Efficient Optimization of the Blended Rolled Edge of a Rectangular Single Offset-Fed Compact Antenna Test Range Reflector Using Genetic Evolution

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***Abstract*—The physical and electrical size of the parabolic reflector largely determines the usable size of the Compact Antenna Test Range (CATR) quiet zone (QZ), with the reflector edge treatment being hugely influential in terms of determining the overall quality and uniformity of the collimated, pseudo plane wave. This is especially true at mm-wave frequencies where the edge illumination combined with the edge treatment can result in QZ ripple that quickly exceeds the widely used 1 dB and 10 degree peak-to-peak amplitude and phase ripple requirements. Recently, it has been demonstrated that modern powerful digital computational simulation technology in combination with evolutionary optimization strategies can be successfully harnessed to optimize the serrated edge treatment of an offset-fed CATR as part of the design process. This is crucial as it simultaneously attempts to maximize the performance of a given solution while ensuring the minimum use of space. In this paper, a further enhancement is presented in which the evolutionary computing technique is applied to the more geometrically complex blended rolled edge (BRE) treatment of a rectangular CATR reflector. Results of the validation of this novel technique are presented together with optimized QZ performance that highlight the successful use of this design procedure in the development of a new testbed for verifying base station system performance for a mm-wave, FR2, 5G New Radio applications.**

Index Terms*—CATR, antenna measurement, blended rolled edge, genetic optimization, 5G.

I. INTRODUCTION

Electromagnetic (EM) optimization problems generally involve the examination and refinement of several different parameters. These can be either continuous or discrete valued and are in many cases bounded. Furthermore, the parameters that are involved within EM optimization problems are frequently complex, nonlinear, multiextremal, and nondifferentiable. In demanding applications such as these, genetic optimization algorithms (GOAs) have found great utility as they are generally robust, stochastic-based, methods which can handle EM optimization problems that involve many parameters that are not easily tractable by other techniques such as linear parameter sweeps, or a fully random optimization strategies. GOAs have been employed in many areas of application, *e.g.* shaped reflector antenna design, array antenna design and excitation optimization. However, these applications tend to be primarily concerned with the optimization of fields radiated within the Fraunhofer region, whereas here the requirement is to optimize the fields within the Fresnel region. In principle this is a closely related problem, although here; far greater importance is attached to the phase function than is typical when far-field performance alone is the primary performance metric. Thus, with the use of a GOA, a broad parameter-search may be conducted during the optimization of the edge treatment that specifically focuses on the CATR quiet zone (QZ) electromagnetic performance, allowing the optimization goal to be tailored to the requirements of the specific application including the facility layout.

An optimization procedure such as that required by a GOA such as this requires the evaluation of an EM problem hundreds, or more likely, thousands of times during the solution run. The evaluation of the field in the CATR QZ from the impressed currents on the parabolic reflector is typically performed numerically with physical optics based algorithms proving popular in many instances [1]. Although this is a computationally intensive, multi-dimensional problem, it is also embarrassingly parallelable. The requisite numerical integration can be performed in parallel, by dividing the CATR QZ into multiple sub-spaces. The CATR QZ in each region may then be computed using a different core. In period, when these computational electromagnetic simulation methods were first developed, this was not practical due to the comparative scarcity of multi-processor computers. However today, even a comparatively modest desktop workstation will contain a multicore CPU which may often possess as many as eighteen cores, whereas high-performance computers will likely contain 64 or more. Thus, such multi-instruction multiple data computational electromagnetic (CEM) algorithms present a very attractive proposition for accelerating computationally intensive processing. This yields a near linear increase in speed with the increase in the number of processing cores which is essential when attempting the evolutionary optimization of multiple variable problems. Such parallelization strategies generally suffer a bottleneck as the growth of communication load among the threads increases however here, this is limited as comparatively few tasks are required with little to no communication required between those respective tasks.

The problem of reflector edge diffraction was quickly identified by early workers as constituting a critical factor in the successful design and implementation of a CATR [2]. The need to spread diffracted energy over a wider region in the QZ thereby avoiding constructive superposition of individual diffraction points which would otherwise be evident when using simple straight knife-edge reflector edges lead to the proposal of a number of edge treatments with the most commonly implemented being perhaps the serrated edge [3], [4] and [5], and the blended rolled edge (BRE) designs [6], [7] and [8]. Either of these treatments may be viewed as being a way to provide a smooth tapering, *i.e.* windowing, of the reflected field thereby providing a smooth transition from the low surface impedance of the reflector body, to the 377 Ω impedance of free-space elsewhere. Typically, we may consider the general characteristics of the serrated edges to rolled edges are as Chebyshev filters are to Butterworth filters, *i.e.* more passband ripple but possessing a faster roll off. Thus here, the BRE reflectors are used to minimize diffraction and scattering inside the quiet zone while simultaneously minimizing the overall physical size of the overall test system.

In [5] the benefits of evolutionary optimizations were demonstrated for the case of the serrated edge treatment and in [9] this was extended to a square BRE reflector. In this paper the authors will expand their previous work to consider the more general, rectangular case. Here, the additional design parameters required by this geometry are readily accommodated by the flexibly and highly efficient GOA as will be highlighted. Thus, a summary of the of the BRE treatment is presented in Section II, after which an overview of the genetic optimization approach and algorithm verification is presented in Section III with results being presented and discussed in Section IV. The paper concludes in Section V and presents plans for the future work.

II. Quiet Zone Simulation

The used simulation- and genetic optimization algorithms have already been discussed extensively in [5] and [9], however for sake of completeness a short summary is presented here which focuses on the crucial points and the modifications implemented for the new test system.

A. Overview of Fast BRE CATR Simulation Technique

The field illuminating the CATR BRE reflector can be determined from the far-field antenna pattern of the feed antenna [2]. This is a very reliable strategy even when the reflector is not in the true far-field of a corrugated horn as these possess a Gaussian shaped pattern which, by virtue of the fact that a Gaussian Fourier transforms to a Gaussian, have a comparatively stable pattern well into the quasi-far-field region. The fields reflected by the, assumed perfect electrical conducting (PEC) surface can be obtained from the well-known physical optics condition [2]. Although many CEM techniques can be utilized for the propagation of these reflected fields into the Fraunhofer- or Fresnel-regions, the current element (CE) method provides an attractive combination of high accuracy and numerical efficiency. Here, the fields illuminating the reflector are replaced with an equivalent, infinitely thin, impressed surface current sheet $\underline{J_s}$ which can be used as an equivalent source. Then, the radiated magnetic fields can be obtained from the vector potential and the free-space Green's function using [2],

$$d\underline{H}\left(\underline{P}\right) = \frac{da}{4\pi}\underline{J_s} \times \nabla\psi, \qquad (1)$$

A detailed examination and verification of the use of this for serrated edge CATR simulation can be found presented in the open literature [10], [11]. The application of this strategy to the BRE CATR requires some adaptation however. Here, the feed illumination of the reflector must be limited to include only that portion of the reflector that is not in the geometrical-shadow region as viewed from the feed. Then, the integration of the current elements must be restricted so that only those current elements for which $\underline{\hat{u}'} \cdot \underline{\hat{n}} \geq 0$ are included where $\underline{\hat{u}'}$ is the unit-vector from the current element to the field point and $\underline{\hat{n}}$ is the outward pointing reflector surface unit-normal. Although this appears to be a relatively insignificant modification, it has a very notable effect on the resulting CATR quiet-zone predictions. Thus, as was the case in [10], [11] this required careful verification by means of a comparison with a proprietary full-wave three-dimensional CEM simulation tool. An initial verification of this for the case of the BRE CATR can be found in [9] with a more extended validation presented in Section IV.A below.

B. Genetic Optimization Algorithm

The optimization of a system comprised of multiple continuous parameters falls under the nondeterministic polynomial (NP) range of problems which cannot be solved in polynomial time. Where polynomial time $f(n)$ is a function of the number of input parameters, and solving means finding a combination of input parameters which provides the optimal solution. While the problem does not fall under NP-hard any parametric solution can be found in polynomial time using the proposed simulation method [12]. Considering that the model of the problem is defined as shown in Section II.A above and validated, the problem fits nicely within the range of problems for which a GOA algorithm can be employed. The GOA used for this purpose is shown Figure 1 below and includes operations typically found therein such as fitness selection, parent selection, parameter cross-over and mutations.

```
Begin
  INITIALIZE POPULATION
  REPEAT UNTIL (TERMINATION CONDITION) DO
   EVALUATE NEW CANDIDATES
   PRUNE POPULATION
   CREATE OFFSPRING
  END DO
END
```

Figure 1: Genetic algorithm expressed in pseudocode

The fitness value is chosen such that both amplitude and phase behavior of the co-polarization component is optimized and has been extended in this study to permit the specification of different objective in different axes. It can be shown that the edge treatment has very little impact on the cross-polarization behavior [5], and is typically of lesser importance to the 5GNR measurement community.

III. Extension of the Junction Contour

The GOA depends fundamentally upon the mathematical form of the BRE reflector, for which in [9] the general form employed for construction of the BRE surface has been detailed. However, the formulation for the junction contour

(JC) was found to be a limiting in case of an elliptical QZ. Where the well-established formulation of the JC defines the corner points depending on the width and the height of the QZ, the curvature itself is predetermined by a single parameter r_e for both the horizontal and vertical sides. In the original formulation [6], a fixed JC parameter was not a problem because the curvature dependent parameters such as x_m, y_m, a_e and b_e are optimized to attain the reflector mechanical dimensions for each rotational angle φ independently. However in the GOA case, the reflector is optimized for the QZ performance and the final shape and may not fill the available space completely for each rotational angle φ and thus it makes sense to uncouple the optimization of the horizontal and vertical edges, adding just a single additional parameter to the optimization pool. Thus, in order to optimize the horizontal and vertical sides of the reflector independently the JC is expanded as:

$$x_j' = \begin{cases} R_{\mathrm{QZ},x} + r_{e,h}(1-\cos\varphi') & 0 \le \varphi' \le \varphi_1 \\ \left(R_{\mathrm{QZ},y} + r_{e,v}\right)\cot\varphi' - r_{e,h}\cos\varphi' & \varphi_1 \le \varphi' \le \varphi_2 \\ -R_{\mathrm{QZ},x} - r_{e,h}(1+\cos\varphi') & \varphi_2 \le \varphi' \le \varphi_3, \\ -\left(R_{\mathrm{QZ},y} + r_{e,v}\right)\cot\varphi' - r_{e,h}\cos\varphi' & \varphi_3 \le \varphi' \le \varphi_4 \\ R_{\mathrm{QZ},x} + r_{e,h}(1-\cos\varphi') & \varphi_4 \le \varphi' \le 2\pi \end{cases} \quad (2)$$

$$y_j' = \begin{cases} \left(R_{\mathrm{QZ},x} + r_{e,h}\right)\tan\varphi' - r_{e,v}\sin\varphi' & 0 \le \varphi' \le \varphi_1 \\ R_{\mathrm{QZ},y} + r_{e,v}(1-\cos\varphi') & \varphi_1 \le \varphi' \le \varphi_2 \\ -\left(R_{\mathrm{QZ},x} + r_{e,h}\right)\tan\varphi' - r_{e,v}\sin\varphi' & \varphi_2 \le \varphi' \le \varphi_3, \\ R_{\mathrm{QZ},y} - r_{e,v}(1+\cos\varphi') & \varphi_3 \le \varphi' \le \varphi_4 \\ \left(R_{\mathrm{QZ},x} + r_{e,h}\right)\tan\varphi' - r_{e,v}\sin\varphi' & \varphi_4 \le \varphi' \le 2\pi \end{cases} \quad (3)$$

with,

$$\varphi_1 = \tan^{-1}\left(\frac{R_{\mathrm{QZ},y}+r_{e,v}}{R_{\mathrm{QZ},x}+r_{e,h}}\right), \quad (4)$$

$$\varphi_2 = \pi + \tan^{-1}\left(\frac{R_{\mathrm{QZ},y}+r_{e,h}}{-R_{\mathrm{QZ},x}-r_{e,v}}\right), \quad (5)$$

$$\varphi_3 = \pi + \tan^{-1}\left(\frac{-R_{\mathrm{QZ},y}-r_{e,h}}{-R_{\mathrm{QZ},x}-r_{e,v}}\right), \quad (6)$$

$$\varphi_4 = 2\pi + \tan^{-1}\left(\frac{-R_{\mathrm{QZ},y}-r_{e,h}}{R_{\mathrm{QZ},x}+r_{e,v}}\right), \quad (7)$$

and $r_{e,h}, r_{e,v}$ are the JC curve parameters in horizontal and vertical direction respectively and $R_{\mathrm{QZ},x}, R_{\mathrm{QZ},y}$ is the radius of the QZ in x and y direction. Similarly, the penalty function of the GOA was adapted to optimize within the elliptically shaped QZ.

IV. Results

The first effective demonstration of the use of this new efficient design strategy was the optimization of a CATR intended for FR2, mm-wave 5GNR testing. As can be seen in the photograph presented in Figure 3, the mm-wave CATR comprised a floor offset fed reflector that was conceived to provide a 45 cm diameter, cylindrically shaped QZ. The GOA presented above was utilized to simultaneously optimize the boundary, blending and roll parameters r_e, x_m, y_m, a_e, b_e. A cosine-squared blending function was chosen to match the parabolic and elliptical sections. Here, the maximum reflector width and height was limited to 1100 x 1100 mm. The optimization was carried out at 18 GHz, the lower frequency of the primary band of interest, after which the CATR QZ performance was evaluated across a broad band of frequencies to confirm the improvements brought were broadband. Here, it was found that the genetic optimization required 25 generations involving circa 5000 QZ simulations and took a few hours to complete when run on a standard office laptop.

The simulation results for this reflector are shown in Figure 2. It can be seen that the performance results of this reflector are expected to be very broad band, having a lower limit at 8.2 GHz which is well below FR2.

In a next step the reflector simulation was expanded to allow the measurement of FR2 mm-wave base station testing with different aspect ratios, based on the extension of the JC to allow separate optimization of the horizontal and vertical shape of the reflector. The chosen aspect ratio of the QZ was an elliptically shape having a width x height of 600 x 450 mm.

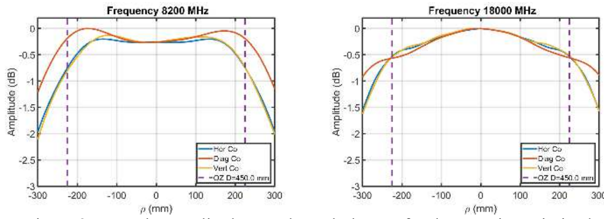


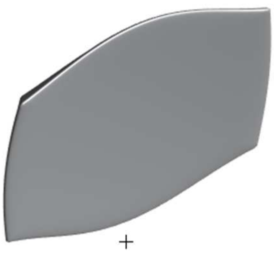
Figure 2: Co-polar amplitude cuts through the QZ for the genetic-optimized reflector, at 8.2, and 18 GHz

The resulting reflector outline from the GOA simulation can be observed in Figure 3. It can be seen that the optimization led to a stronger curvature in the horizontal sides of the reflector as opposed to the vertical sides. This is congruent to the horizontal to height aspect of the elliptical QZ. A main benefit of this result is that the total weight of the reflector is reduced as opposed to a full rectangular reflector while keeping maintaining full performance inside the QZ.

While the results shown in Figure 4 are for the reflector optimized at 18 GHz, the reflector was also optimized at 26 GHz which has shown to provide close to the same solution are performance, which proves the stability of the approach.

A. Validation of the Parallel PO Simulation.

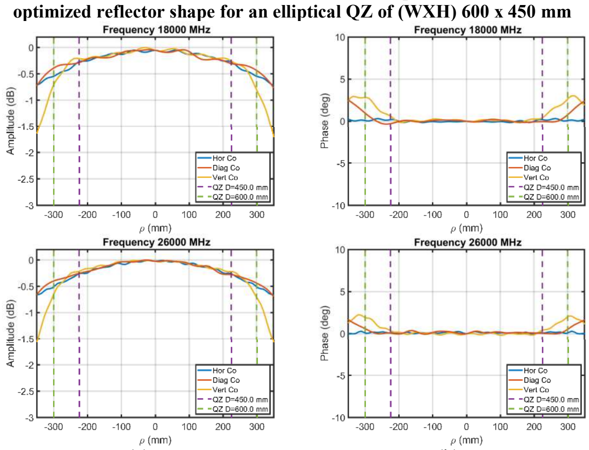
To further verify and validate the results predicted by the in-house parallel CE based PO code, simulations of a similar blended rolled edge reflector were performed using the well-established proprietary CEM package FEKO [13]. The first challenge was to create a very complex surface in the solver which was not implementable using standard geometric primitives. General purpose three-dimensional full-wave CEM software packages are not typically designed to compete directly with highly specialized CAD/CAM packages, which results in some degree of complexity when importing or creating very specialized, complex surfaces such as those necessitated by the BRE CATR reflector. Of course, options are available for import geometries from some file formats, *e.g.* STEP, *etc.* however, usually, this results in a loss of parametrization of the models, and can potentially result in some issues when meshing those surfaces. Thus saving time in an initial design phase can yield delays and result in issues when performing parametric studies. Therefore, the model of the BRE reflector was entirely constructed within FEKO with the exported surface being validated against that which was used by the custom in-house CE PO based model.



(b)

(a)

Figure 3: (a) Photograph of realized 450 mm QZ diameter BRE CATR without absorber treatment installed on reflector pedestal and (b) GOA optimized reflector shape for an elliptical QZ of (WXH) 600 x 450 mm



(a) (b)

Figure 4: Co-polar amplitude (a) and phase (b) cuts through the the Genetic-optimized rectangular shaped reflector, at 18 and 26 GHz

In order to create a model and avoid some issues with connecting complicated surfaces together (which can be a common problem when meshing and joining complex surfaces) a new method was utilized. Firstly, the surface was represented as a set of analytical curves which comprised a blend of parabolic and elliptical functions with several controllable parameters. After this, each of these curves were "lofted" together thereby creating a smooth surface. This can be seen in Figure 5 which clearly shows that even after simplifying the model, one can see a "skeleton" of ribs that comprise the BRE reflector surface.

In order to accelerate the, otherwise tedious, process of creating all of the necessary individual curves and intermediate surfaces, a Lua [14] code was written to automate this task. Thus, for this example, the 160 defining curves used to determine the BRE reflector only took *circa* 3 to 4 minutes to construct the complete reflector.

Another challenge was presented by the next step which was to convert the infinitesimally thin surface to a solid comprising some surface "thickness". It is a usual practice for CEM packages to make surfaces infinitesimal thin, or simply of "zero thickness". This dramatically improves simulation time and decreases the required resources, however, to some extent this also detaches the model from reality and imposes some limitations on the final solution. In the presented study, a very important issue concerned the backward and wide out radiation characteristics. The CATR reflector is intended to be installed within an anechoic chamber as part of a complete test system. Thus, it is important to know level of diffraction is present not only in the QZ region but also within the surrounding space too. To modify the original BRE reflector model in FEKO and make it closer to a manufactured prototype it was necessary to add 3-5 mm of aluminum to the "rear side" of the existing surface. Due to complexity of the surface, it was impossible to simply "extrude" the surface into the backward direction. As a consequence of this a scaled copy of the original surface was created which intersected with another surface and by "unioning" these surfaces a single solid body could be formed. This was the only practical way in which the surface currents results could be obtained. The final model can be seen presented in Figure 5. An example of the current distribution at one of design frequencies is demonstrated in Figure 5. Crucially, it is clear that although the surface currents do flow into the geometrical shadow region they are comparatively small and therefore align with the CE simulation method presented above and used by the PO code.

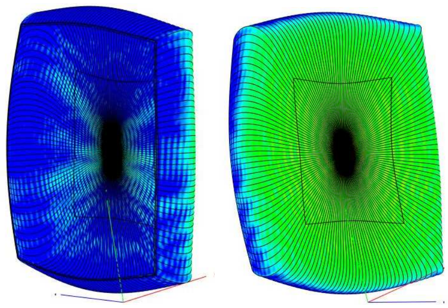
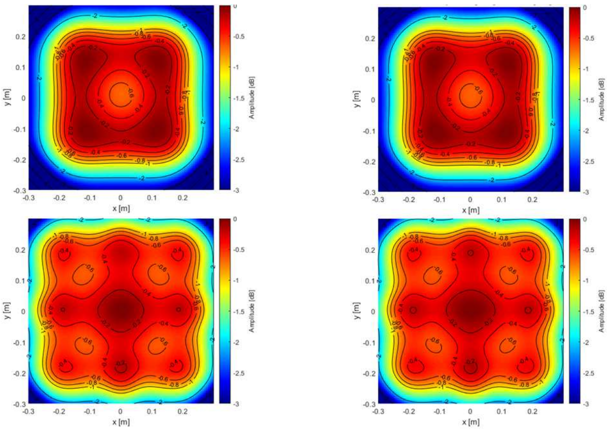


Figure 5: Two images of the BRE CATR reflector model in FEKO showing the impressed surface currents across the reflector.

Here, the *circa* 1.1 m square BRE reflector CATR was simulated in FEKO using a number of different solvers. However, the most encouraging results, those presented above, were obtained when the Multilevel Fast Multipole Method (MLFMM) [13] was used. This, is an acceleration method that is based on the well-known and very accurate Method of Moments (MoM) [13]. This technique reduces both complexity and the memory requirements of the EM problem. A comparison of the QZ fields can be seen presented in Figure 6 in the form of a false-color checkerboard plot with the co-polar fields being tabulated across a transverse *xy*-plane. Here, from inspection, the degree of agreement between FEKO (a) and CE PO (b) can be seen to be very encouraging indeed. This comparison is presented at 6 GHz and 15 GHz, where 26 GHz is shown in [9] as well. Other simulations at other frequencies, both higher and lower, were performed with similarly encouraging results attained however due to the confines of available space, they are not reproduced here. As noted above, there were small differences between the reflectors in the respective models and as such, the degree of agreement is all the more encouraging. Additionally, as noted, the MLFMM method includes currents all the way around the reflector. This is important as it helps validate the modified CE method that was implemented for this case. Furthermore, as this MLFMM method is more accurate that the CE method, especially at lower frequencies it was possible to verify that the model was reliable even when the reflector was electrically small, *circa* 10 wavelengths, which is smaller than would typically be used for a practical CATR and helps demonstrate the model is reliable throughout its range of use.



(a) (b)

Figure 6: Copolar BRE CATR QZ prediction from (a) FEKO, (b) CE PO Simulation at 6 and 15 GHz

Again, not shown as a consequence of space constraints; similarly encouraging results were obtained for the cross polarized fields, phase functions and elsewhere in the QZ. Thus, when taken together with the previous verification results presented in [9], this can be seen to confirm and reliability and validity of the extended CE based, parallel, PO CEM model.

V. Summary, Conclusions and Future Work

This paper has presented the successful application of computational evolution to the design of a rectangular BRE CATR using a parallel implementation of an efficient, accurate CE based PO CEM simulation. The boundary, blending and roll parameters of a blended rolled edge single offset CATR reflector have been optimized for the rectangular reflector using a genetic algorithm and a refined penalty function with the presented approach opening new possibilities in tailoring a CATR specifically to a particular customer's requirements. This yielded a stable design that operated well over a wide range of frequencies and was comparatively insensitive to the precise frequency at which the optimization was performed.

The paper has presented the initial work performed within an ongoing study and as such a number of areas for future investigation are still being considered. Among others, replacing the boundary function with a continuous function in φ' will ascertain less discontinuity in the reflector surface profile, particularly in the corners of the reflector. Another possible limitation of the current approach is that it is predicated on the assumption that the blended rolled edge provides CATR performance that is inherently broadband in nature, with the optimization process being limited to the examination of a single chosen frequency. This analysis can be readily expanded to operate across a band of frequencies by utilizing the extension of a multi-objective genetic algorithm [15], and this is an area that is intended for future investigation.

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References

[1] S. Avila, W. Carpes and J. Vasconcelos, "Optimization of an Offset Reflector Antenna Using Genetic Algorithms," *IEEE Transactions on Magnetics,* no. 40 NO 2, pp. 1256-1259, 2004.

[2] C. Parini, S. Gregson, J. McCormick, D. Janse van Rensburg and T. Eibert, Theory and Practice of Modern Antenna Range Measurements, 2nd Expanded Edition ed., vol. 1, London: IET Press, 2020.

[3] E. Joy en E. Wilson, „Shaped Edge Serrations for Improved Compact Range Performance," in *AMTA Proceedings*, 1987.

[4] J. Hartmann en D. Fasold, „Improvement of compact ranges by design of optimized serrations," in *Millennium Conference on Antennas & Propagation (AP2000)*, Davos, Switzerland, 2000.

[5] M. Dirix and S. F. Gregson, "Optimisation of the Serration Outline Shape of a Single Offset-Fed Compact Antenna Test Range Reflector Using A Genetic Evolution of the Superformula," in *EuCAP*, Düsseldorf, 2021.

[6] W. Burnside, M. Gilreath, B. Kent en G. Clerici, „Curved Edge Modification of Compact Range Reflector," *Antennas and Propagation, IEEE Transactions on,* vol. 35, nr. 2, pp. 176-182, 1987.

[7] I. Gupta and W. Burnside, "A Method to Design Blended Rolled Edges for Compact Range Reflectors," The Ohio State University, ElectroScience Laboratory, Columbus, 1989.

[8] T.-H. Lee and W. Burnside, "Compact Range Reflector Edge Treatment Impact on Antenna and Scattering Measurements," *Antennas and Propagation, IEEE Transactions on,* vol. 45, no. 1, pp. 57-65, 1997.

[9] M. Dirix, S. Gregson and R. Dubrovka, "Genetic Evolution of the Reflector Edge Treatment of a Single Offset-Fed Compact Antenna Test Range for 5G New Radio Applications," in *AMTA Annual Meeting and Symposium*, Daytona Beach, Florida, 2021.

[10] C. Parini, R. Dubrovka and S. Gregson, "CATR Quiet Zone Modelling and the Prediction of 'Measured' Radiation Pattern Errors: Comparison using a Variety of Electromagnetic Simulation Methods," in *AMTA 37th Annual Meeting & Symposium*, Long Beach California, 2015.

[11] C. Parini, R. Dubrovka and S. Gregson, "Compact Range Quiet Zone Modelling: Quantitative Assesment using a Variety of Electromagnetic Simulation Methods," in *Loughborough Conference on Antennas and Propagation*, Loughborough, 2015.

[12] A. Eiben and J. Smith, Introduction to Evolutionary Computing, Berlin: Springer-Verlag, 2015.

[13] Altair, *FEKO - EM Simulation Software; Feko info retreived 2016-09-28.*

[14] „Lua the programming language," [Online]. Available: https://www.lua.org. [Geopend 15 10 2021].

[15] K. Deb, Multi-Objective Optimization using Evolutionary Algorithms, Wiley, 2001.