometrical laws [1]. Ray-tracing packages, based on this assumption, have proved to be very successful. In the millimetre regime, however, the wavelength may be an appreciable fraction of component sizes and so cannot be neglected. Diffraction effects become important and the approach of geometrical optics is inadequate. Diffraction problems tend to be difficult and rigorous solutions are rare. Other approximations, suitable for this wavelength regime, must be used for speed and for analysing complex systems.

In optical design a source field must be propagated from one optical component to the next. Techniques such as the Method of Moments attempt to calculate source fields in a rigorous manner, others, such as those used by the software packages we considered, make simplifications. When a field is incident upon an aperture, for example, it is often assumed that the field over the opaque region is zero, whereas over the transparent region it is the same as it was in the absence of the aperture. The field over the input surface is generally a vector field but the assumption of

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paraxial propagation (made in ASAP, CODE V and GLAD) reduces it to a product of scalar solutions that propagate independently.

Propagating a field accurately onto the next optical component (solving the wave equation) requires diffraction integrals to be evaluated for each field point calculated. Rather than evaluating the integrals directly, it is possible to decompose the assumed source field into modes and then propagate the modes as required. This often simply consists of slipping the mode phases with respect to each other. A plane wave analysis [2] has the significant advantage that it is not limited to paraxial fields. Gaussian modes, on the other hand, are solutions of the paraxial wave equation [3]. Appropriately scaled, they allow an efficient representation of paraxial systems. In the Gabor approach [4], a field is decomposed into a discrete set of Gaussian beams shifted both laterally and in phase slope. In this paper we compare some results obtained using the commercial packages ASAP, GLAD, and CODE V (beam propagation algorithm). These are scalar diffraction packages based on a modal analysis of fields. GLAD and CODE V decompose the fields into plane waves, ASAP uses Gabor modes. In addition we have used results from the 'in-house' software package, PROFILE, which is based on a Gaussian Beam Mode Analysis (GBM) technique specifically applied to submillimetre-wave optical systems (see *e.g.* [5]).

The term physical optics, as we use it here, refers to the calculation of the field radiated by a reflector using an approximate surface current distribution determined from the incident magnetic field. The field on that part of the reflector not directly illuminated by the incoming field is assumed to be zero. We use GRASP, which combines Physical Optics and the Physical Theory of Diffraction (PTD, developed to correct for edge effects), as our benchmark.

TEST CASES

Our aim is to study the essential differences between packages using a relatively small number of components. As well as examples chosen from regimes where the approximations made by all packages are valid and good agreement would be expected, we have probed more extreme examples, though still typical of quasi-optical systems in the far infra-red. The cases we describe in this paper, aperture stops and off-axis reflectors, are the basic fundamental components of many quasi-optical systems. They illustrate many of the essential features of modelling techniques and the results we present allow the estimation of the accuracy with which more complex multi-element systems can be analysed. Apertures and off-axis mirrors are readily modelled by GRASP.

We have investigated components with diameters down to a few wavelengths and quasi-collimated beams with F-number between 3 (typical of a horn antenna) and 30 (typical of quasi-collimated beams in interferometers and diplexers). We have used uniform illumination by an infinite plane wave in certain examples. The off-axis mirrors we investigate have a large angle-of-throw typical of many current optical designs (e.g. HIFI [6]). In the following section we describe some of the example test cases chosen.

TEST CASE RESULTS

Apertures

The first set of test cases modelled the diffraction effects of beam truncation at an aperture stop in a screen. The near and far field intensity patterns were calculated for uniform plane wave illumination of apertures of radius between 3λ and 30λ. Some results are shown in Figures 1 and 2. Figure 1 shows an example of the near-field results for the paraxial packages (GBM analysis results closely matched those of GLAD). For the paraxial packages the results simply scale with aperture diameter as expected. These examples were chosen so that an on-axis minimum is predicted using a simple Fresnel diffraction calculation. The paraxial packages do produce this on-axis minimum. However, when compared with GRASP (Figure 2), some interesting differences arise particularly in the case of the smallest aperture (radius = 3λ). In the GRASP data there is no on-axis minimum and the overall pattern is smoother.

In terms of paraxial Fresnel diffraction, the on-axis minimum in these examples can be predicted by summing the contribution to the overall fields of neighbouring Fresnel zones [1]. The examples were chosen so that an even number of zones (four in our case) are seen to fill the aperture, and when viewed from the ouput plane their contributions approximately cancel. However, the non-constant obliquity factor from zone to zone is not included in such calculations. The GRASP plots suggest such an omission has a significant effect on the beam patterns calculated for the smallest aperture, where the angle associated with the obliquity factor is largest, destroying the perfect cancellations of neighbouring Fresnel zones. For the largest (30λ) aperture, where the on-axis minimum is present in the GRASP data, the obliquity angle of the outermost zone is relatively small (7.6°). In that case the off-axis structure predicted by the paraxial packages is in very good agreement with those predicted GRASP. The similarity of the GRASP near-field results when calculated with and without PTD show that it is the obliquity factor rather than edge effects that is the dominant source error in these cases. This indicates that propagation over short distances ($z < 2.5\ a$) can result in errors in the fine structure of the beam pattern for collimated beams.

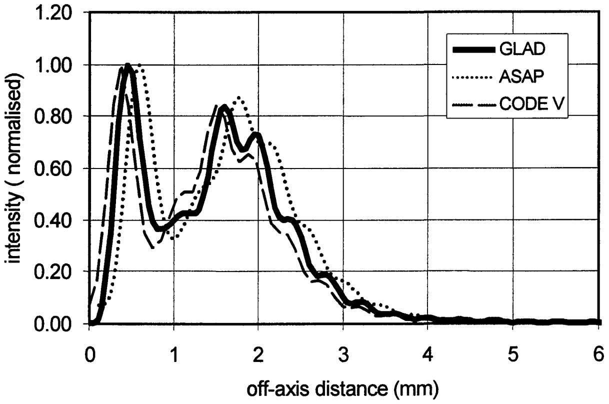

FIGURE 1. Intensity distribution in the near field (z_{out} = *25*mm) of an aperture of radius 10mm calculated using GLAD, ASAP and CODE V. λ = 1mm.

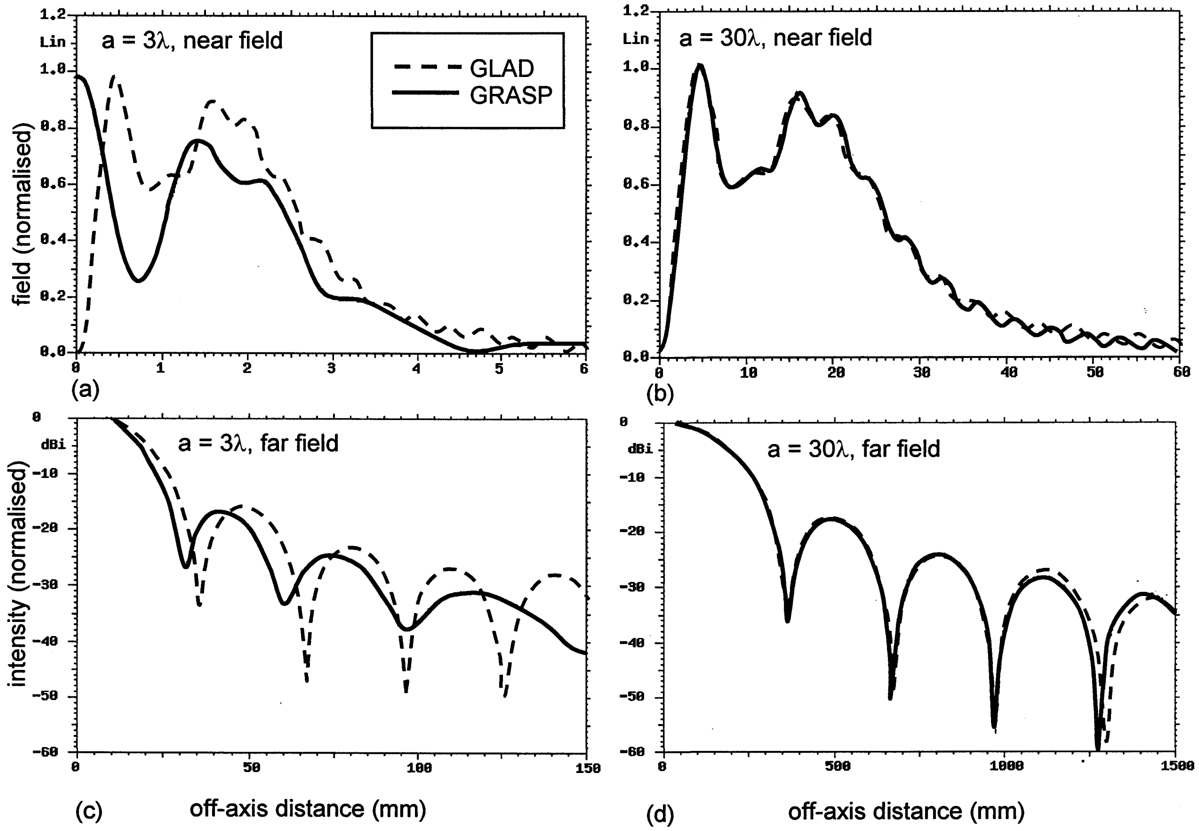

FIGURE 2. Beam amplitude in the near ($z_{out} = a^2/4\lambda$) and far ($z_{out} = 20a^2/\lambda$) field of an aperture of radius $a = 3\lambda$ and $a = 30\lambda$, calculated using GLAD and GRASP. GLAD is taken to be representative of the paraxial packages. λ = 1mm in all cases.

In the far field, by contrast, the angles associated with the obliquity factor are always relatively small and one would expect much closer agreement in the form of the beam between GRASP and the paraxial packages. This is clearly seen in the plots of Figure 2 (c) and (d) which show the far field patterns of the two apertures. Our data show that the paraxial packages are in broad agreement with each other, predicting the familiar Fraunhofer radiation pattern.

The discrepancy that appears in Figure 2(c) in the smallest aperture result is not due to an obliquity term, but rather due to the fact that the beam spreads out into a large (non-paraxial) angle. For the modal approach used in some packages, for example, the highest order modes may not be propagating paraxially. There is also the issue that, in far field calculations involving the paraxial approximation, it is assumed that $\theta \approx \sin\theta \approx \tan\theta$. An increasing lateral discrepancy between GRASP and the other paraxial programs will occur at off-axis distances corresponding to large angles as viewed from the beam waist.

Off-Axis Mirrors

This second set of test cases involved modelling diffraction effects associated with re-imaging a coherent beam at off-axis paraboloidal or ellipsoidal mirrors of finite size (see Figure 3).

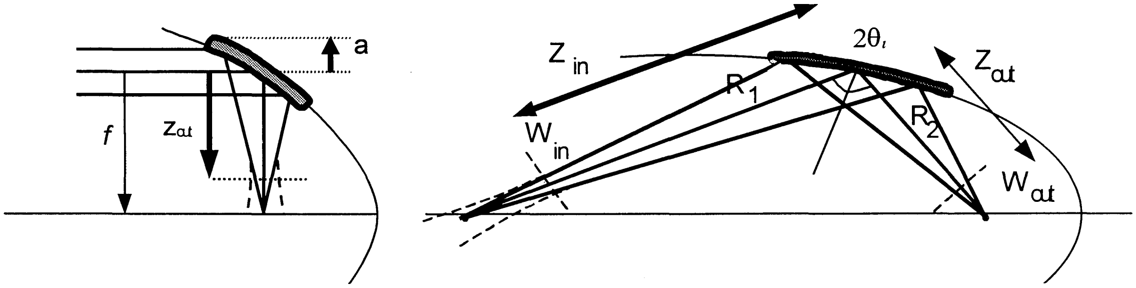

FIGURE 3. Off-axis mirror test cases. (a) Paraboloidal mirrors of focal length *f* and projected aperture a are used to reflect parallel beams forming a waist at z_{out}. (b) Ellipsoidal mirrors reflect wavefronts with a finite radius of curvature (R_1) producing an output beam waist at z_{out}.

In the short wavelength limit ellipsoids and hyperboloids are perfect phase-transforming reflectors of wavefronts with a finite radius of curvature. Paraboloidal mirrors are used as reflectors of parallel wavefronts. For strongly diffracting beams, however, phase aberrations occur beacause the radius of curvature of the phase front is not simply linearly related to distance along the beam. In the submillimetre regime, projection effects give rise to cross-polar scattering and spatial aberrations even at the wavelength for which the mirror was designed. We chose the test cases in this section to investigate the ability of the selected software packages to handle off-axis reflection and the resulting phase and amplitude distortions. All our test cases involved a 90° angle of throw. The sources investigated were Gaussian beams, with plane wave illumination chosen for one of the parabolic examples to mimic the operation of a telescope. There were software bugs in the first release of the CODE V beam propagation algorithm and so we do not include the results here

Figure 4 shows poor agreement between the packages, especially in the plane of where we would expect some asymmetry. Both ASAP and GLAD fail to predict the correct sidelobe structure or level. GLAD underestimates the sidelobe level by up to 10dB and predicts an almost symmetric beam. The sidelobe level and asymmetry calculated by ASAP are closer to those of GRASP, but the main beams differ by several dBs. There is better agreement in the other plane where the output beam is expected to be symmetric. GLAD and GRASP match down to -25dB, with GLAD's sidelobe level again lower, but in this case by about 5dB. ASAP, on the other hand overestimates the sidelobes by up to 10dB. The main beams show good agreement out to ~15°.

The approximations inherent in the packages must be considered in order to understand this level of disagreement. In the Gabor approach an electromagnetic field is decomposed into individual Gaussian beamlets, which can then be propagated through optical components using ray tracing methods. While ASAP is based on such a Gaussiam beam decomposition, the full Gabor representation is not implemented. One elementary Gaussian beam, rather than a fan of beams, is used to represent the field at each point on a spatial grid. This causes problems when attempting to model structure in beams on the scale of a few wavelengths. GLAD makes several simplifications which we might expect to affect the results of these test cases. The first is that it is restricted to apertures placed normal (or with small tilts) to the beam. Mirrors are infinite and their edges are defined by placing a suitable aperture in front. The level of trucation by the mirror is therefore an approximation. The second source of possible errors is the level of amplitude distortion caused by the mirror. The mirror can be designed so that it acts as an almost perfect phase transformer producing very little phase aberration, but projection effects will always introduce amplitude distortion. GLAD calculates aberrations by ray-tracing through the volume of conic sections before switching back to the ususal diffraction propagation. When doing this it considers the optical path length difference introduced, and uses these to calculate the phase aberration imposed on the beam. Amplitude distortions do not appear to be adequately modelled in this analysis.

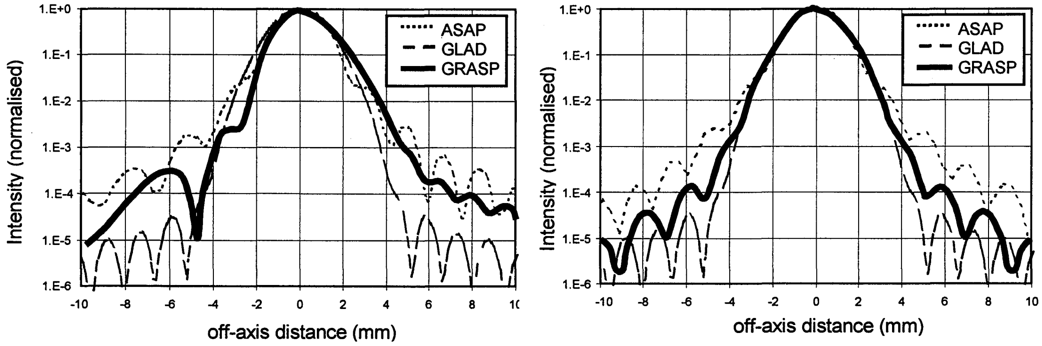

FIGURE 4. Intensity pattern at the output beam waist ($z_{in} = z_{out} = f$=12.57mm) for an ellipsoidal mirror of projected aperture *a* = 1.5×W. (a) shows a cut in the plane of asymmetry, (b) in the plane of symmetry. λ = 1mm and W_{in} = 2mm in both cases. The beams were calculated using ASAP, GLAD and GRASP.

In some test cases the Gaussian input beam was replaced with a scalar horn aperture field. Both ASAP and GLAD can take an arbitrary complex field as input. Modelling the sharp cut-off in the horn field posed some particular problems for ASAP, however. Main beam predictions could be improved by using an alternative decomposition of the input field into a single fan of Gaussian beams centred on the origin. A full Gabor representation of the field was not possible. ASAP was the only paraxial package to predicted differences due to the polarisation direction of the input field, though they were significantly smaller than those calculated by GRASP.

CONCLUSIONS

In conclusion, it is clear that none of the commercially available software investigated is ideally suited to model submillimetre optical systems. Under certain conditions discussed they do give good results but it is important to bear their limitations in mind particularly when interested in sidelobe structure. All our results have been compared with those of GRASP, which we take to be correct, and our test cases have been restricted to those that can be easily modelled by it. We have tested some GRASP predictions against both Method-of Moments calculations and experimental results at microwave frequencies, and found good agreement. Future work will look at an experimental verification of some GRASP results.

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REFERENCES

1. Born, M., and Wolf, E., Principles of Optics, Cambridge University Press, 1999.
2. Lawrence, G., "Optical system analysis with Physical Optics codes", SPIE no 766-18, O-E/Lase, 1987.
3. Goldsmith, P. F., Quasioptical Systems: Gaussian Beam Quasioptical Propagation and Applications, IEEE Press, 1998.
4. Einziger, P. D., Raz, S., and Shapira, M., J. Opt. Soc. Am. A, 3, 508-522 (1986).
5. Murphy, J. A., and Withington, S., Infrared physics & Technology, 37, 205-219, (1996).
6. de Graauw, Th., and Helmich, F.P., "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, 45-51, (2001)