Comparison of GAP, GRASP and REFLECT Simulations with Measurements of the BEMRAK Quasioptics

Aleksandar Đurić, Thomas Lüthi and Vladimir Vasić

Institute of Applied Physics   Dept. of Microwave Physics

Sidlerstr. 5   Tel.   : +41 31 631 89 11
CH-3012 Bern   Fax   : +41 31 631 37 65
Switzerland   E-mail : iapemail@iap.unibe.ch

Abstract

Quasipotical methods using the fundamental Gaussian mode provide important analytical tools for the design of optical systems at millimeter- and sub-millimeter wavelenghts. Due to the neglect of higher-order modes that arrise from diffraction effects and the reflection from curved mirrors, no accurate modelling of field distribution can be made. Therefore, when higher accuracy is required, physical optics and other methods together with numerical computations must be used.

The General Antenna Programm (GAP), applying a combined method using both geometrical (GO) and physical optics (PO) for field calculation, has been used at IAP for antenna analysis for several years. At the end of the year 2002 another comprehensive antenna tool, the General Reflector Antenna and Antenna Farm Analysis Program Package (GRASP) has been acquired. It performs simulations in the GO-mode as well as in the PO-mode and is intended for accurate field pattern calculations of antennas and quasioptical systems. For comparing the different software packages with each other and with measurements, a simple offset mirror configuration was used as test bed.

All simulations and measurements were performed for BEMRAK (Bernese Multibeam Radiometer for KOSMA), a 210 GHz multibeam receiver for the observation of solar bursts. Its quasioptics consists of three horns, a wire grid and an elliptic mirror. The first near-field simulations in the focal plane of the KOSMA 3m-telescope with GAP gave unexpected results. Therefore, field calculations were repeated by the MAAS (Microwave and Antenna Systems company) using their REFLECT software and with GRASP. In this report we compare the results of the above mentioned simulations with near-field measurements.

The results have shown that GAP and REFLECT as well as GRASP (with spherical wave expansion of the feed field) simulations for two of the three BEMRAK beams are in a very good agreement. However, GAP results for one beam show a significant difference in the position and beam shape. A cause for this might be the GO-method, as the simulations with GRASP, using the GO-method, showed almost identical deviation in the position of this beam.

GRASP and REFLECT simulations for all 3 beams are in a very good agreement with the measurements up to the -20 dB level, and with small deviations a good agreement up to the -30 dB level was found.

Contents

1 Introduction

Although in the past many mm- and sub-mm quasioptical systems have been developed, it is still debated which method is suited best for the design of these systems. Analytical methods, based on the propagation of the fundamental Gaussian mode [1], are used for calculations of the Gaussian field distribution. Due to the neglect of higher-order modes that arrise from diffraction effects and the reflection from curved mirrors, no accurate modelling of field distribution can be made. Hence, numerical simulations are often the only tool for an accurate design of a quasioptical system. Methods with high accuracy, such as physical optics (PO), require much processing time so that simulations of complex systems may last unacceptably long. On the other hand, fast calculation methods as geometrical optics (GO), are not accurate enough for many applications. Both physical and geometrical optics methods belong to the same group of methods for electromagnetic field calculations - the Approximate Source Field methods - but their results, as it will be shown in the following, differ significantly. Several widely used commercial software packages are based on them.

GAP, a trademark of COMSAT Laboratories, uses a hybrid of geometrical and physical optics methods for the field calculation [4, 5]. GAP represents the feed field by bundles of rays, originating in the phase center of the feed. The rays propagate to the reflector, where GAP offers two options for the calculation of the reflected field: an Aperture-method and a Current-method. Of these two methods only the latter is convenient for near-field calculations, as the former does not calculate field elements on the reflector surface, but rather in the aperture. The Current-method is also generally considered as more accurate [5].

GRASP, a software package made by TICRA[1], in contrary uses either geometrical or physical optics for the calculation of the reflected field. The PO-method calculates currents induced on the reflector surface by the feed field, assuming that the surface current on a curved reflector is the same as the surface current on an infinite planar surface which is tangent to the reflector surface at this point [7]. The reflected field is obtained by integrating the elementary fields originating from these current elements (using retarded vector potentials) [7]. This method is therefore qualified for both near- and far-field calculations.

In order to drastically reduce computation time for multireflector systems, both PO- and GO-method can be applied to the same system. The GO-method starts the calculation by defining significant rays for the required angular range, and then determines reflection and diffraction points for all these rays. For every field point of interest the direct, reflected and diffracted rays are summed up in resepect to their phases in order to obtain the total field at that point. The largest disadvantage
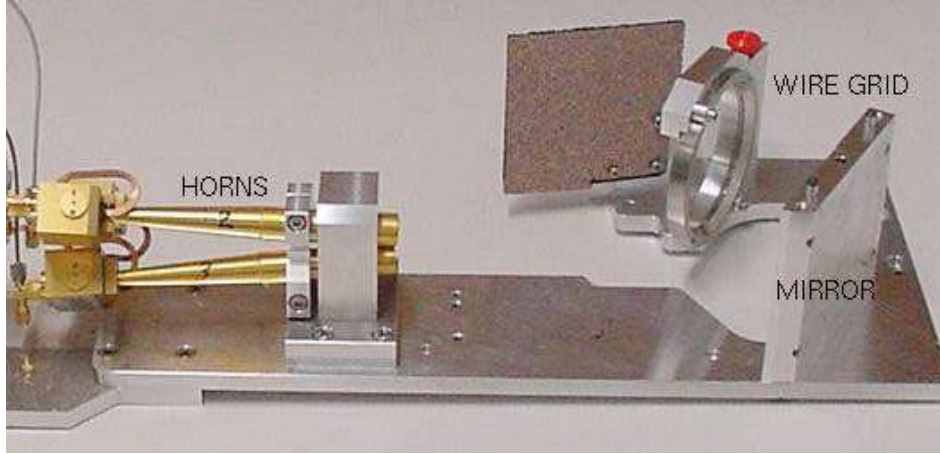
---

[1]www.ticra.com

Figure 1: BEMRAK quasioptics: Horns with mixers are shown on the left side. The elliptic mirror focuses the horn beams in the focal plane of the telescope. The wire grid splits the received signal between BEMRAK and the KOSMA receivers.

of GO is that it cannot accurately predict the field at points near caustic surfaces[2] [7]. This is particulary true for focusing surfaces in the areas near foci. On the other hand GO is considered accurate for wide-angle field calculations [7].

REFLECT calculations are based on the physical optics method. They were performed for BEMRAK by Dr. P. Foster, the results being summarized in [2].

The quasioptics of BEMRAK offered us the first comparison case for GAP and GRASP near-field simulations with measurements. The simulations using RE-FLECT provided an additional benchmark.

2   BEMRAK Quasioptics

BEMRAK is a 210 GHz multibeam receiver for the observation of solar bursts and is installed in the 3 m KOSMA telescope on Gornergrat. BEMRAK consists of three radiometer channels, with a fourth beam synthesised from the other three. The four intersecting beams allow measurements of source locations with arcsecond resolution and, for the first time, also the determination of the source size [8, 9]. Its quasioptics consists of three feedhorns, a focusing elliptic mirror and a wire grid, for splitting the incoming signal between the BEMRAK and KOSMA receivers, thus allowing simultaneous observations (Figure 1) [8, 9]. The horns

---

[2]Caustic surfaces are those surfaces where in all points the field radiated from one point in the system (e.g. focus) has the same phase. In a system with a parabolic reflector, all the points on the main ray belong to a caustic.
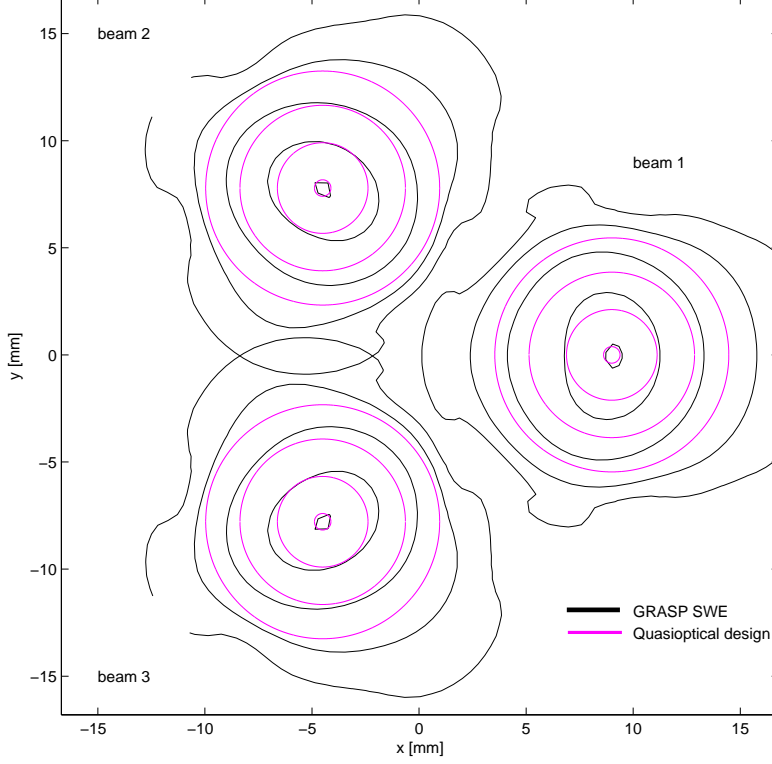
Figure 2: Field distribution of the BEMRAK beams in the focal plane of the telescope, calculated with quasioptical principles (magenta) and the results compared with the simulations with GRASP-PO/SWE (black). The contours show the -0.1, -3, -10 and -20 dB levels.

are linearly polarized, the E-vectors being inclined $45°$ relative to the horizontal plane. The intended antenna pattern directions (beams intersecting at half-power levels) require the beams at the focal plane of the telescope to be nearly parallel with their axes pointing to the corners of an equilateral triangle [5]. Modelling of beam propagation by ray tracing lead to the positions and the skew angles of the feedhorns summarized in Table 1 (see Appendix). As the beam waist radii in the focal plane of the telescope, the focal length of the elliptical mirror, waist radii and position of the feedhorns etc. depend on each other, an iterative approach was used to determine a suitable set of these parameters.

The expected field distribution in the focal plane, calculated with quasioptical principles, should lead to an intersection of beams 1-3 at the -3 dB level in the far-
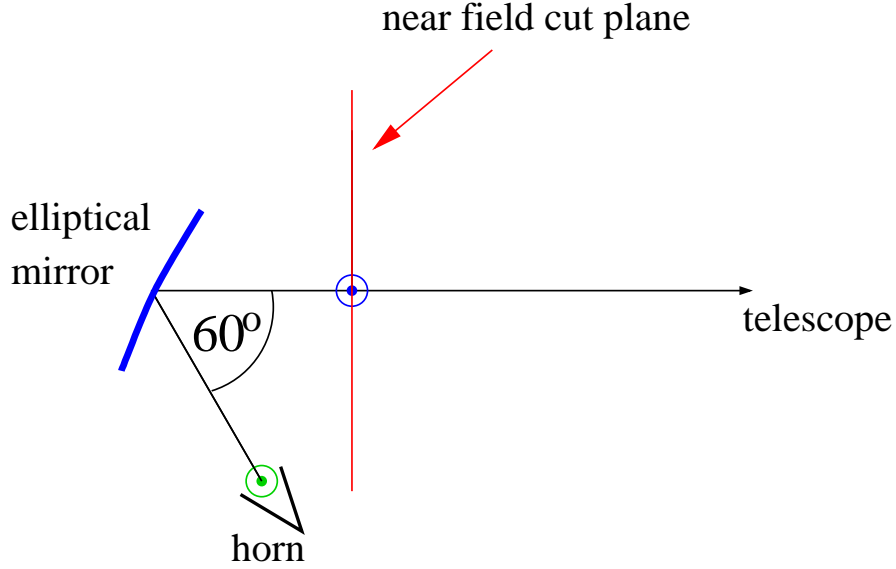
Figure 3: Geometry of the simulated BEMRAK quasioptics. A horn close to the quasioptical focus of the elliptic mirror (see Appendix) illuminates the mirror surface. The resulting distribution of the near field is calculated in the focal plane of the telescope. This calculation is repeated for all three horns.

field of the telescope. The centers of the three beams (Fig. 2) also form an equilateral triangle. The detailed specifications of BEMRAK quasioptics are given in the Appendix and in [6, 9].

3 GAP and REFLECT simulations

The simulated BEMRAK quasioptics consists of the three feedhorns and the elliptic mirror, the grid being omitted (Figure 3). For simplicity only one horn is shown. First simulations of the three BEMRAK beams were made with the GAP software. As the feed-field we used the modelled field pattern of the horn made by Thomas Keating Ltd. (see Appendix, Fig. 8).

Although the elliptical mirror is used in an offset configuration, significant differences between the three beams are not expected as the centers of the beams in the focal plane form a small equilateral triangle around the central ray of the cluster. Minor differences of beam 2 and 3 in respect to beam 1 are expected, as the elliptical mirror exhibits different curvature radii of the reflection area.

The near-field distributions obtained with GAP and REFLECT are shown in Fig-

ure 4. For beams 2 and 3 the power patterns calculated by GAP and REFLECT are in very good agreement, down to the -20 dB level. For beam 1 however, there are significant differences between the beam-center positions (~ 0.6 w_{out}, w_{out} being the waist radius, see Appendix) and the beam shapes [6]. On the other hand, by comparing the quasioptical (Fig. 2) with the REFLECT results (Fig. 4) one finds an acceptable agreement. Based on this the quasioptics was built and the actual focal plane patterns measured in amplitude and phase with our vector network-analyzer from AB-Millimetre.

The measured beams are found to agree very well with all three beams simulated with REFLECT (Fig. 7) and the GAP-simulated beams 2 and 3 (Fig. 5). A possible explanation for the shifted beam center location and the strong asymmetry of beam 1 in the GAP simulation is given in the Section 4.1.
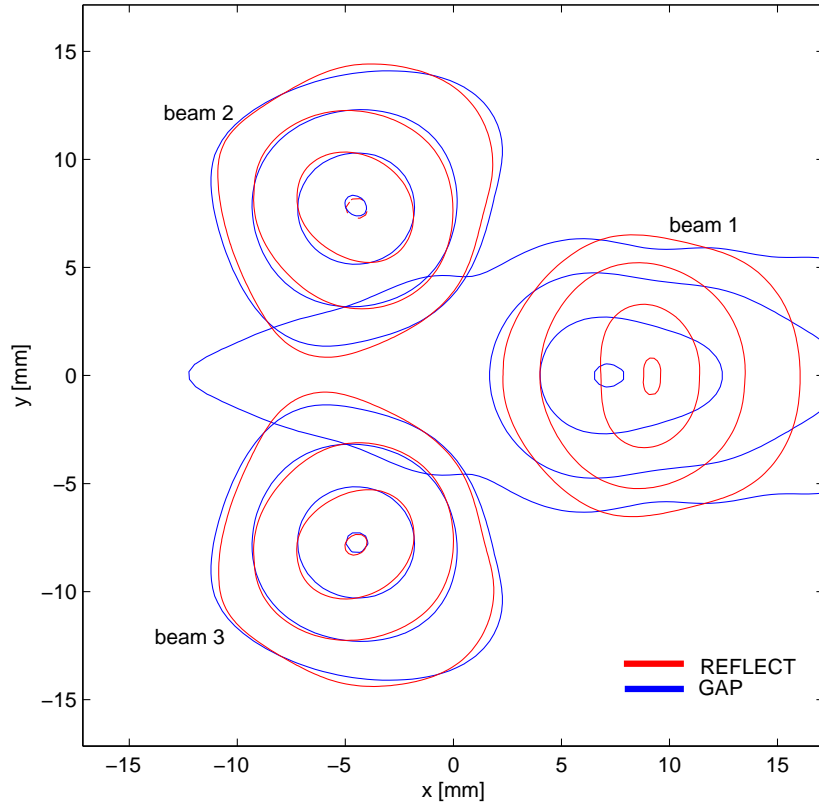

Figure 4: GAP (blue) and REFLECT (red) simulations of the near field in the focal plane of the telescope. While beams 2 and 3 are in a very good agreement, the center of GAP beam 1 is dislocated by ~ 0.6 w_{out} and also exhibits a strong asymmetry in the x-direction. The contour levels are -0.1, -3, -10 and -20 dB.

10

4 GRASP simulations

4.1 Simulations with the geometrical optics method

In order to investigate the poor results of GAP for beam 1, we performed a GO-simulation with GRASP. This method is common for both programs, at least for the determination of reflection points on the reflector surface. As GAP uses a combination of the PO- and GO-method, differences are expected (Figure 5). The positions of the beam centers differ less than $0.15w_{out}$ (beams 2 and 3), whereas beam 1 is shifted by $\sim 0.6w_{out}$ respective the REFLECT result (denoted by a haircross in the Figure 5). Also the asymmetry of beam 1 is emphasized along the same dimension as in the GAP simulations, which also might be due to the GO-method.
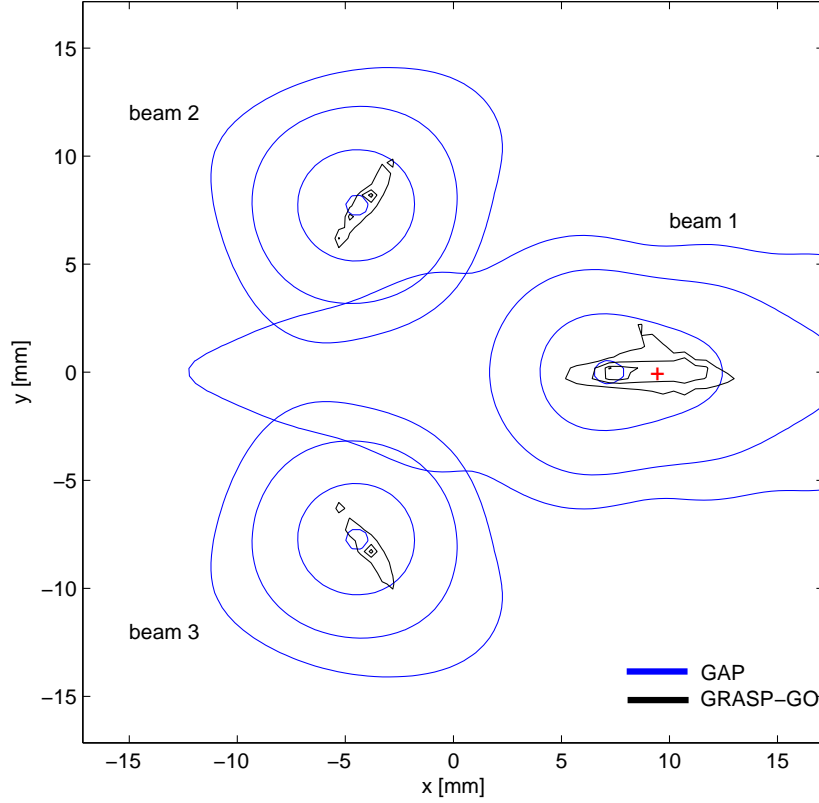

Figure 5: GAP (blue) and GRASP-GO (black) simulations. The contour levels are at -0.1, -3, -10 and -20 dB levels. GRASP contours are unusable due to the pure GO-method. A red haircross in the beam 1 denotes the position of the beam 1 maximum calculated by REFLECT.
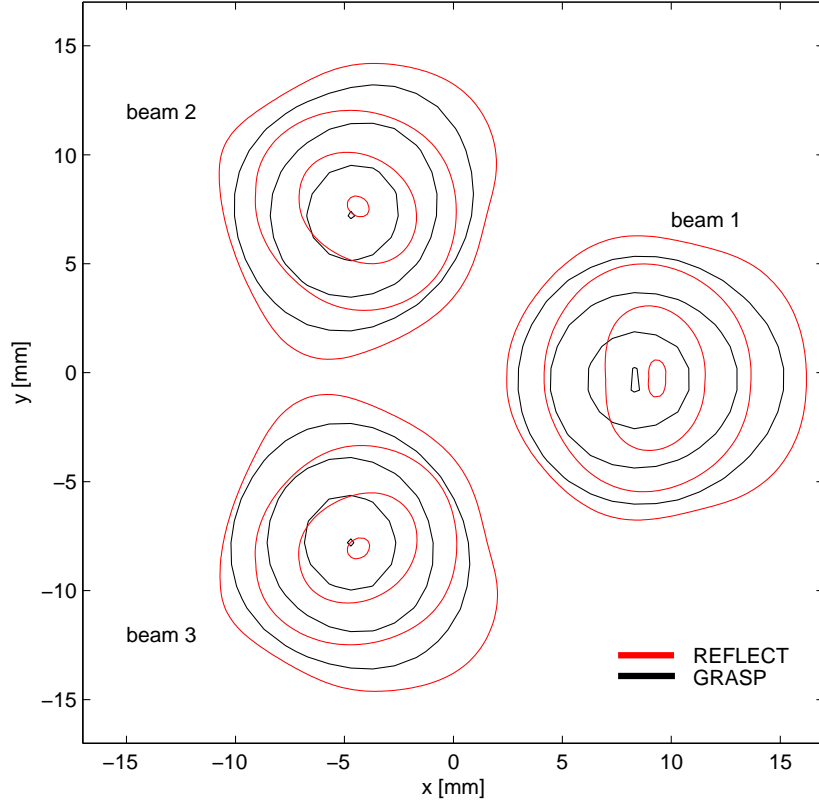
11

Figure 6: GRASP/SWE simulations with Gaussian beam feed compared to the focal plane power patterns obtained with REFLECT. Due to the idealized feed model in GRASP, the contour shapes and their centers differ from those modelled by REFLECT. The contour levels are -0.1, -3, -10 and -20 dB.

As expected, GRASP with the GO-method gives wrong results for the beam shape (Figure 5). Therefore, they can not be considered for the design. We conclude that the pure GO-method of GRASP cannot be used for the calculation of the near-field beam contours, and that GAP provides erroneous beam positons and distorted beam shapes. The very good agreement between GAP and REFLECT results for the beams 2 and 3 implies that the GAP combined PO- and GO-method offers significant advantages over the pure GO-method for near-field simulations.
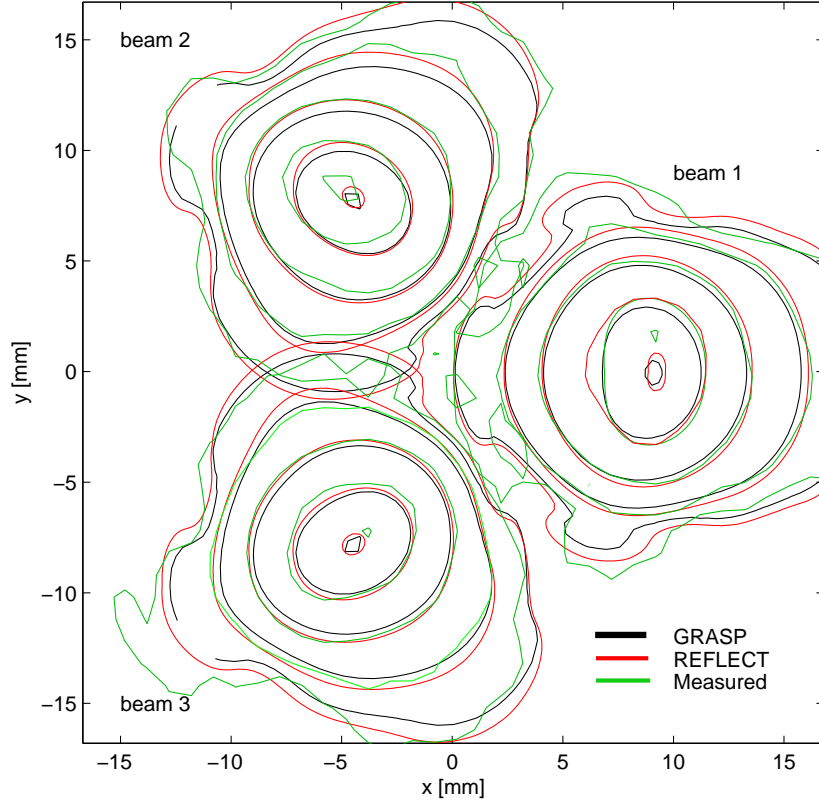
Figure 7: GRASP simulations with modelled horn field compared to the RE-FLECT results and the measured focal plane power patterns. The contour levels are -0.1, -3, -10, -20 and -30 dB.

4.2 Simulations with the physical optics method

Gaussian beam feed. For the sake of simplicity, the first GRASP-simulations for BEMRAK assumed a Gaussian beam as the feed-field (Appendix, Fig. 8). The resulting focal plane patterns are shown in Figure 6. The beam center locations, exhibiting a mean offset of $\sim 0.15 \mathrm{w_{out}}$, are in an acceptable agreement with the ones calculated with REFLECT. However, the differences of the beam shapes are still significant, so that these GRASP results are considered as not satisfactory, in the view of the very good agreement of REFLECT simulations (and GAP for beams 2 and 3) with the measurements.

Simulations with the horn model and SWE. Therefore, further simulations were made using the spherical wave expansion (SWE) add-on to GRASP as it allows a precise characterisation of the feed-horn radiation pattern over the full solid

13

angle [7]. The spherical wave expansion has been done by taking 355 sphere samples in the theta-plane and 4 in the phi-plane[3] [3, 7]. Figure 7 shows a comparison between GRASP and REFLECT results and the measured field patterns, in the focal plane of the telescope, down to the -30 dB level.

Here, we must note that the GRASP beam center positions exhibit an estimated offset of less than $0.08\mathrm{w_{out}}$ in respect to the REFLECT beams. The measured beams were all offset by the amount of $\sim 0.34\mathrm{w_{out}}$ (x-direction) and $\sim 0.22\mathrm{w_{out}}$ (y-direction) in respect to the REFLECT calculations. This is most likely due to the measurement setup, where we do not have a clear reference for the position. Hence, the plots are shown with all beams shifted simultaneously for the maximum coincidence. The measurements and PO-simulations exhibit a good agreement down to the -30 dB level, considering also that the simulations and the measurements were performed on different integration grids. Evidenced by the GRASP simulations with a Gaussian feed, it can be seen how important the accurate feed field distribution is.

5   Conclusions

We compared near-field simulations performed with several antenna design tools with measurements in order to validate the design of the BEMRAK quasioptics. The results of the design using ray-tracing and fundamental Gaussian mode are not suitable as simulated beam shapes deviate strongly from the GRASP results and measurements (Figures 2 and 7). The simulations using physical optics show a significant advantage over those made with geometrical optics. Measurements and PO-simulations exhibit a very good agreement at least down to the -20 dB level, and with small deviations a good agreement down to the -30 dB level.

GRASP simulations using a fundamental Gaussian mode as feed-field show significant differences in the contour shape and positions, due to the idealized feed. Thus, for accurate predictions of the near field the exact radiation patterns of the feed horn must be used in the PO-calculations. This was successfully done with the spherical wave expansion (SWE) add-on to GRASP.

Acknowledgements

---

[3]We do not know how the feed field was sampled for the REFLECT simulations.

Appendix: Specifications of the quasioptics

The feedhorns aperture radius and length are 7.0 mm and 140 mm, respectively. They produce a feed pattern with a half-power beamwidth of $7.6°$, which corresponds to a beam waist radius of $w_{horn} = 4.03$ mm (Fig. 8). They are tilted to the central ray of the cluster, as shown in the Table 1. A more detailed description is given in [6, 9].
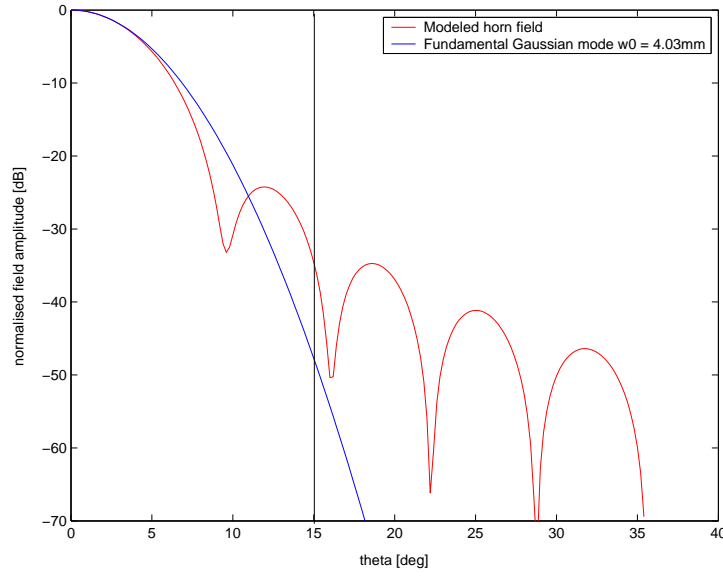

Figure 8: Modelled horn field pattern in E-plane (red) and fundamental Gaussian mode (blue) corresponding to the feedhorn waist radius of 4.03 mm. The mirror subtends the angular region (in average) left from the black line at $15°$. Hence a Gaussian beam represents a significant idealization.

Feedhorn	Horizontal [°]	Vertical [°]
1	4.8	0.0
2	-2.6	4.2
3	-2.6	-4.2

Table 1: Feedhorn skew angles in respect to the central cluster ray.

The main parameters of the BEMRAK quasioptics are as follows:

- Frequency: $f = 210$ GHz
- Half axes of ellipsoid: $a_e = 213.34$ mm and $b_e = 184.40$ mm
- Focal length: 106.25 mm
- Focal distances: $R_{telescope} = 200.30$ mm and $R_{horn} = 226.64$ mm
- Beam reflection angle: $60°/2 = 30°$
- Projected mirror radius: $r_{mirror} = 50$ mm
- Input/Output waist distances: $d_{telescope} = 196.00$ mm and $d_{horn} = 220.81$ mm
- Input/Output waist radii: $w_{out} = 3.57$ mm and $w_{horn} = 4.03$ mm
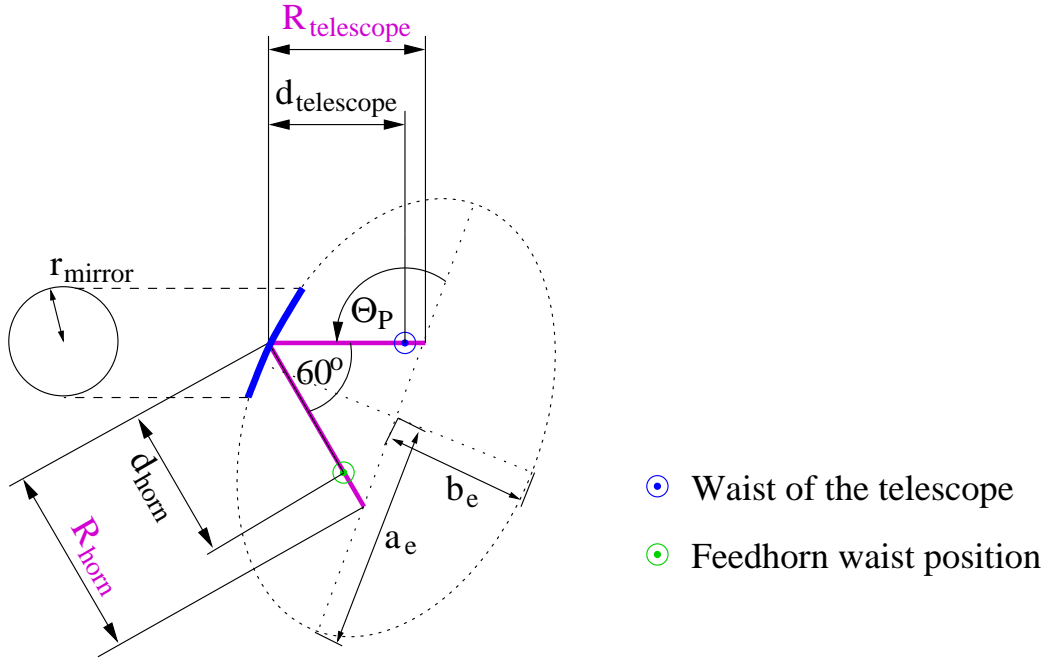

Figure 9: Geometrical arrangement of the quasioptical components of BEMRAK. The chief ray reflected from the elliptical mirror makes an $\theta_P = 113.8°$ angle with the larger half-axis of the ellipsoid. The waist of the telescope (blue circle) coincides with the quasioptical focus of the elliptic mirror. The feedhorn waist position (green circle) coincides with the other quasioptical focus of the mirror.

References

[1] P. F. Goldsmith
'Quasioptical Systems'
Institute of Electrical and Electronical Engineers, Inc. , New York, 1998

[2] MAAS Company
'Nearfield for KOSMA feeds'
MAAS Report 492, Issue No 1, September 2002

[3] J. E. Hansen
'Spherical Near-field Antenna Measurements'
Peter Peregrinus Ltd, London, UK, 1988

[4] 'General Antenna Program Version 3.2 - User's Guide'
Comsat Laboratories, 1998

[5] A. Lüdi, 'Solares Submillimeterteleskop: Berechnungen und theoretische
Betrachtungen zur Antenne', Master Thesis, University of Bern, 1998,
http://www.iapmw.unibe.ch/publications/pdffiles/138.pdf

[6] T. Lüthi, A. Lüdi, A. Murk, A. Đurić and A. Magun
'The Bernese Multibeam Radiometer for KOSMA (BEMRAK) - Instrument
design and First Antenna Measurements', IAP Research Report No. 2003-
18, http://www.iapmw.unibe.ch/publications/pdffiles/543.pdf

[7] Editor: K. Pontoppidan
'Technical Description of GRASP8'
TICRA Engineering Consultants, Copenhagen, Denmark, 2002

[8] T. Lüthi, A. Murk, A. Magun, A. Lüdi, V. Vasić
'A Multibeam Instrument for Solar Flare Observations at Millimete Wave-
lengths - Quasioptical Design and First Antenna Pattern Measurements'
The 28th International Conference on Infrared and Millimeter Waves, pp.:
219-220, Otsu, Japan, 2003

[9] T. Lüthi, A. Lüdi, and A. Magun
'Determination of the location and angular size of solar flares with a
210 GHz multibeam radiometer'
submitted to Astronomy and Astrophysics, 2003