Detailed Electrical Design of a Novel High Performance Compensated Compact Antenna Test Range

C. Cappellin [(1)], P. G. Nicolaci [(1)], S. B. Sørensen [(1)], W. H. Yatman [(1)], M. M. Bilgic [(1)], D. Trenta [(2)], L. Rolo [(2)]
[1] TICRA: Copenhagen, Denmark, cc@ticra.com
[2] ESA ESTEC: Noordwijk, The Netherlands, damiano.trenta@esa.int

***Abstract*—The detailed electrical design of a new compensated compact antenna test range (CATR) to be installed in the HERTZ 2.0 measurement facility at the European Space Agency (ESA) is described. The CATR meets the stringent requirement of an overall peak-to-peak amplitude ripple of 0.5 dB and phase ripple of 4 deg, from 1 GHz to 400 GHz. To design the system, a novel approach making use of an initial trade-off with ray tracing and a subsequent detailed full wave analysis and optimization of the serrations profile, length and orientation was used. In this paper we describe the choices taken during the design and show the detailed performances at L band.**

***Index Terms*—RF performances, RF predictions, RF measurements, Compact Antenna Test Range, Serrations**

I. Introduction

A Compact Antenna Test Range (CATR) is an antenna measurement system given by one or two reflectors illuminated by a feed, and generating an almost perfect plane wave, called quiet zone (QZ). The antenna under test (AUT) is placed in the quiet zone and its measured pattern is the result of the interaction between the AUT aperture field and the quiet zone field [1-2]. Under ideal conditions, the quiet zone field is a perfect plane wave with uniform amplitude and constant phase. In practice, the feed taper, the finite surface accuracy of the reflectors and the diffraction from their edges introduce ripples on the uniform distribution of the quiet zone field in amplitude and phase.

Compact Antenna Test Ranges allow the measurement of the far-field pattern of an antenna under test (AUT) in an in-door and controlled environment. Moreover, CATR measurements do not need probe correction, near-to-far-field transformation, and accurate mechanical alignment, and thus perform a pattern measurement in significantly shorter time relative to near-field measurements. Due to these numerous advantages, and in spite of the measurement inaccuracies given by the non-perfect quite zone, CATRs are the most widely used facilities for payload and antenna measurements [3].

In the early 90's the first very large compensated CATR for payload measurements (CPTR) was designed by TICRA and installed at the European Space Agency in Noordwijk in The Netherlands. The range is located in the HERTZ facility [4], which now also includes a near-field system for planar, cylindrical and spherical near-field measurements, sharing the same antenna positioner. The ESA CPTR was a pioneering facility which performed until today countless antenna and payload measurements from 4 GHz to 24 GHz. The facility was continuously maintained and recently upgraded with a baffle and SERAP (Serration Radiation Protection) [5] to increase the measurement accuracy.

Current and future satellite missions work however over a much wider frequency band and require higher measurement accuracy than the one available in the ESA CPTR. A new measurement facility with a CATR for high performance payload and antenna measurements from 1 GHz to 400 GHz became therefore necessary. The facility will be called HERTZ 2.0 and will be a state-of-the art test centre including also sub-millimetre wave, optical and optoelectronics laboratories. The CATR for HERTZ 2.0 required a custom-made design to meet the tough electrical requirements set by the Agency and at the same time comply with the geometrical constraints given by the available room size. Thanks to its wide experience in reflector system designs and the progress made by RF modelling software tools over the past decade [6], TICRA was appointed to provide the electrical design of the new CATR for the upcoming HERTZ 2.0 facility.

The purpose of the present paper is to describe the approach used in the electrical design and show the detailed full wave analysis of the CATR at L band. In particular, Section II lists and discusses the requirements provided by the Agency, while Section III summarizes the design trade-offs that allowed to identify a promising candidate. The detailed electrical design is presented in Section IV and the quiet zone performances at L band are shown in Section V. Conclusions are finally summarized in Section VI.

II. Design Requirements

A number of electrical and geometrical requirements for the HERTZ 2.0 CATR were set by the Agency and are discussed in the following paragraphs.

A. Geometrical Requirements

The radio-anechoic chamber dimensions are shown in Fig. 1. Besides the CATR, a planar scanner will be installed in the room, creating a no-go area of width of 3 m. A dedicated feed room is planned for the feeds, see the lower part in the figure, both in the nominal position and displaced position for scan up to ±5 deg. The subreflector is shown at the top of the figure and must be contained in the upper 7 m x 20 m section to reduce diffractions into the quiet zone. The total height of the room is 18 m. A green area is indicated in the lower left part of the figure. It is a volume at the floor level with a square cross section of 2.5 m x 2.5 m, reserved for transportation of equipment to the quiet zone, which shall thus be kept free. Furthermore, the positioner will be placed at 6 m from the end wall. A clearance of at least 18 inches is required between the reflectors and the walls to allow room for 18 inches absorbers, while the remaining walls are covered by 26 inches absorbers.

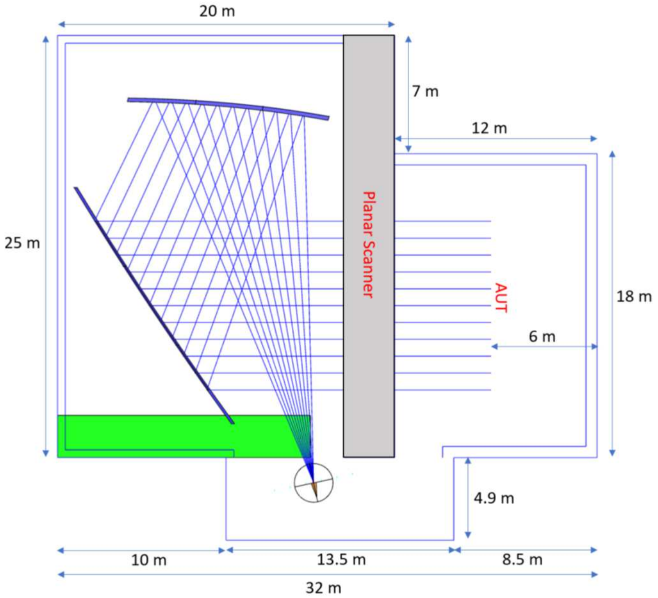

Fig. 1. HERTZ 2.0 chamber dimensions with example of dual CATR. The envelope of the 18 inch and 26 inch absorbers is also indicated.

B. Electrical Requirements

The new CATR for the HERTZ 2.0 facility shall work from 1 GHz to 400 GHz and be a compensated dual reflector system with serrations, ensuring low cross polarisation and small scan aberrations in all bands. As opposed to single reflector CATRs which can be designed by a few rules of thumbs [3], a compensated dual reflector system requires careful electrical modelling in a dedicated software [7], as we will address in Sections III-V. At L band, the overall peak-to-peak (PtP) amplitude and phase ripple of the quiet zone field shall be smaller than 0.5 dB and 4 deg, respectively. For frequencies higher than L band, the overall quiet zone PtP ripple requirements are 0.4 dB and 4 deg, respectively. It is noted that these requirements are a factor two more stringent than the ones met by COTS CATR systems, see for example [8]-[9], especially at L band. Moreover, they are overall PtP requirements, including both the effect of the feed taper and the effect of the reflector edge diffractions, which are typically quantified separately. To be met, the feed shall have a very flat pattern and the serrations shall be carefully designed to push the diffractions to a minimum. Finally, the size of the quiet zone shall be at least 5 m x 5 m with a depth of 9 m, and its centre shall be at an equidistant distance from the ceiling, the floor, and the side walls.

III. Design Trade-Offs

The main and sub reflector are arranged in a so-called compensated configuration satisfying the Mizuguchi condition. Moreover, when operating the CATR with several feeds simultaneously, the plane wave in the quiet zone will scan for the feeds not located in the focal point. A scan of up to ±5 deg is desired. This leads to an oversizing of the subreflector to reduce spill-over and maintain high quality in the scanned plane wave front. Finally, the design shall be made in a way to move the unwanted triply reflected ray (from feed, to main, then to sub and finally to main) out of the quiet zone.

The geometry of the optics is shown in Fig. 2. The main reflector is an offset paraboloid with focal length f and diameter D (without serrations) and the subreflector is the concave branch of a hyperboloid with inter-foci distance $2c$ and eccentricity e. The feed is located in one of the hyperboloid's focal points whereas the other focal point coincides with the focal point of the paraboloid. The axis of the hyperboloid is tilted the angle α with respect to the paraboloid axis and the feed axis is tilted the angle ψ with respect to the hyperboloid axis.

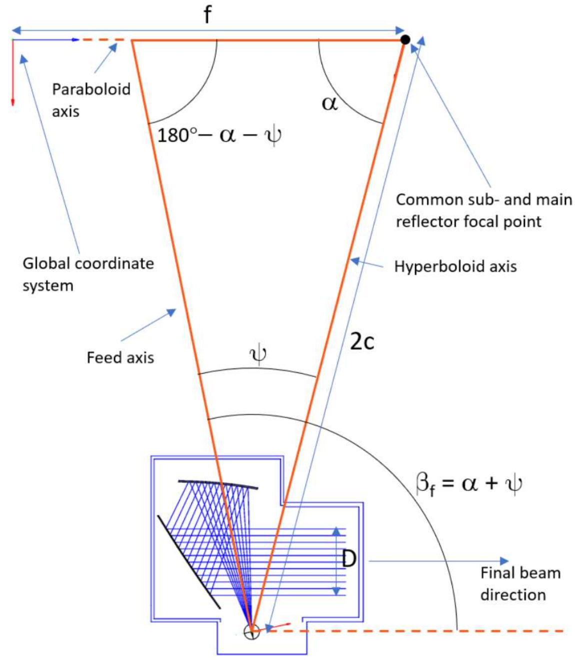

Fig. 2. Geometry of CATR optics and its defining variables.

By imposing that the angles α and ψ are related by the so-called Mizuguchi condition, it is possible to obtain a system that is optically equivalent to a rotationally symmetric single reflector system, ensuring low cross-polarization and small scan aberrations. The Mizuguchi condition is written as

$$\tan\frac{\psi}{2} = M \tan\frac{\alpha}{2} \tag{1}$$

where $M = (e+1)/(e-1)$ is the magnification factor and e is the eccentricity of the hyperboloid. For the concave branch of a hyperboloid, the eccentricity becomes a negative number less than -1. In Fig. 2 the angle β_f between the feed axis and the final beam direction is introduced. It is a useful design variable and is related to α and ψ through $\beta_f = \alpha + \psi$. It is noted that the final beam direction is parallel to the axis of the main reflector paraboloid.

In summary, the CATR geometry is defined by the following six parameters:

- D Main reflector diameter (without serrations)
- f Focal length of main reflector paraboloid
- 2c Foci distance of subreflector hyperboloid
- e Eccentricity of subreflector
- α Angle between main and sub reflector axis
- ψ Angle between feed axis and sub reflector axis

Since the Mizuguchi condition gives a constraint between the angles and the eccentricity, the parameters are reduced to five, and from these the geometry of the reflector system can be calculated.

The above design formulas were used to implement a parametric model of the CATR in the GRASP software [10] to study by ray tracing the effect of the five variables relative to the geometrical and electrical constraints of Section II, and find an optimal set of values which could move the triply reflected ray away from the QZ. An example of the ray tracing for a certain set of values is shown in Fig. 3.

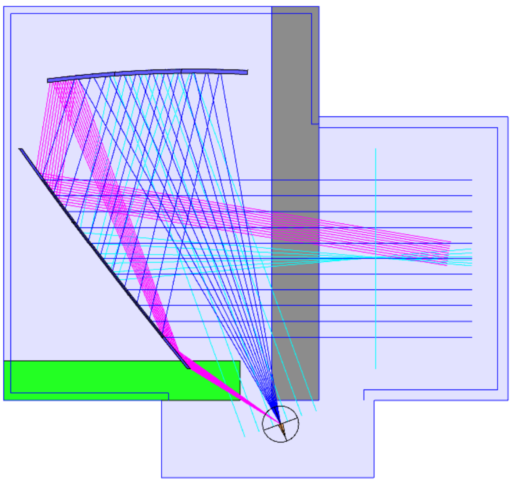

Fig. 3. CATR parametric model for ψ= 27.5 deg: the plot shows in blue the nominal rays, in pink the triply reflected rays and in cyan the focal point of the plane wave launched by the feed and the quiet zone plane at 6 m from the end wall.

After that, the geometry of the serrations was studied. In general, a CATR is requested to have a quiet zone as large as possible and as flat as possible. The size of the quiet zone is controlled by the size of the main reflector, while its flatness is controlled by the taper of the feed and the level of the diffractions from the edges of the reflectors, which are highly illuminated by the feed pattern. To reduce the edge diffractions and/or direct them away from the quiet zone two common solutions are used at the edge of the reflectors, i.e. serrations and rolled edges [11]. For the HERTZ 2.0 CATR, serrations with the same surface (paraboloid/hyperboloid) of the reflector were considered. The length and width of the serrations are determined by the lowest frequency at which the CATR shall operate, in our case L band. The length of a serration determines how well the currents are tapered to zero and thus how smooth the transition over the reflection boundary becomes in the quiet zone. Long serrations are best. If the width is too small, an electric field polarized orthogonal to the length of a serration will not be able to induce currents on the serration, and the serration will have no effect. It was found that a length of at least five wavelength and a width larger than one wavelength at the lowest frequency of 1 GHz were required.

IV. Detailed Electrical Design

With the parameters identified by the trade-offs of Section III a detailed model of the CATR was built in GRASP to accurately describe the surface and rim of the reflectors and each serration. The final CATR design was obtained by running a series of optimizations within the TICRA Tools SW at L band in terms of serration surface, profile, length, and orientation as well as subreflector illumination, to fully comply with the geometrical constraints of the room and get as close as possible to the required overall performances of amplitude and phase ripple. The global Multilevel Coordinate Search (MCS) method was used first, followed by the local minmax. Since the CATR shall work already at 1 GHz, high frequency analysis methods like Physical Optics (PO) and Physical Theory of Diffractions (PTD) would have been inaccurate [6], therefore full wave analysis of the full system was the only option. All the analyses and optimizations performed in the detailed design phase at L band were thus done using the higher-order MoM/MLFMM solver of the commercially available ESTEAM SW product within the TICRA Tools suite, see [12]-[13]. By considering the cluster given by the main and subreflector, it was possible to account for the coupling between neighbouring serrations, for the coupling between main and sub reflector and for the direct illumination of the main reflector by the feed at all stages of the optimisation. The direct illumination of the feed in the quiet zone (QZ) was always disregarded since it will be shadowed by a baffle. A MoM/MLFMM analysis of the CATR reflectors with serrations at 1.1 GHz used 4.7 GB of RAM and could run in 9 minutes on a laptop with a 2.3 GHz Intel Core i7. The reflectors are illuminated by the feed pattern shown in Fig. 4, characterized by a flat region around the boresight direction and a high taper, which provide an almost constant illumination of the subreflector and a low illumination of the subreflector serrations. This ensures an optimal illumination of the main reflector and low ripples in the quiet zone. The same pattern is used at all L band frequencies.

The final main and sub reflector are shown in Fig. 5 and Fig. 6. The main reflector has a total size of 18.5 m x 16.1 m with 32 serrations with length of around 3 m and width of 1.5 m. The main reflector serrations have a sharp cosine profile and a tilt to direct the diffractions away from the QZ. The subreflector has a total size of 15.2 m x 14.4 m with 40 serrations with length of around 1.5 m and a sharp cosine profile.

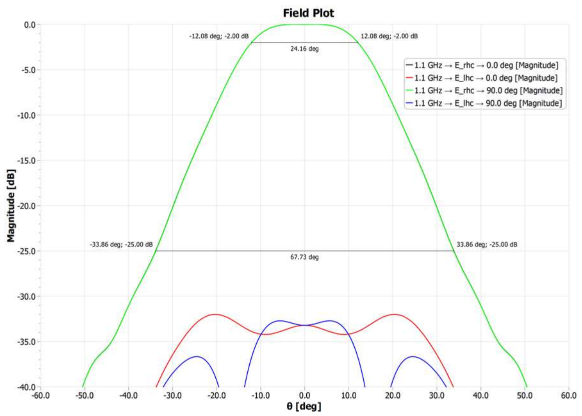

Fig. 4. Feed radiation pattern used to illuminate the CATR.

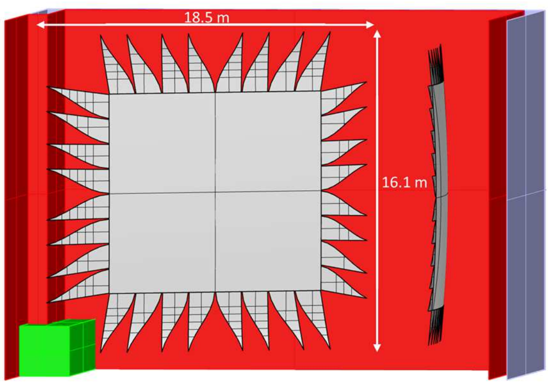

Fig. 5. Main reflector of the final CATR in the HERTZ 2.0 room.

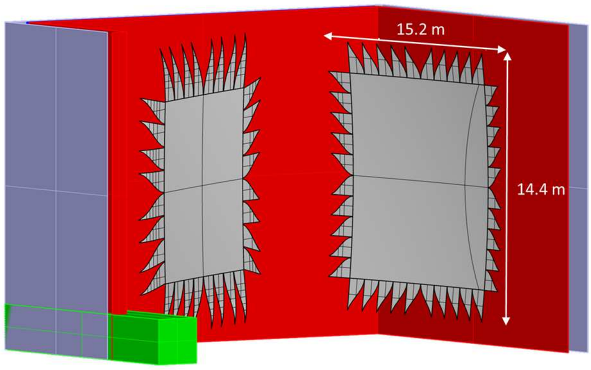

Fig. 6. Subreflector of the final CATR in the HERTZ 2.0 room.

V. DETAILED RF ANALYSIS

A cut of the two principal planes of the QZ at 6 m from the end wall is seen in Fig. 7 where the vertical dashed lines delimit the 5 m QZ region and the horizontal solid lines delimit the 0.5 dB peak-to-peak interval. The performances of the CATR are listed in TABLE I. in amplitude and phase. The percentages are computed with MoM/MLFMM over a grid with 109 x109 points over the 5 m x 5 m quiet zone with a sampling step of 45.87 mm. It is seen that the 0.5 dB peak-to-peak is achieved in L band for more than 89.9 % of the QZ points, and that the 4 deg peak-to-peak is met by more than 82.4 % of the QZ points. It is noted that the PtP % are worst case values, since in practice the radiation of the subreflector towards the quiet zone will partly be shadowed by the absorbers on the wall parallel to the quiet zone, which were not considered in the analysis. It is also repeated that the PtP% do not consider the direct field of the feed in the QZ, which will be shadowed by a baffle.

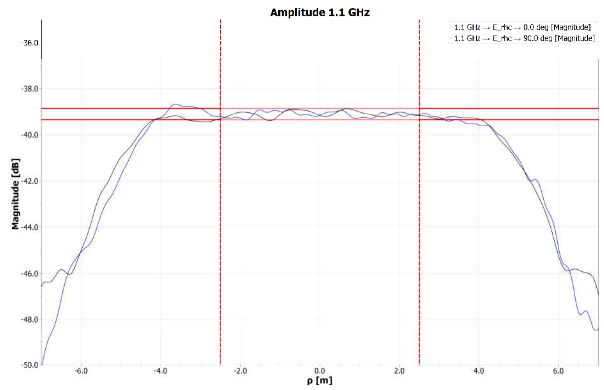

Fig. 7. Amplitude in the QZ at 6 m from the end wall at 1.1 GHz.

TABLE I. PERCENTAGE OF AMPLITUDE AND PHASE POINTS WITHIN THE RIPPLE REQUIREMENTS AT 6 M FROM THE END WALL

Frequency [GHz]	0.5 dB PtP [%]	4 deg PtP [%]
1.1	89.9	82.4
1.2	90.8	88.5
1.5	96.7	94.6

Finally, it is interesting to see how well Physical Optics (PO) agrees with full wave Method of Moments (MoM) at L band. To get a good understanding of the field contributions to the quiet zone, Method of Moments is applied in two ways, first considering a cluster given by the two reflectors, to account for mutual interactions between the reflectors, as done above and in Section IV. Secondly, as "sequential" MoM, where the same sequential approach of Physical Optics is used, and thus no mutual coupling between main and subreflector is considered, but full wave is used on the separate reflectors. The purpose of the "sequential" MoM analysis is to study the effect of the coupling between the serrations belonging to the same reflector, which is not included in the Physical Optics solution, and to make sure that all fields contributing to the quiet zone are considered. A list of all field contributions used in sequential MoM and PO is given in TABLE II.

TABLE II. FIELD CONTRIBUTIONS IN PO AND SEQUENTIAL MOM

#	Contribution	Note
1	Feed → sub → main → QZ	Nominal field
2	Feed → main → QZ	Should be blocked in principle by a SERAP. In this case the CATR is designed to make this contribution negligible
3	Feed → main → sub → main → QZ	Triply reflected ray, in this case the CATR is designed to make this contribution negligible
4	Feed → sub → QZ	Nominal field, main cause of ripple in the QZ. Part of that will in practice be shadowed by the wall
5	Feed → sub → main → sub → QZ	Extra bounce, causes ripple in the QZ
5x	Feed → sub → main → sub → main → QZ	Extra bounce for accuracy check

The results in Fig. 8 show that full MoM (black curve) is identical to sequential MoM (red curve), indicating that the mutual interaction between reflectors is insignificant and that sequential MoM correctly describes all fields contributing to the quiet zone. We also see that removing contribution 2, 3 and 5x from sequential MoM (blue curve) does not significantly change the results. This verifies that the design is such that we do not need a SERAP between the feed and the main reflector, and that the triply reflected ray can be neglected. The plot also shows that PO results (green curve) are inaccurate at L-band, as expected, since the PO solution does not account for the coupling between adjacent serrations, which is significant at L band.

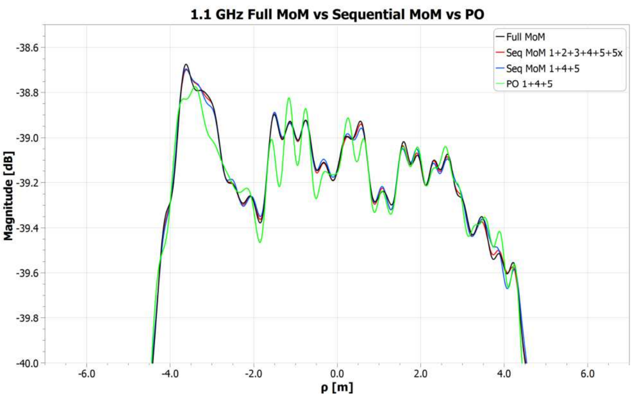

Fig. 8. Quiet zone over the principal plane of the QZ, at 6 m from the end wall with different analysis methods.

VI. Conclusions

The paper described the detailed RF design and analysis of a new CATR for the HERTZ 2.0 measurement facility at the European Space Agency, specifically developed by TICRA to meet the geometrical and electrical requirements set by the Agency. The CATR is a compensated dual reflector system with serrated edges, with a paraboloid as main reflector and a hyperboloid as subreflector, working from 1 GHz to 400 GHz. The serrations have the same surface of the reflectors, sharp edges and no gaps between them, and are slightly tilted. The electrical design was performed with a novel approach making use of an initial trade-off with ray tracing in the GRASP SW and a subsequent detailed full wave analysis and optimization of the serrations profile, length and orientation in the ESTEAM SW, both commercially available in the TICRA Tools suite.

References

[1] A. D. Yaghjian, "Efficient computation of antenna coupling and fields within the near-field region", IEEE Transactions on Antennas and Propagation, Vol. AP-30, No. 1, Jan. 1982, pp. 113-128.

[2] C. Cappellin, S. B. Sørensen, M. Paquay, A. Østergaard, "An accurate and efficient error predictor tool for CATR measurements", Proc. EuCAP 2010, Barcelona, Spain, April 2010.

[3] C. Parini, S. Gregson, J. McCormick, D. J. van Rensburg, Theory and Practice of Modern Antenna Range Measurements, IET, 2014.

[4] Antenna Measurements Facilities at ESTEC, https://esamultimedia.esa.int/docs/space_engineering/Antenna_Measurement_Facilities.pdf

[5] C. Cappellin, P. H. Nielsen, D. Trenta, L. Rolo, "Baffle and SERAP design for Compact Antenna Test Ranges", Proc. EuCAP 2019, London, United Kingdom, 2019.

[6] O. Borries, P. Meincke, E. Jørgensen, H.-H. Viskum, F. Jensen, C. H. Schmidt, "Design and validation of compact antenna test ranges using computational EM", Proc. AMTA conference, Long Beach, USA, 2015.

[7] C. H. Schmidt, A. Geise, J. Migl, H.-J. Steiner, H.-H. Viskum "A detailed PO/PTD GRASP simulation model for compensated compact range analysis with arbitrarily shaped serrations", Proc. AMTA Conference, Columbus, USA, 2013.

[8] https://www.nsi-mi.com/products/compact-range-reflectors

[9] https://www.compactrange.de/index.php/testi-facility/detailed-description

[10] GRASP software, https://www.ticra.com/software/grasp/

[11] A. Muñoz-Acevedo, S. Burgos, M. Sierra-Castañer, "Performance comparison between serrated edge and rolled edge reflectors inside CATR facilities", Proc. EuCAP 2011, Barcelona, Spain, 2011.

[12] E. Jørgensen, J. Volakis, P. Meincke, and O. Breinbjerg, "Higher Order Hierarchical Legendre Basis Functions for Electromagnetic Modeling," IEEE Transactions on Antennas and Propagation, vol. 52, no. 11, pp. 2985–2995, Nov. 2004.

[13] ESTEAM software, https://www.ticra.com/software/esteam/