Optimisation of wide angle scanning antennas by genetic algorithms; application to reflector antennas for automotive radars at 76 GHz

#Gabrielle Landrac, Eddy Jehamy, Michel Ney
[1]Laboratory of Electronics and Systems for Telecommunications (LEST, CNRS),
GET-ENST Bretagne, CS 83818, 29238 BREST Cedex , France
Gabrielle.Landrac@enst-bretagne.fr
Eddy.Jehamy@enst-bretagne.fr,
Michel.Ney@enst-bretagne.fr

Abstract

This paper presents the application of genetic algorithms for the optimisation of millimetre-wave antennas for automotive radars, for which maximum compactness is required. The objective is the determination of the profile of a reflector in order to enhance the scanning angle while keeping low side lobe levels. This study calls for aberration theory and calculation of the phase error by geometrical optics (GO). The minimum cumulative phase error is obtained through the application of genetic algorithms (GA) and the radiation patterns are calculated by physical optics (PO). Finally, a scanning angle from –30° to 30° with side lobes below -20dB is achieved with a high compactness (F/D=0.4; D=15λ), hence meeting requirements for application to automotive radars.

1. INTRODUCTION

Automotive radars at millimetre wavelengths require a wide angle scanning together with low side lobes and high gain. The specifications given in table 1 consider the case where long-range and short-range radars are mounted on the same antenna.

TABLE 1: SPECIFICATIONS OF ANTENNAS VALID FOR BOTH LONG AND SHORT RANGE RADARS

Centre frequency	76.5 ± 0.2 GHz
Antenna gain	> 26 dB
Azimuth detection	± 30 degrees
Azimuth 3dB beamwidth	4 degrees
Elevation Angle field of view	5 degrees
Polarization	Linear
Side lobes rejection	> 20-25 dB
Isolation	-30dB
Volume	Below 10λx10λx10λ

To achieve the above specifications, we are considering the enhancement of the scanning properties of focusing systems, such as lenses, artificial lenses and reflectors, by using switched primary sources (horns or printed antennas) [1]. This paper focuses on the use of single reflector antennas, while artificial lenses are presented in [2]. Both technologies have some potential for low-cost mass production at millimetre wavelengths.

Note that the main challenge is to obtain both high gain and wide scanning angle together with maximum compactness.

2. ABERRATION THEORY AND SCANNING ANGLE ENHANCEMENT

A. Aberration theory

In the case of focusing systems such as reflectors or lenses, the desired field of view is obtained by antenna beam steering. This is achieved by placing several primary sources in the focal plane and, then, by switching them alternatively or by monopulse techniques. However, the classical parabolic reflector does not ensure the required specifications, especially concerning low side lobe level. Indeed, for scanning angles off broad-side primary sources are no longer at the reflector focus. This leads to higher side lobe levels, wider main lobe and lower gain. In addition, the focal pattern is also modified.

This effect, called aberration phenomenon, exists because the wave front coming out from the parabola is no longer plane (see figure 1).

It is possible to calculate the phase error Δ between the reference plane wave front and the actual wave front. With the notations indicated in figure 1, it is given by :

$$\Delta = \frac{2\pi}{\lambda}\left(FM + MH - FO - OH_0\right)$$

The analytical formulation is then obtained by geometrical calculations. Classical developments of the aberration theory consist in developing the phase error in terms of a polynomial form by using Taylor series up to the 6^{th} order [3].

This formulation allows to separate the aberrations into odd and even aberrations. For instance, among odd aberrations, there is the distortion term which is responsible for the deviation of the beam (wanted effect). On the other hand, the coma leads to radiation pattern dissymmetry by tilting the main lobe and raising the side lobe level on the side opposite to the tilt. Finally, aberration even terms (e.g. quadratic , astigmatism, the spherical) cause only symmetrical effects like the enlargement of the main lobe, lower gain and less deep nulls.

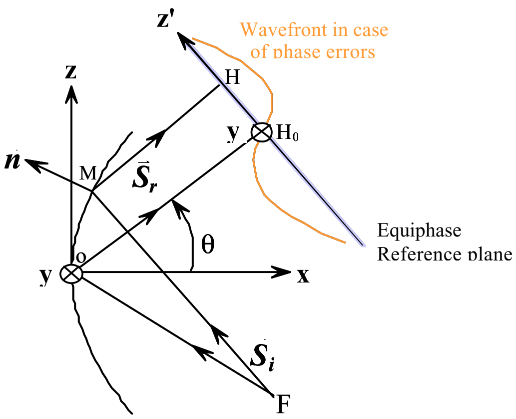

Fig. 1: Illustration of the aberration phenomenon

B. Decreasing the side lobe levels

Many studies have been carried out about wide angle scanning antennas using focusing systems. Most of them, like [4] and [5], concern terrestrial antennas for satellite communications and are based on aberration reduction of reflector antennas. However,

cases investigated concern reflectors having large diameters D or large F/D (F is here the focal length). For embarked applications like the automotive radar, the size of the antenna has to be reduced as much as possible. As a result, large F/D or D values are not suitable in those applications.

The radiation patterns can be enhanced by modifying the reflector profile.

- Some authors like Kondo [6] obtained the profile of the reflector by merging several parabolas having different foci.
- Albertsen [4] proposed an iterative method to improve the scanning performances of dual reflectors; their surfaces are shaped in order to distribute the aberrations uniformly in the desired region.
- In case of Craig and Rappaport's approach [7][8], the mean square error method is applied to minimize the phase error between the central beam and the most deviated beam. The profile is a 4^{th} order polynomial form in y and z, including cross terms like x^4y^2 ; different areas of the reflectors are illuminated for each scanned beam, like in the torus antenna.
- P. Cousin [9] carried out a Taylor development up to the 10^{th} order. This leads to reflector profiles that cancel either odd or even aberrations for a specific angle (both types cannot be cancelled simultaneously). Then, he then proposed a zoned reflector based to the corresponding surfaces. However, diffraction at the edge between zones may raise the side lobe level. For that reason, a continuous surface reflector was finally proposed for a multi-satellite receiver [10]. This approach gave also some good results in case of millimetre wave automotive radars [11].
- The variational approach, as explained in [12] for artificial lenses, may also be used for reflectors. However, it leads to numerous tedious calculations. Moreover, it is a local optimisation method and it cannot take into account cross terms x^ny^m.
- Genetic algorithms are global optimisation methods which can account for a large number of variables and avoid tedious calculations. They may lead to solutions that cannot be found by analytical formulations. Moreover, they can include x^ny^m cross terms, leading to better optimisation [13].

  Their drawback is mainly due to the calculation time that can be exhaustive. However, very good results for artificial lenses were obtained with this technique [14][2]. Thus, good performances is also expected in the case of reflector profile optimisation.

After a brief description of genetic algorithms, this paper describes their use for the reduction of reflector phase error over a wide scan angle. Simulation results are shown, demonstrating the good performance of the approach.

3. GENETIC ALGORITHMS

Genetic algorithms (GA) give very good results to obtain optimal performances when many parameters have to be adjusted. They are based on the natural selection and evolution and their basic principle is described in figure 2.

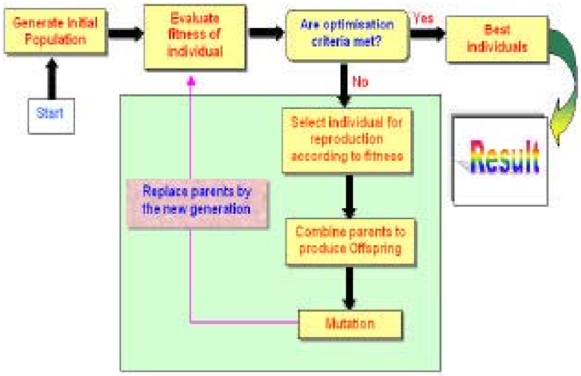

Fig. 2: Basic GA procedure

The first step consists in initialising a population of individuals that will be candidate solutions for the problem. Individuals are encoded as strings called 'chromosomes', which contain the information parameters . In the case described here, individuals are the possible reflector shapes and their parameters are constants a_i, b_i and c_i pertaining to the polynomial form describing the profile as shown below :

$$x = a_1.y^8+a_2.y^6+ ... +a_4.y^2+b_1.z^8+b_2.z^6+ ... +b_4.z^2 +c_1.z^2.y^2+c_2.y^4.z^2+c_3.y^2.z^4+c_4.y^4.z^4$$

The most common alphabet to encode those chromosomes is the binary one composed of bits {0, 1}.

The individuals are evaluated to assess their performances with the fitness function which takes into account the evolution of the phase error over the required field of view.
More precisely, we define it as the cumulated absolute value of the phase error over the field of view (by steps of 1°) and the profile (by steps of 1mm):

$$\text{Fitness} = \sum_{y=-30mm}^{30mm} \sum_{z=-30mm}^{30mm} \sum_{\theta=-30°}^{30°} |\Delta| = \text{cumulated phase error}$$

For comparison purpose, the fitness has been evaluated relatively to a value equal to 97408 . This correspond to the case of a parabola with a 60mm diameter (15λ) and F/D=0.4.
This is one of the survival criteria for an individual: its fitness function has to be as low as possible and below the reference value mentioned above.

A population is composed of several individuals, randomly created and containing random parameter values. Then, a new population is created by randomly varying the characteristics of the chromosomes composing the current population.
This step is fundamental for the creation of the parents that will compose the next generation of population. In our case, the individual with smaller fitness has more opportunity to deliver his genetic information to the new generation, which is made by crossover and mutation processes applied to their parents' chromosomes.
In our case, two methods were used and compared:

- in the first case (AG 1), the same cross over function is used for all individuals; the same principle applies for mutation and selection.
- in the second case (AG 2), the process is based on a mix between different kinds of cross over: some individuals evolve by simple cross over, other by heuristic crossover, other by intermediate cross over, (etc. ? ou point?). The same principle applies for mutation and selection.

Note that in the basic scheme described in figure 1, only one population is used.
Finally, in order to check the convergence of the process, the radiation patterns of the best individual is calculated at each generation by the use of physical optics [15].

4. RESULTS

Simulations started with the following parameters:

F= 24mm, D=60mm (hence F/D=0.4)

The primary source was a horn having the following dimensions:

Aperture size: 2λ x 1.5 λ at 76 GHz
Length: 2λ

First, tests were made to check the process. Usually, 30 to 100 individuals are recommended for a population. It was found that 30 individuals and 50 generations are enough to ensure the convergence of the process (as shown in figure 3), whatever the method used.
Finally, the mix process (AG2) selected an individual having the best radiation pattern for our problem.

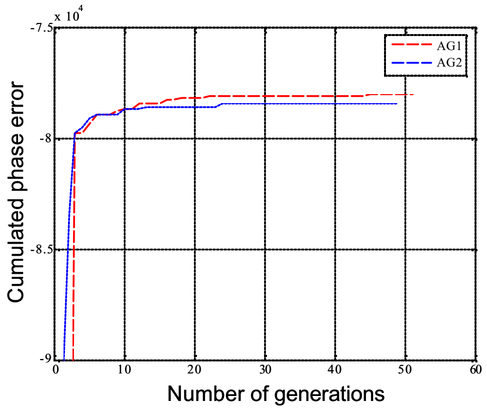

Fig. 3 : Evolution of the fitness function for the best individual as a function of the number of generations

The following results were obtained by using the mix process (AG2) :

a1 = 2.7654707854026 07e-012
a2 = 1.300639174940132e-009
a3 = 1.500000000000000e-006
a4 = 0.00942585798706
b1 = -5.774870132739978e-012
b2 = 6.739156978378711e-009
b3 =1.500000000000000e-007
b4 = 0.00894389356951
c1 = -1.500000000000000e-007
c2 = 8.312509510567367e-009
c3 = 6.794835403714807e-009
c4 = -2.167038016745689e-011

In this case, the cumulated phase error was 79041, which is much less than for the reference parabola.

The corresponding radiation patterns given in figure 3 are in accordance with the requirements for automotive radar:

- The main lobe gains are between 26 and 27 dB.
- The side lobe level is below –20dB for all radiation patterns from 0 to 30° deviation.

The comparison with the parabola having the same diameter and focal length (see figure 4) shows that the side lobes have been reduced for the 20° and 30° deviation cases, at the price of higher lobe level for 0° and 10° beam angles.

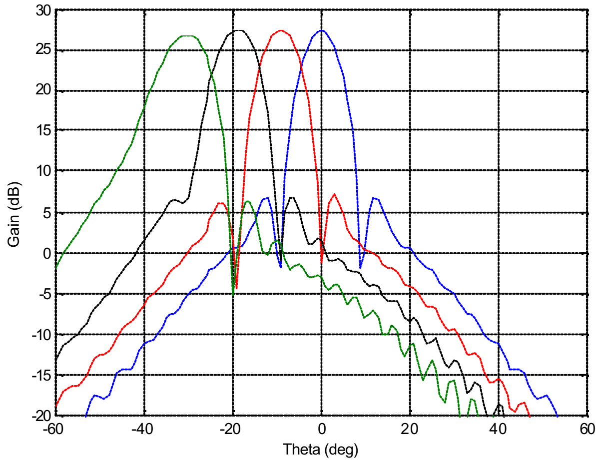

Fig. 3 – Gain patterns of the best individual

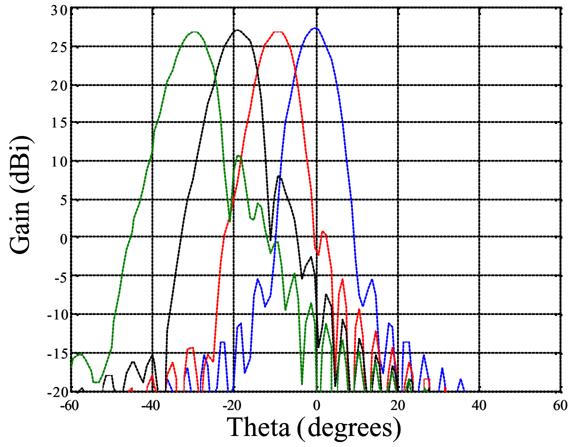

Fig. 4 – Gain patterns of the parabola (D=60mm, F=24mm)

5. CONCLUSION AND FUTURE WORK

As shown in this paper, the genetic algorithms yield good results for reflector shape optimisation. A new profile was determined to obtain sufficient gain while keeping side-lobe levels below –25 dB over ±30° steering angle. The antenna system has now to be optimised globally by adapting the primary source to the focal field pattern.

Further work also concern the optimisation of dual reflector antennas which are more suitable in case of automotive radars because of the required compactness. In case of the Cassegrain configuration similar to figure 5 [2], the expected size of the antenna system should be 60 x 30 x 24 mm.

Concerning the use of genetic algorithms, the method described here for the optimisation of focusing systems is interesting because the calculation of the phase error is fast and leads to short computation times. However, it suffers from the limitation of the geometrical optics approximation. As a result, antennas with low fitness may correspond to higher side lobe levels using physical optics or full-wave analysis. However, this method can be seen as a preliminary step in the optimisation process.

Further development should be carried out by using genetic algorithms together with the calculation of the fitness function as the sum of side-lobe rejections for each position. This will allow us to take directly into account the radiation pattern and to consider more parameters in the optimisation process (like the dimensions of the horns, the diameter and the focal length).

However, this requires the computation of the radiation pattern of each individual and physical optics requires a rather long computation time. This is why we are now exploring genetic micro-algorithms which may be more suitable. Indeed, they require smaller populations and fewer generations.

Finally, neuronal network is considered to accelerate the computation of radiation patterns.

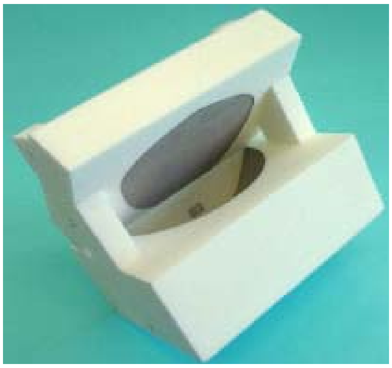

Fig. 5 – Example of Cassegrain reflector made of foam technology and silver painting

ACKNOWLEDGEMENT

The authors wish to thank Pierre-Amaury Brun, Guillaume Habault and Chen Pengfei, students in GET/ENST Bretagne for their great efforts and high quality work during their student project which was a preliminary step for this study.

REFERENCES

[1] E. Jehamy, G. Landrac, M. Résibois, M. Ney, "Comparison of some antennas for automotive long range radars at millimeter wavelengths", *5th conference on "Intelligent Transport System Telecommunications"*, ITST 2005, Brest, June 2005.

[2] E. Jehamy, M. M. Ney, G. Landrac, "Fast optimisation of 3D focusing system using genetic algorithm", *accepted to EuCap conference*, November 2006, Nice, France.

[3] M. Born , E. Wolf, "Principles of optics", 6th edition, Pergamon Press, Oxford, 1980.

[4] Albertsen, N.; Pontoppidan, K.; Sorensen, S., "Shaping of dual reflector antennas for improvement of scan performance", Antennas and Propagation Society International Symposium, 1985, Volume 23, Jun 1985, pp. 357 – 360.

[5] Hay, S.G.; Barker, S.J.; Granet, C.; Forsyth, A.R.; Bird, T.S.; Sprey, M.A.; Greene, K.J., "Multibeam Earth station antenna for an European teleport application**",**
Antennas and Propagation Society International Symposium, 2001, IEEE Volume 2, 8-13 July 2001, pp. 300 - 303 vol.2

[6] A. Kondo, T. Hori, K. Kagoshima, 'Reflector design and radiation characteristics of a multi-focal parabola antenna', *Journées Internationales de Nice sur les Antennes*, 1992, p.271-3.

[7] C.M Rappaport, W.P Craig, 'High aperture efficiency symmetric reflector antennas with up to 60° field of view', *IEEE Trans. on antennas and propagation*, Vol.39, N°3, Mars 1991.

[8] W.P Craig, C.M Rappaport, J.S Mason, 'A high aperture efficiency, wide-angle scanning offset reflector antenna', *IEEE Trans. on antennas and propagation*, vol.41, N°11, Nov.1993.

[9] P. Cousin, "Etude d'antennes mono-réflecteur à très large champ de vision. Conception de nouvelles antennes à zones de Fresnel et à réflecteur conformé", PhD Thesis, Université de Bretagne Occidentale (University of Western Brittany, Brest, France), 10 March 1998.

[10] G. Landrac, E. Jehamy, M. Ney, F. Averty, F. Gallée, P. Cousin, "High Gain Large Scan Angle Antennas : from Multi Satellite Reception to High Rate Wireless Networks and Automotive Radars", *International Conference on Information and Communication Technologies : from theory to applications*, Damascus, Syria, April 2004.

[11] F. Schäfer, F. Gallée, G. Landrac and M. Ney, "New Reflector Shapes For Anti-Collision Radar at 76 GHz", Microwave and Optical Technology Letters (MOTL), vol.24, no.6; 20 March 2000; p.400-4.

[12] G. Landrac, E. Jehamy, M. Ney, "Phase errors reduction procedure for new antenna shapes : application to wide scan angle multibeam metal plate lenses", *International Symposium on Antennas and Propagation,* ISAP 2005, Seoul, Korea, August 2005.

[13] C.M Rappaport, W.P. Craig, "A 60 degree scanning offset reflector antenna with high aperture efficiency", *Antennas and Propagation Society International Symposium, 1990. AP-S. 'Merging Technologies for the 90's'. Digest*., pp148 - 151 vol.1, 7-11 May 1990

[14] E. Jehamy, M. M. Ney, G. Landrac, "Procedures to improve convergence and efficiency of genetic algorithms : application to antenna focusing elements", *International Symposium on Antenna technology and applied electromagnetics (ANTEM06),* Montreal, Canada, July 2006

[15] Leo Diaz and Thomas Milligan, *Antenna engineering using physical optics : practical CAD techniques and software*, Boston, MA : Artech House, The Artech House antenna library, 1996.