一般社団法人　電子情報通信学会
THE INSTITUTE OF ELECTRONICS,
INFORMATION AND COMMUNICATION ENGINEERS

信学技報
IEICE Technical Report
A･P2023-200(2024-02)

Development of an ISO8729 compliant passive RCS enhancer, part1.

- design of natural plastic lenses -

Derek GRAY　and Julien Le KERNEC

James Watt School of Engineering,　University of Glasgow,　Glasgow,　UK.

E-mail:　(Derek.Gray,　Julien.LeKernec) @glasgow.ac.uk

Abstract　An aplanatic lens backed by an offset conductive bowl was found to satisfy the ISO8729 passive RCS enhancer requirements in a 12GHz scaled model across ±15°.　Here the effects of permittivity on $4\lambda_0$ radius lens weight,　focal arc angular spread and position were studied in simulation at 9.41GHz for f/D=0.9.　Increasing permittivity decreased lens weight. Cutting a circular lens to a square reduced the focal arc and angular spread.　A novel lens consisting of a dielectric rod with 2 concentric toroids increased the focal peak from 6V/m to 6.6V/m and decreased the plastic mass from 1.7kg to 1.2kg,　but will require an aerogel or foam support.

Key words　lens antenna,　RCS enhancer.

1. Introduction

Fishing boats,　yachts and other small marine vessels under 150 gross tonnage (GT) are poor reflectors of radar signals as these sit low in the water and the hulls are either low reflectivity glass fibre reinforced plastic (FRP) or wood.　This lack of radar detectability contributes to the 2 or so small vessel collisions per day in Japanese green waters.　Without a legal compulsion for small vessels to at least carry ISO8729 compliant passive RCS enhancers,　the only alternative is to reduce the cost to a point where there is no economic disincentive to the adoption of those.　As a follow on to a programme at Tokyo Univerity of Marine Science and Technology,　a range of potentially low cost passive RCS enhancers were studied as 12GHz scaled models [1].　The 8 corner reflector arrays found on approximately one in fifty small vessels harbored in the Kobe – Himeiji – Ako area was about 30% of the size required to meet the ISO8729 recommendation.　A spherical homogeneous natural plastic lens fitted with a thin foil cap would meet the recommendation across ±65°, requiring a set of 3 for full horizon coverage as is the case for commercially available Luneburg lenses.　A double convex aplanatic lens cut to a square fitted with a reflective bowl worked across ±25°.　A set of 7 would be needed for full horizon coverage although 5 would satisfy the ISO8729 horizon coverage specification,　Figure 1. Both these and the spheres would presumably be suspended in a foam matrix attached to the mast top. Here the design of the aplanatic lens is examined with some care at the actual operating frequency of 9.41GHz.

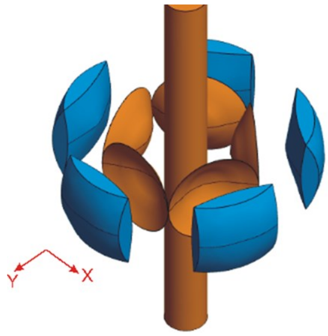

Figure 1:　CAD of 5 aplanatic lens passive RCS enhancers around a small vessel mast,　from [1].

The ISO8729 recommendation for passive RCS enhancers specifies an RCS of 8.75dBm^2 at 9.41GHz [2]. This is the RCS of a 88.5mm radius flat disk,　Figure 2.

Adding 6dB as a margin would require the disk radius to be increased to 125mm ($4\lambda_0$), which was used as the aperture size for this work on aplanatic lenses.

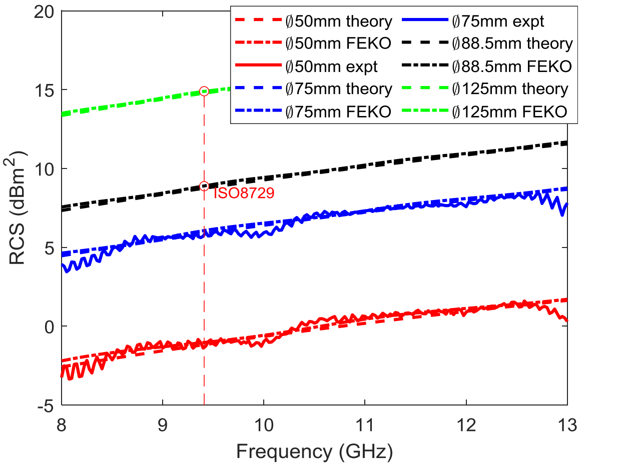

Figure 2: Theoretical, simulated & measured on axis RCS of flat 1mm thick aluminium disks.

The design procedure and measured results for the first successful radio frequency aplanatic lens were published in 1889 [3]. That work was largely ignored until WW2 when there was both a need for medium to high Gain X-band radar antennas and consistent high quality and low loss natural plastics like cross-linked polystyrene (xPS, ε_r=2.54) became freely available. Several design methods were developed in the following 2 decades with one finally been automated in FORTRAN [4]; a Matlab™ transcription was used here.

Acknowledging that 3D printing has an advantage in producing one-off prototypes, 3D printed plastics have relatively short lifetime and are not suitable for field deployment where will be exposed to water ingress. Mass production complicated lens shapes by injection molding has the advantages of minimal unit cost and the plastics will have long operational lifetimes. The electrical properties and density of a given natural plastic are manufacturing process dependent, with the values in Table 1 drawn from our prior work been indicative. It is assumed here that high density polyethylene (HDPE) and Ultra High Molecular Weight Polyethylene (UHMWPE) are interchangeable and have a specific gravity of 0.94g/cm^3; this material will float in water.

TABLE 1: Natural plastic properties, from [7].

plastic	ε_r'	density g/cm^3
PTFE	2.1	2.16
polymethyl pentene (TPX)	2.1	0.83
polyethylene (HDPE)	2.3	0.94
polystyrene (xPS)	2.54	1.05
acrylic (PMMA)	2.6	1.2
polycarbonate (PC)	2.7	1.1

The aim of this work was to prepare a library of natural plastic lenses for which the ±45° focal arc is as close to lens as possible that will be fitted with customized reflective bowls in future work.

2. Plano-convex lens for baseline

A 2 diffracting surface plano-convex lens design was generated for 125mm radius and ε_r=2.3 with a 5mm edge using the equation in Figure 14-2 of [5], to be used as a baseline lens design. The marine passive RCS enhancer application is simple in that it is horizontally polarized and as the lenses are rotationally symmetric it only required scanning in the plane of the E-field vector in FEKO™ MoM simulation. The Electric near field was calculated for z=-50 to 250mm as a fixed standard for all lenses, then processed in Matlab™.

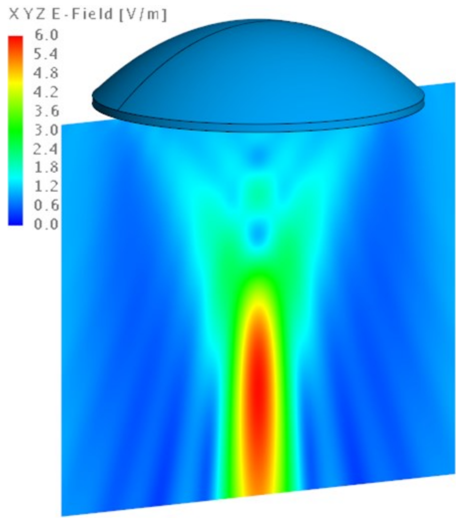

Figure 3: Electric near field of HDPE plano-convex "baseline" lens for scan angle 0°; data used for 0° yellow contour on Figure 4, from FEKO™.

As expected the lens focused to a cigar shaped region and not a point as was electrically small at $4\lambda_0$ radius, Figure 3. The FEKO™ model was run for plane wave incident angles of 0° to 45° in 5° steps, the electric near field was retained and processed to find the peak positions which were then plotted as the focal arc, Figure 4. This lens had an *f/D*=0.9 been about the shortest *f/D* typically used for a cluster fed antenna historically.

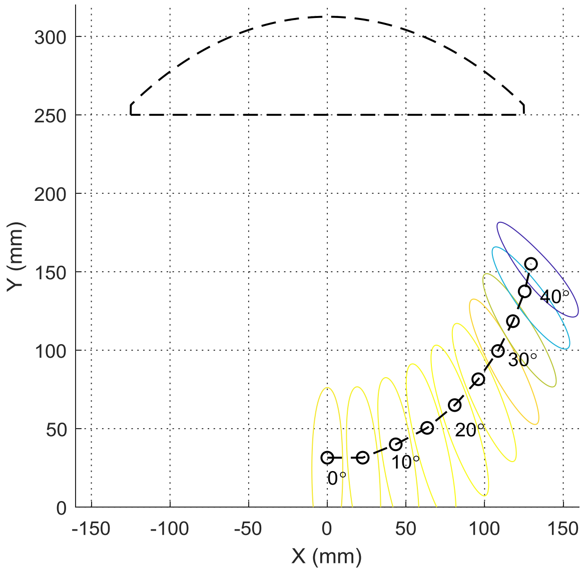

Figure 4: Electric near field 90% contours & peaks of plano-convex "baseline" lens for scan angles 0° to 45°; from FEKO™.

This lens had a volume of 1,723.5cm^3, which if manufactured in HDPE would give a mass of 1.6kg in contrast to 7.7kg for a spherical lens of the same radius.

3. Double convex lenses

The optimal optical lens is coma and aberration free having the double convex shape [6]. The presumed equivalence between optical and radio is misleading in that lenses of a small number of λ_0 radius focus to a cigar shaped zone and not a point, and that the dielectric material surface will support significant unwanted magnetic currents that cause standing waves and thus resonant effects. However, these can be conveniently ignored when working across a narrow band as in [4]. The code derived from [4] was used to design *f/D*=0.9 lenses for ε_r=2.1 to 2.7, Figure 5. The focal arcs of these 4 lenses were close to indistinguishable, and identical to the baseline for 0° to 15°. There was a 450cm^3 decrease in volume across ε_r=2.1 to ε_r=2.7, Table 2. The ε_r=2.3 lens was 180cm^3 smaller than the baseline design.

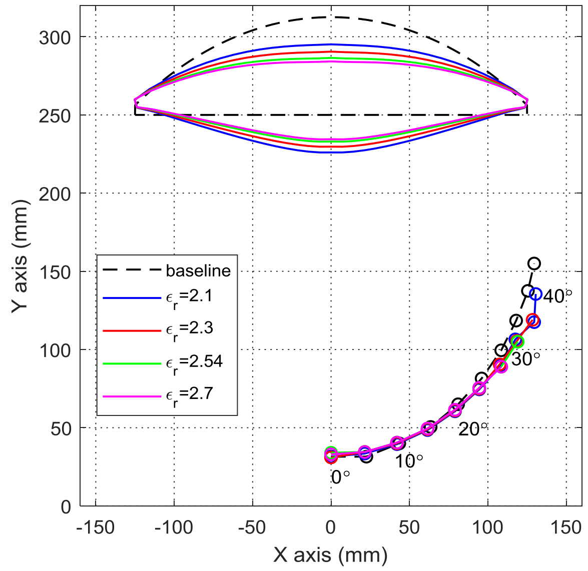

Figure 5: Electric near field for scan angles 0° to 45° of double convex lenses of different ε_r; from FEKO™.

TABLE 2: Natural plastic lens volume & mass.

ε_r'	volume (cm^3)	mass (kg)
2.1	1763.4	3.8 / 1.5
2.3	1567.6	1.5
2.54	1397.6	1.5
2.7	1309.9	1.4

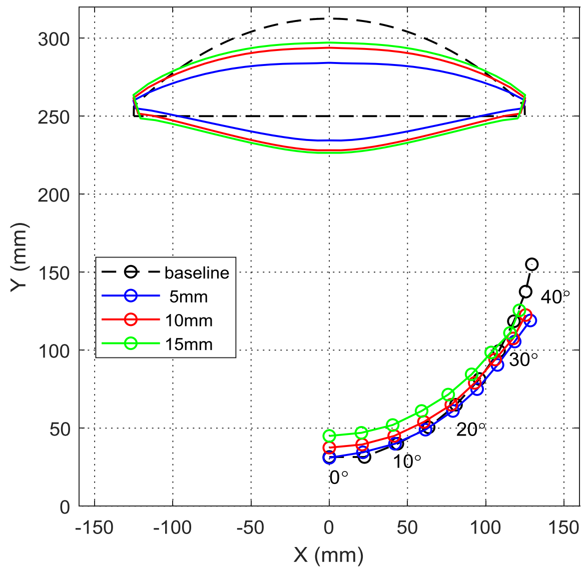

Figure 6: Electric near field for scan angles 0° to 45° of double convex lenses with varied edge thickness; from FEKO™.

ε_r=2.3 alone was used for all further work. The ε_r=2.3 lens edge thickness was increased to 10mm and 15mm, which moved the focal arc at the nearer angles, Figure 6. Aligning the focal arcs would likely require moving the inner surface down and some fiddling of the lens locus ζ.

With edge thickness at the original 5mm and *f/D*=0.9, the lens locus ζ was varied from 185mm to 200mm, giving a wild variation in shape from dimpled to flat topped, Figure 7. This had minimal effect upon the shape of the focal arc.

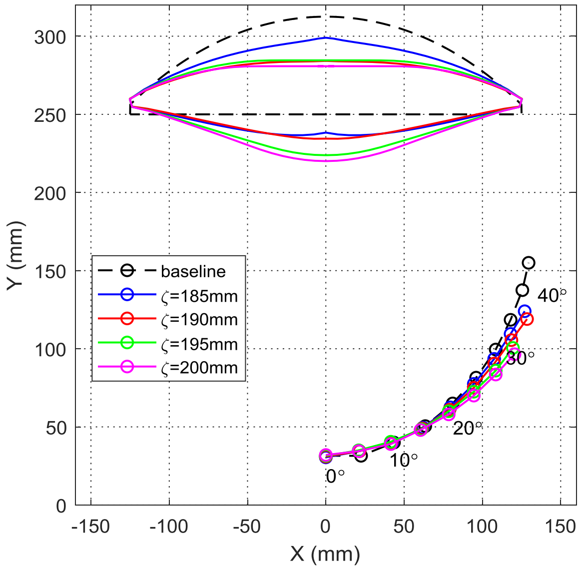

Figure 7: Electric near field for scan angles 0° to 45° of f/D≈0.9 double convex lenses with different locii; from FEKO™.

The exercise was repeated for *f/D*=1.2, with the same minor effect, Figure 8.

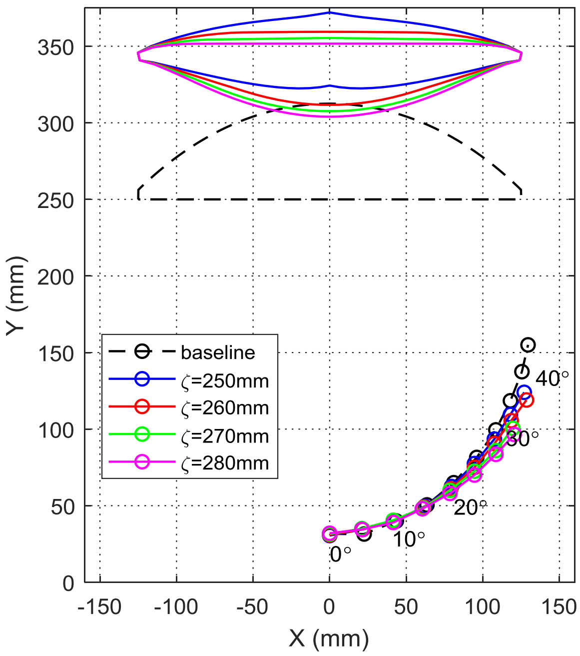

Figure 8: Electric near field for scan angles 0° to 45° of f/D≈1.2 double convex lenses with different locii; from FEKO™.

It is understood that zoning and lens truncation modify the focal arc [5]. All of the lenses of Figure 7 were cut to a 177mm sided square as in Figure 1 and rerun in FEKO™. The focal arcs of all 4 lenses reduced to *f/D*=0.7, Figure 9, confirming that cutting down to a square reduced *f/D* as was guessed at during development of the 12GHz scaled model lens presented in [1].

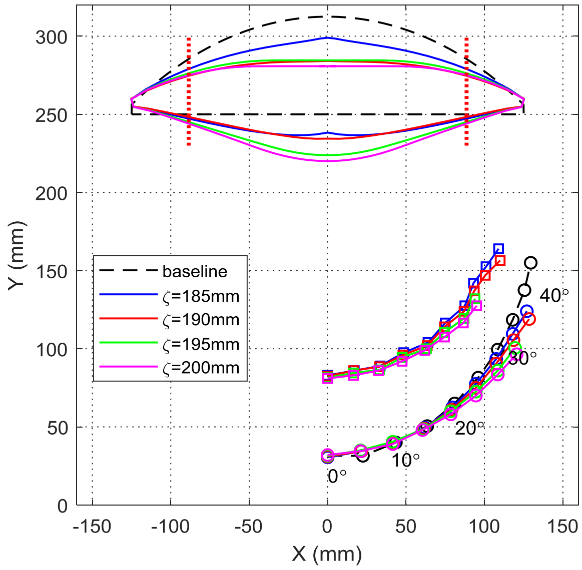

Figure 9: Electric near field of circular to square lens comparison for scan angles 0° to 45°; vertical red dotted lines indicate truncation position, from FEKO™.

4. Genetic algorithm plano-convex lenses

A Genetic Algorithm (GA) was successfully used to find improved scanning 10λ_0 plano-convex lenses [7]. Here the lower surface was kept flat as per the baseline design, and the upper convex surface was replaced with a rotationally symmetric Non Uniform Rational B-Spline (NURBS) in FEKO™, and the GA run until an E-field greater than 6V/m was obtained at some target focal position. This was done for *f/D*=0.7 down to 0.3, Figure 10. The shapes of the *f/D*=0.7 and 0.6 designs did not diverge greatly from that of the baseline, whereas the *f/D*=0.5 and 0.4 designs had axial dimples. The *f/D*=0.35 design shows a trend toward a sphere, as was expected as the focal zone is pushed toward the lens surface, Figures 10 and 11. This lens had a volume of 3,852.2cm^3, more than double that of the baseline. Overall, the focal arcs of these GA found lenses were good in that the curves were smooth and consistent but the mass is likely to be a disadvantage.

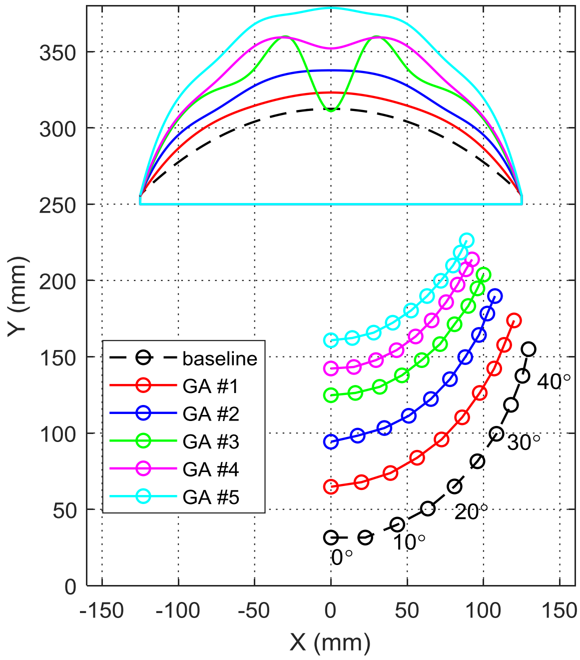

Figure 11: Scan performance of lenses Electric near field of GA plano-convex lenses for scan angles 0° to 45°; from FEKO™.

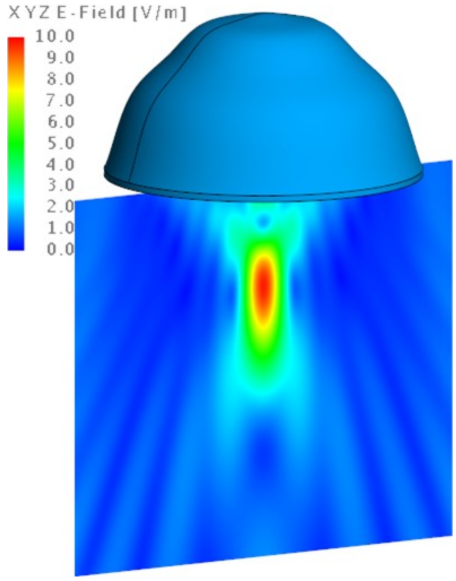

Figure 11: Electric near field of a GA plano-convex lens for scan angle 0°; light blue trace in Figure 10, from FEKO™.

5. Genetic algorithm hub-membrane lenses

A presumed disadvantage of plano-convex, double convex and GA lenses is that the large mass of plastic will have significant thermal gradients during likely marine temperature cycling from -30°C to 140°C; the thick lens cores will remain cold while the thinner edges warm rapidly resulting in deformation. An exotic metallic focusing device such as [8] or its dielectric implementation [9] could presumably be adapted to become limited scan passive reflectors thus avoiding the thermal mass problem but at the expense of using multiple dielectrics for the latter. The so-called doughnut lens of [10] is a better starting place in that it can be injection molded from a single plastic and had mass mostly in the outer rim avoiding a thick heavy core. Thus in a radical departure from the plano-convex and double convex lenses, a ε_r=2.3 125mm outer radius thick rim or hub supporting a thin membrane akin to a drumhead was formed by an upper and lower rotational NURBS, which were varied by a GA until an E-field greater than 6V/m was obtained at some target focal position.

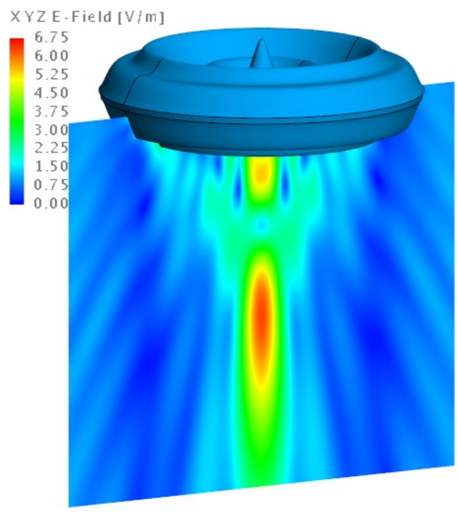

Figure 12: Electric near field of *f/D*=0.7 hub-membrane lens for scan angle 0°; blue trace in Figure 14, from FEKO™.

For for *f/D*=0.7 the thick hub still contained the majority of the mass, Figure 12, whereas the hub thinned to downward shell with a thick pipe containing most of the mass at half the lens radius for *f/D*=0.4, Figure 13. Curiously, all 4 lenses had a near identical volume about 1,850cm^3, been fractionally about that of the baseline. The focal arcs obtained were flatter than from the GA plano-convex lenses which is expected to be an further advantage for this application, Figures 11 and 14.

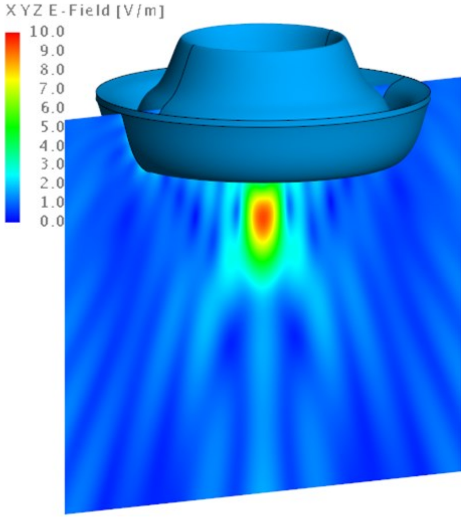

Figure 13: Electric near field of *f/D*=0.4 hub-membrane lens for scan angle 0°; pink trace in Figure 14, from FEKO™.

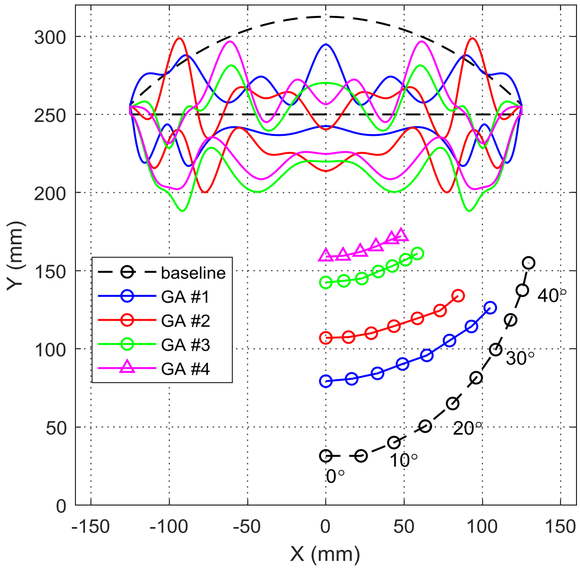

Figure 14: Electric near field of hub-membrane lenses for scan angles 0° to 45°; from FEKO™.

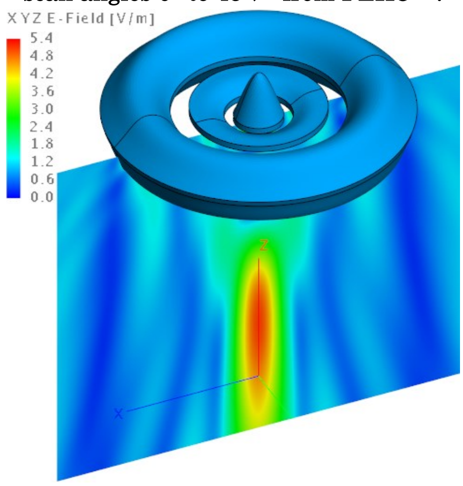

Figure 15: Electric near field of *f/D*=0.9 3 ring lens for scan angle 0°; from FEKO™.

The thinner sections of the "GA #1" design in Figure 14 were cut out, to leave a cone with 2 concentric donuts which still operated as a lens, Figure 15. This pared down structure is akin to the stacked dielectric ring design of [11]. Realization will require an accurately molded negative foam holder. The plastic volume was 1,202cm^3 been a small reduction from the original lens.

6. Conclusions

A series of aplanatic lenses were investigated to find types that had focal arcs for ±45° scanning close to the lens for a marine passive RCS enhancer application. Good performance scan performance for *f/D*=0.35 was found for a GA modified plano-convex lens and an exotic rotational NURBS lens consisting of joined concentric pipe sections. The latter had a lower mass and is expected to suffer less deformation during operational temperature cycling.

7. References

[1] D. Gray & J. Le Kernec, "Scan performance of small boat RCS enhancers," *IET Int radar conf.*, Comisky, China, 2023.

[2] Ships and marine technology - marine radar reflectors - part 1: passive type, ISO 8729-1 1st ed., 2010-01-15.

[3] O.J. Lodge & J.L. Howard, "On electric radiation and its concentration by lenses," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 28, iss. 170, pp. 48-65, 1889.

[4] J.F. Kauffman, "Microwave lenses for amplitude and phase transformation," Ph.D. dissertation, Dept. Elect. Comp. Eng., North Carolina State University, Raleigh, 1970.

[5] S.B. Cohn, "Lens-type radiators," in *Antenna engineering handbook*, H. Jasik, Ed., New York: McGraw-Hill, 1961, sec. 2, pp. 14-3 to 14-5.

[6] F.E. Jenkins & H.E. White, *Fundamentals of optics*, McGraw-Hill, 1937.

[7] T. Maruyama, K. Yamamori & Y. Kuwahara, "Design of multibeam dielectric lens antennas by multiobjective optimization," *IEEE Trans. Antennas Propag.*, vol. 57, pp. 57-63, Jan. 2009.

[8] M. Clénet & L. Shafai, "Investigations on directivity improvement of wide flare angle conical horns using inserted metallic discs," *IEE Proc. Micro. Ant. Propag.*, vol. 147, pp 100-105, April 2000.

[9] I. Gashi, A. Paraskevopoulos, S. Maci & M. Albani, "A novel approach to the design of inhomogeneous dielectric lens antennas based on geometrical optics," *EuCAP*, 2023.

[10] J. R. Sanford & B. Comisky, "The doughnut lens," *IEEE Antennas Propagat. Symp.*, 2008.

[11] L.P. Kamburov, J.M. Rodriguez, J.R. Urumov & H.D. Hristov, "Millimeter-wave conical Fresnel zone lens of flat dielectric rings," *IEEE Trans. Ant. Propag.*, vol. 62, no. 4, April 2014.