Final Design and Testing of the 94 GHz Quasi-Optical-Feed for the EarthCARE'S Cloud Profiling Radar

J. Hartmann[#], Chr. Hartwanger[#], R. Wylde[+], C. Cappellin*, H. Horie[x]

[#] *Astrium GmbH - Satellites, ASP81 - Measurement Technology, 81663 Munich, Germany*
Juergen.Hartmann@Astrium.EADS.net

[+] *Thomas Keating Ltd., Billingshurst, West Sussex, RH14 9SH, UK*
r.wylde@terahertz.co.uk

**TICRA, Læderstræde 34, 1201 Copenhagen, Denmark*
cc@ticra.com

[x] *NICT, Koganei-shi, Tokyo 184-8795, Japan*
horie@nict.go.jp

Abstract— **Instruments for Earth observation working from W-Band up to mm-wave frequencies mainly use quasi-optical feed systems (QOF) to illuminate the corresponding reflector antennas. The final design of the QOF for the Cloud Profiling Radar System (CPR) for the EarthCARE satellite is presented. Such QOF achieves polarization and frequency tuning, as well as separation of transmit and receive channels. The initial design of the QOF was made by MAAS and Thomas Keating (TK) as subcontractor of Astrium GmbH. The final contractor of QOF at JAXA and ESA/ESTEC is NICT in Japan.**

The final design verification was performed by Astrium with QUAST, a new add-on to the GRASP software, especially developed by TICRA for a fast and accurate set-up and analysis of quasi-optical networks.

Within the paper, the modeling of the QOF will be explained in detail and a description of QUAST will be given. Finally, a validation with measurement performed at the National Physical Laboratory (NPL) in UK will be provided.

Keywords— **Millimetre Wave Instruments, Quasi-Optical Systems**

I. INTRODUCTION

The Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) is the sixth Earth Explorer mission of ESA's Living Planet Program. The mission is developed in co-operation with JAXA, the Japanese Aerospace Exploration Agency, and Astrium GmbH, who is responsible for the satellite design, development and integration. The purpose of the mission is the understanding of the interactions between clouds and radiative and aerosol processes in order to provide more reliable climate predictions and better weather forecasts.

A central instrument of the EarthCARE satellite is the Cloud Profiling Radar (CPR), a 500 m range Doppler radar working at 94.05 GHz. The front end consists of a parabolic reflector of 2.5 m diameter, fed by a Quasi-Optical Feed (QOF) with integrated hyperbolic sub-reflector.

The QOF converts the linear polarized Tx and Rx waveguide signals into circular polarized transmit and receive beams, providing high isolation of the Tx and Rx channels, across the system bandwidth of 7 MHz. In particular, the QOF consists of planar mirrors, refocusing mirrors, a polarization grid and a Martin-Puplett interferometer. The design of the QOF is optimized in order to use the minimum number of components with minimized size, for quasi-optical good undistorted transmission.

In this paper, the final design and testing of the QOF will be described. The QOF will be modeled by QUAST, an add-on to the GRASP software especially developed for a fast and accurate set-up and analysis of beam waveguides and quasi-optical networks. The program is able to model plane and conic mirrors, beam splitters, lenses and interferometers in addition to one or several feeds. A Gaussian beam analysis assists the designer in placing the components properly and selecting the geometrical properties. The interaction between the components and their radiation are conveniently described by the so-called chain command, a single GRASP command where all the components and their order in the quasi-optical network are taken into account. Besides physical optics, QUAST includes the possibility of a Gauss Laguerre expansion, for an even faster computation of beam shape and cross-polarization. Finally, a plane wave expansion of the field incident on a beam splitter and/or interferometer makes the computation exceptionally accurate.

In the paper the final design of the CPR QOF will be described in detail and the advantages of using QUAST will be underlined, with respect to design and computation time, available algorithms and obtained accuracy. Results will finally be validated by measurements performed at the National Physical Laboratory (NPL) in Teddington (UK).

II. DESCRIPTION OF QOF

The functionality of the QOF for the Cloud Profiling Radar System (CPR) of the EarthCARE weather radar is already described in [1]. As shown in a side view of the hardware (see Figure 1) the transmitter part of the QOF consists of a transmit feed (FH-Tx) which is a corrugated horn, a switch mirror unit (SMU-Tx) with a plane mirror, an elliptical mirror (MD1-Tx) and the interferometer FSP1 and FSP2 in order to create a circular polarized beam transferred to the subreflector SR. The interferometer is an Inatani type polarizer consisting out of two plane mirrors with a grid in front [2]. The convex offset hyperbolic shaped subreflector is one part of the whole antenna system belonging to the offset parabolic shaped main reflector (not shown in the picture) with 2.5 m in diameter and resulting in a cross-polar compensated Cassegrain antenna system.

The transmit and receive beams of the 94 GHz radar system are divided by a polarization grid (GRID) so that the receive beam will be forwarded by the elliptical mirror (MD1-Rx) and switching mirror unit (SMU-Rx) to the receive feed (FH-Rx). Both switching mirror units are foreseen to switch between redundant transmit and receive systems which are located symmetrically on each side of the QOF.

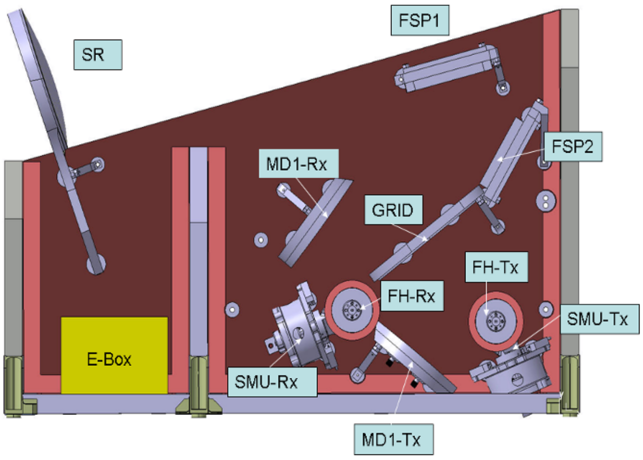


Figure 1 - Side View of EarthCARE CPR QOF

III. SIMULATION OF QOF

For simulation of the QOF the QUAST add-on of TICRA's GRASP9 software is applied. A detailed description of QUAST is given in Section IV. Within QUAST, all components of the QOF from the corrugated horn to the subreflector are modeled. Within this paper, only the transmit part will be described.

The modeling of the components is performed as described in the following:

a) Corrugated Horn (FH-Tx):
   The feed horn is a radial corrugated horn with about 200 corrugations, WR-10 standard waveguide input interface and a 23.5 mm aperture. The performance of the horn is computed with well proven standard in-house software based on mode matching and method of moments. The feed is incorporated in the QUAST model via spherical wave expansion coefficients.

b) Flip Mirror (SMU-Tx):
   The flip mirror is a plane mirror with 90 mm x 70 mm elliptical rim.

c) Elliptical Mirror (MD1-Tx):
   The mirror consists of a 116 mm in diameter elliptical shaped mirror.

d) Polarization Grid (GRID):
   The polarization grid contains of a frame and associated gold plated tungsten wires in 45 deg. orientations in order to separate the Tx and Rx beam.

e) Interferometer (FSP1, FSP2):
   The interferometer is an Inatani variant of a Martin-Puplett interferometer [2]. It transforms a linearly polarized input beam into a circularly polarized beam, by applying a Pi/2 phase change to half of the incident beam, with respect to the orthogonally polarized other half. The exact distance between the grids and the back mirrors is based not only on the nominal geometry to give the Pi/2 change, but includes an offset to reflect phase changes suffered by both reflected and transmitted beams as they interact with the grids. Each of the mirrors of the interferometer is modeled in QUAST by a planar mirror with two electrical properties. One property it the perfect conducting plane, the other one is the wire grid with its specific displacement to the plane, the diameter of the wire and the spacing. The Inatani variant of a Martin-Puplett Interferometer with input and output beam is shown in Figure 2.

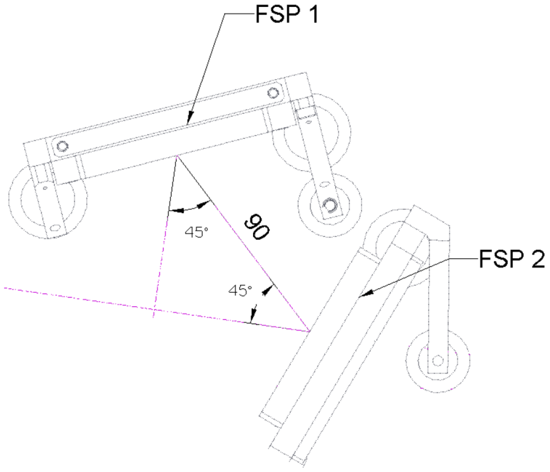
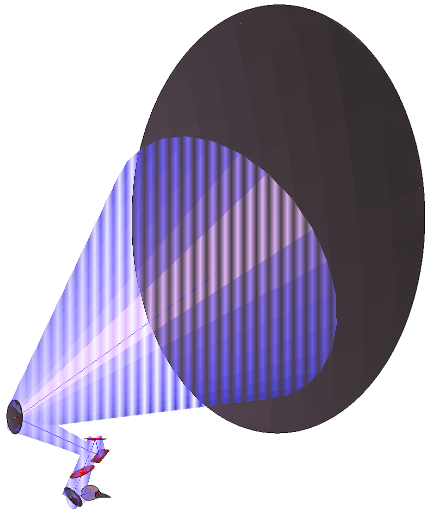


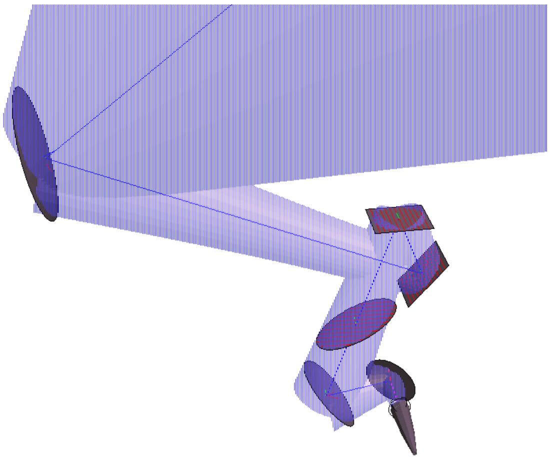
Figure 2 - Inatani Variant of Martin-Puplett Interferometer

f) Subreflector (SR):
   The subreflector is an offset hyperbolic convex shaped surface. The diameter of the subreflector is 140 mm and the rim is equipped with an additional rolled edge design in order to minimize diffraction effects.

The QOF and the feed horn are designed so that the edge of the beam is at a signal level of - 30 dB on each related component. This minimizes the interference of scattering effects and ensures enough performance margin w.r.t. scattering effects within the QOF as well as at subreflector rim. A plot of the Gaussian beams within the QOF from the corrugated horn up to the subreflector is shown in Figure 3.



(a) QOF with Main Reflector



(b) QOF (zoomed)

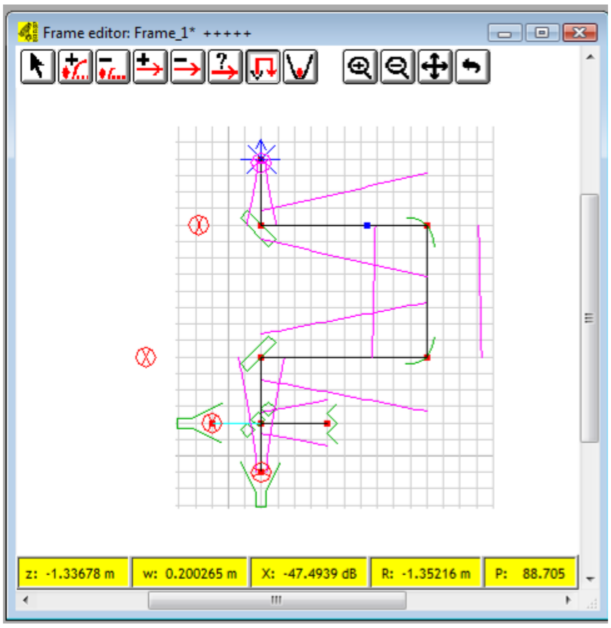
Figure 3 - Plot of QOF Simulation with Gaussian Beams Visualized; (a) QOF with Main Reflector, (b) QOF (zoomed)

IV. DESCRIPTION OF QUAST

QUAST is a new add-on module for GRASP9, especially intended for the analysis and design of quasi-optical networks and beam waveguides.

At the basis of the QUAST add-on is the concept of frame, i.e. a two dimensional grid that allows simple mouse operations and acts as a wizard. The frame provides the facility for setting up all the components of a beam waveguide, such as plane and conic mirrors, beam splitters, lenses, interferometers and feeds. Several frames can be created and connected if the beam waveguide is not confined to a single plane. Since the design principle of such systems is very often based on Gaussian beam tracing rather than pure geometrical ray considerations, the frame also includes a Gaussian beam analysis feature that assists the designer in placing the components properly and defining their geometrical properties.

An example of a frame is given in Figure 4. It is possible to distinguish two feeds, a beam splitter, two plane mirrors, two conic mirrors, a load and a far-field grid. The feeds work at two different frequencies. The -20 dB level hyperbolas of the Gaussian beam launched by one of the feeds and propagating along the beam waveguide are shown in pink. In the yellow bar it is possible to read the beam parameters at any position along the beam waveguide, such as beam radius *w*, radius of curvature *R* of the phase front, cross-polar component *X* and phase slippage *P*, see Figure 4. The values shown in the figure refer to the point indicated by the blue marker. The beam waist radius as well as the *f*-values of the conic reflectors can be interactively modified in the frame, in order to move the output waist of the Gaussian beam at the desired position.



z: -1.33678 m

w: 0.200265 m

X: -47.4939 dB

R: -1.35216 m

P: 88.705

Figure 4 - Example of a QUAST Frame

Once an attractive design is obtained, the object wizard assists the designer in generating the objects for all the components as well as all the elements necessary for the analysis in GRASP9. In this process, the user will define the surface and the rim of the conic reflectors, the rim of the plane mirrors, and the electrical properties of the beam splitter. "Autosize" buttons allow to automatically sizing the component with respect to the level of the hyperbolas of the Gaussian beam launched by the feed. Once the objects are created, they appear in the GRASP Navigate Project window, see Figure 5. All objects can there be accessed and additional parameters can be inserted, i.e. tabulated rims, electrical properties, etc. At this point, the beam waveguide can be visualized within the GRASP software in an OpenGL plot, as shown in Figure 5.

The full analysis of the system is finally set-up through the command wizard of QUAST. The wizard, with a few inputs from the user, generates a so-called chain command, identifying the initial component and all the components that the beam encounters, in the right order. Referring to Figure 4, the beam path identified by QUAST will originate from the feed and propagate to the beam splitter, the first flat mirror, the two curved reflectors, the second flat mirror and finally the output far-field grid.

After the chain command is generated, it is possible to specify the analysis method necessary for each component. Physical Optics (PO), with an automatic determination of the number of PO current samples, is automatically chosen for most of components of the beam waveguide. The user has also the possibility of performing, instead of PO, a fast multi-mode Gaussian beam analysis, i.e. Gauss Laguerre, for preliminary investigations, where only the beam shape and the cross-polarization are calculated. As final option, the user can increase the accuracy of PO computations by performing a plane wave expansion of the field incident on the component of interest. This is highly recommended for beam splitters and interferometers, whose electrical properties are normally described by reflection and transmission coefficients for an incident plane wave.

A detailed description of QUAST is given in [3].

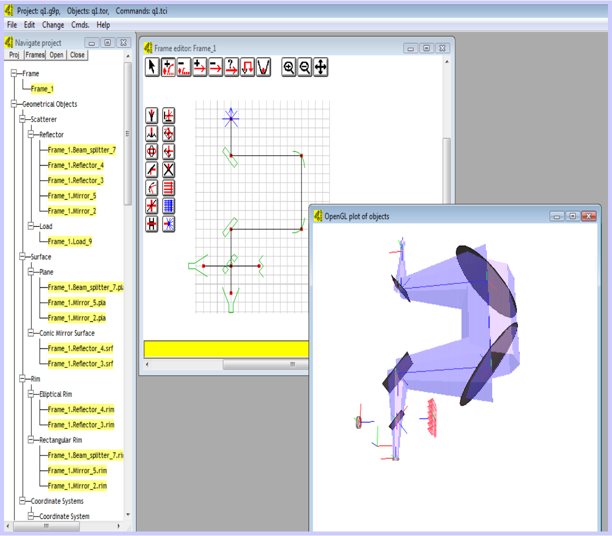


Figure 5 - An OpenGL Plot of the Frame in GRASP9

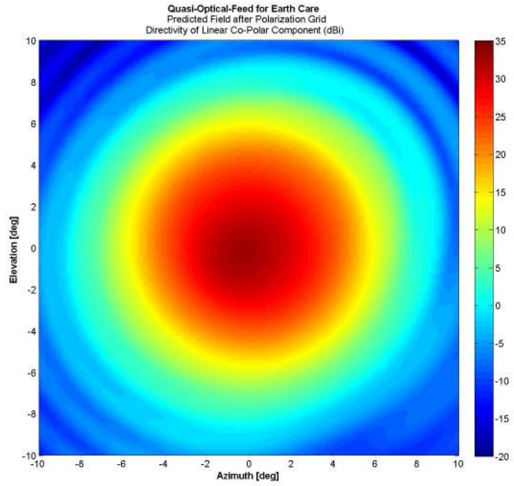
V. VERIFICATION OF SIMULATION MODEL

To test the accuracy of the QUAST model of the QOF, the field at each component was computed and its behavior verified. The verification comprised

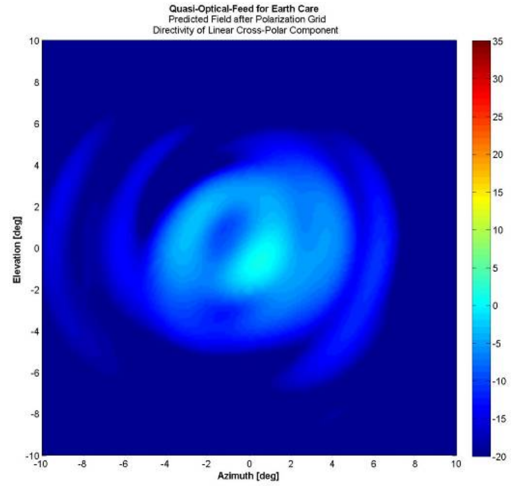
- Beam Pointing
- Edge Illumination and Taper
- Polarization

It was especially important to verify the polarization of the field coming from components containing grids or other polarization sensitive devices and materials.

Figure 6 shows exemplarily the electric field amplitude after the polarization grid..



(a) Co-Polar Field Amplitude

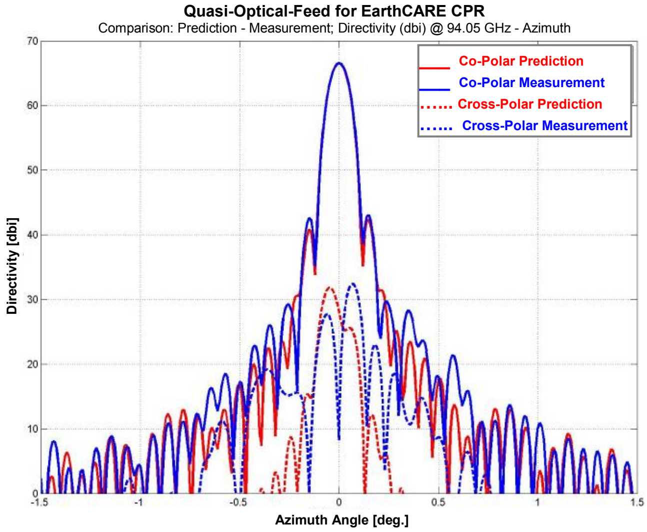


(a) Cross-Polar Field Amplitude

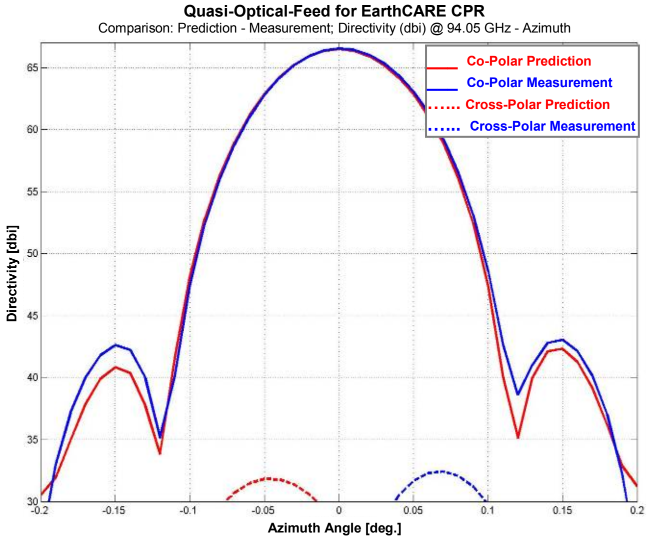
Figure 6 - Two dimensional Plot of E-Field Amplitude after Separation Grid for Verification of Beam Performance

VI. COMPARISON OF RESULTS

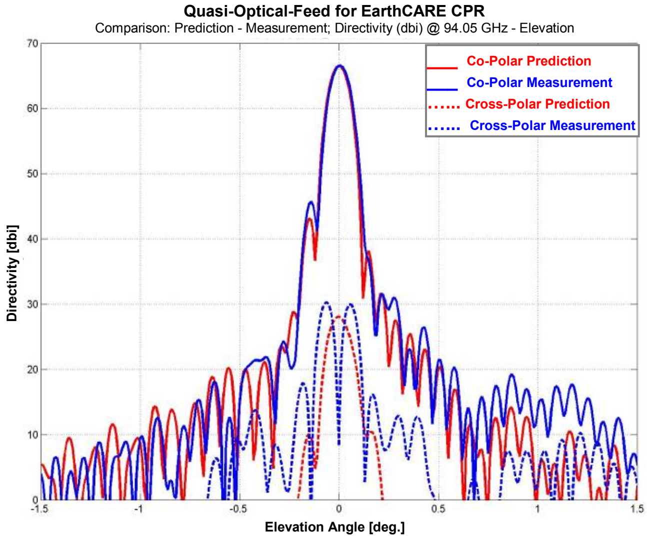
In the following, comparisons of the antenna pattern from calculations out of the QUAST tool and from measurements of the QOF at the NPL "Antenna Extrapolation Range" in Teddington, UK, will be shown. QUAST computation and measurements were performed for the QOF, i.e. at the QOF inherent subreflector. Via generation of swept coefficients, the generation of a secondary pattern via the main reflector can be calculated from both QOF pattern data. This was mainly done in order to verify system inherent parameter like gain, beam width, side lobe and cross-polar performance. Figure 7 shows the comparisons of the secondary pattern in azimuth and elevation for the EarthCARE CPR antenna system.



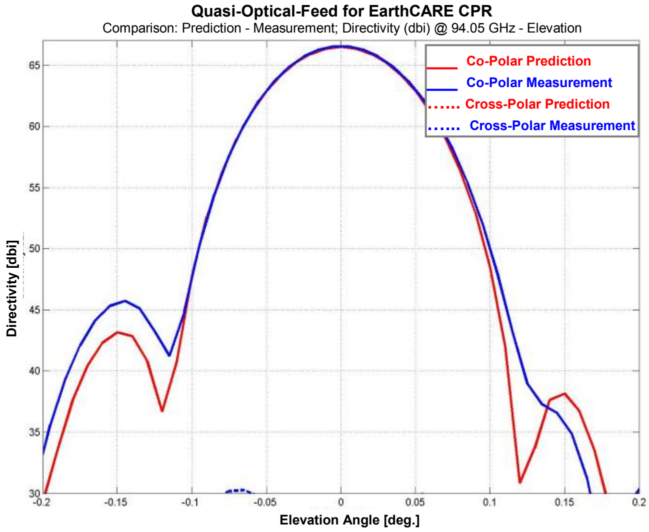
(a) Azimuth Pattern of CPR



(b) Azimuth Pattern of CPR (zoomed)



(c) Elevation Pattern of CPR



(d) Elevation Pattern of CPR (zoomed)

Figure 7 - Comparison of Azimuth (a, b) and Elevation (c, d) Pattern of CPR Antenna calculated via Main Reflector

It can be concluded that the pattern comparisons show a good agreement in azimuth and elevation. Main antenna parameters like beamwidth and gain exhibit also excellent conformity.

VII. CONCLUSIONS

For verification of the performance of the QOF of the EarthCARE satellites CPR system, a full modeling of the quasi-optical components from corrugated horn up to the subreflector of the Cassegrain antenna system was performed. For modeling and calculation of the antenna pattern, the new add-on QUAST to the GRASP9 software from TICRA was applied. The antenna pattern of the QOF was measured in the Antenna Extrapolation Range of NPL in UK. The comparisons of both results are given in this paper. It can be concluded that a good agreement could be achieved so that further analyses of the performance w.r.t. structural, thermal and other environmental effects can be analyzed via QUAST.

ACKNOWLEDGMENT

The authors would like to thank TICRA for providing the QUAST tool and related support to Astrium. Many thanks to Phil Miller from NPL for performing the QOF measurements, also to Soe Min Tun from S.M.T. Consultancies for performing CPR pattern predictions as well as Pat Foster from MAAS for support of this work. Thanks also to NICT in Japan which is responsible for the development of the QOF.

REFERENCES

[1] P. Foster, J. Hartmann, H. Horie, R. Wylde, *Performance Verification of the 94 GHz Quasi-Optical-Feed for EarthCARES's Cloud Profiling Radar*, 5th ESA Workshop on Millimetre Wave Technology, Noordwijk, The Netherlands, May 2009.

[2] J. Inatani, S. Ochiai, T. Manabe, M. Seta, R. Wylde, and D. H. Martin, “A New Configuration of the Martin-Puplett Interferometer with Low Reflection”, 7th International Conference on Terahertz Electronics, Nara, Japan, pages 260–263. IEEE, November 1999

[3] Technical description of the QUAST add-on to GRASP9, available from TICRA