Synthesis Study of a 6-Element Non-Uniform Array with Tilted Elements for CLARREO Project

Vahraz Jamnejad
Jet Propulsion Laboratory,
California Institute of Technology
Pasadena, CA 91109
818-354-2674
Vahraz.Jamnejad@jpl.nasa.gov

Ahmad Hoorfar
ECE Department
Villanova University
Villanova, PA, 19085
610-519-4436
ahoorfar@villanova.edu

Abstract—**the results of a preliminary study of the gain/pattern properties of a 6-element Radio Occultation (RO) array for the proposed CLARREO (Climate Absolute Radiance and Refractivity Observatory (CLARREO) Project. There are two array antennas at each observatory. Each array is attached to a vertical end of the spacecraft bus with the beam tilted to point towards the Earth's limb. The requirement is the attainment of a tilted beam with respect to the plane of the array with a maximized uniform coverage over a range of +/- 45 degree angles, namely a sector beam. The novelty of this array design is that it is non-uniform and non-planar and falls into the category of spatial arrays where the location and orientation of the array elements are variable. The beam shaping is performed, in general, by variation of a number of spatial and electronic phase and amplitude parameter. We reduce the number of required parameters by taking advantage of various symmetries. Then an overview of the analysis of such arrays is presented. Subsequently we use two approaches to the synthesis problem: one analytic and other a numeric global optimization method using a new evolutionary programming technique. The results for two designs with simultaneous near optimum performance at two different required GPS frequencies of L1 (1.575 GHz) and L2 (1.2 GHz) are presented.**

TABLE OF CONTENTS

1. INTRODUCTION

This paper presents the results of a preliminary study of the gain/pattern properties of a 6-element Radio Occultation (RO) array for the proposed CLARREO (Climate Absolute Radiance and Refractivity Observatory (CLARREO) Project. CLARREO is one of the 4 highest priority missions recommended in the National Research Council Earth Science Decadal Survey. It is an Earth Science mission that will provide the measurements needed to make informed decisions about responding to climate change. The foundation for CLARREO is on-orbit calibration that is traceable to international standards. This will provide the climate record required for: Long-term climate trend detection, Improvement and testing of climate, predictions and Calibration of operational and research sensors [1].

In one scenario, CLARREO will use two identical observatories in a 600 km orbit separated by 90 degrees in longitude of the ascending node (Figure 1). GNSS (Global Navigation Satellite Systems) receivers will use radio occultation (RO) to measure atmospheric refractivity through Doppler shifts. There are two array antennas (ram and wake orientations) at each observatory. Each array is attached to a vertical end of the spacecraft bus with the beam tilted to point towards the Earth's limb (Figure 2). The requirement is the attainment of a tilted beam with respect to the plane of the array with a maximized uniform coverage over a range of +/- 45 degree angles, namely a sector beam. The novelty of this array design is that it is non-uniform and non-planar and falls into the category of spatial arrays where the location and orientation of the array elements are variable. The beam shaping is performed, in general, by variation of location (three parameters), orientation angles (two parameters), as well as phase and amplitude of each element (two parameters), for a total of 7 parameters per element and a total of 42 parameters for the array. However, here we dictate the elements to be located on a plane but tiltable, and by symmetry considerations and other simplifications we reduce the total number of variable parameters for optimization and synthesis to just 3! We first present an overview of the analysis of such arrays. Then we use two approaches to the synthesis problem: one analytic and other a numeric global optimization method using a new evolutionary programming technique. We will present the results for two designs using the 3 suggested parameters with simultaneous near optimum results at two different required GPS frequencies of L1 (1.575 GHz) and L2 (1.2 GHz).

978-1-4577-0557-1/12/$26.00 ©2012 IEEE

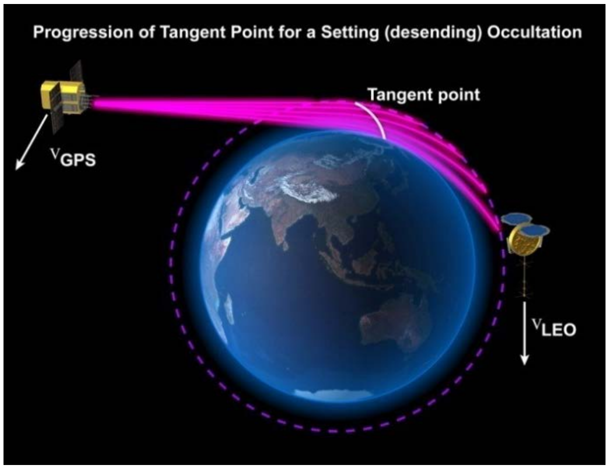


Figure 1 – The CLARREO orbit configuration

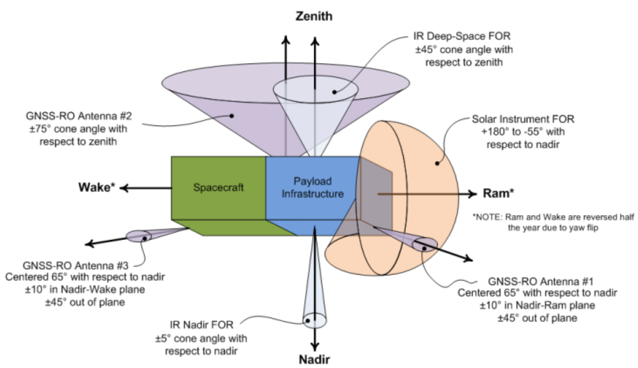


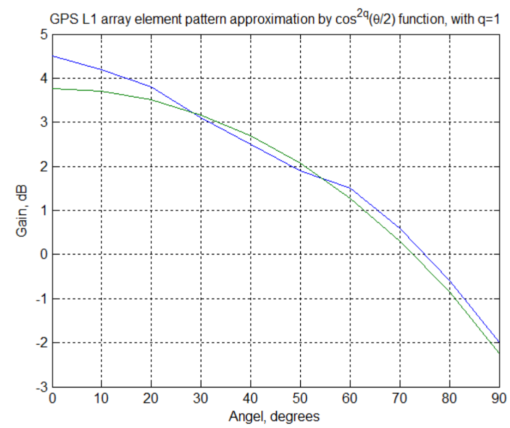
Figure 2 – The CLARREO spacecraft configuration

2. GPS ARRAY ELEMENT PATTERN APPROXIMATION

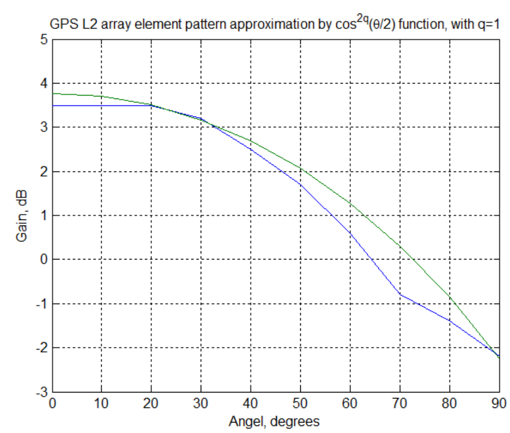
The element considered is the DM C146-13 GPS Antenna by AIL Systems Inc., NY. It has a hemispherical coverage and is omnidirectional in azimuth. It is a circularly polarized antenna with good CP performance with minimal axial ratio. The element size is approximately 13 cm in diameter.

We start with the approximation of element pattern by a simple rotationally symmetric cosine half angle model [$\cos^2 q(\theta/2)$]. We approximate the tested patterns by the cosine half angle with q=1 in a near least square approximation, as shown in Figures 4(a, b), for two frequencies of interest L1 (1.575 GHz) and L2 (1.2 GHz).

Figure 3 – A GPS antenna element (DMC146) by DM Antenna Technologies.



a) For L1 (1.575 GHz)



b) For L2 (1.2 GHz)

Figures 4(a, b) – Feed pattern approximation by $\cos^{2q}(\theta/2)$ approximation with q=1.

3. The Array analysis

Analysis of a General Array of Antennas

We have developed a program for the analysis of a general 3-D array of elements with identical elements but different orientations and different locations (in x, y, z space) using numerical integration [2]. A code is developed in MATLAB that implements the analysis in an easy to use format, with plotting capability and a simple graphical user interface. The computation engine of this program is used in the synthesis and optimization of the array, while the graphical user interface is used for plotting the filed. A discussion of the formulation and details of this program is beyond the scope of this paper and will be documented in another paper.

Formulation of the array problem

As shown in Figures 5 and 6, We desire to obtain maximum gain values in a plane that is tilted 30 degrees from broadside and covers the scan angle range α (-45 to 45 degrees). The actual polar angle θ and azimuth angle, ϕ, of the extreme scan positions are obtained from the formulas

$$\cos(\theta) = \cos(\theta_0)\cos(\alpha)$$
$$\tan(\phi) = \tan(\alpha)/\sin(\theta_0)$$

in which

θ_0 = central polar tilt angle

α = lateral coverage angle

θ = lateral polar tilt angle

And
$$\sin(\theta_0) = \frac{\sin(\theta)\cos(\phi)}{\sqrt{1-\sin^2(\theta)\sin^2(\phi)}}$$
$$\sin(\alpha) = \sin(\theta)\sin(\phi)$$

Thus for

θ_0=30° and α=±45°

we get

θ = 52.24° and ϕ = ±63.435°

For a planar representation of the spherical pattern we use the so-call [u,v] representation where u and v are defined as

U = sin(θ) cos(ϕ), v= sin(θ) sin(ϕ)

In this coordinate system the extreme scan positions are given as u=0.3535, v=±0.707

The variations of θ and ϕ, with and versus u and v for θ_0=30° and α in the scan range of 0 to 45 in different forms are presented in Figures 6(a, b, and c).

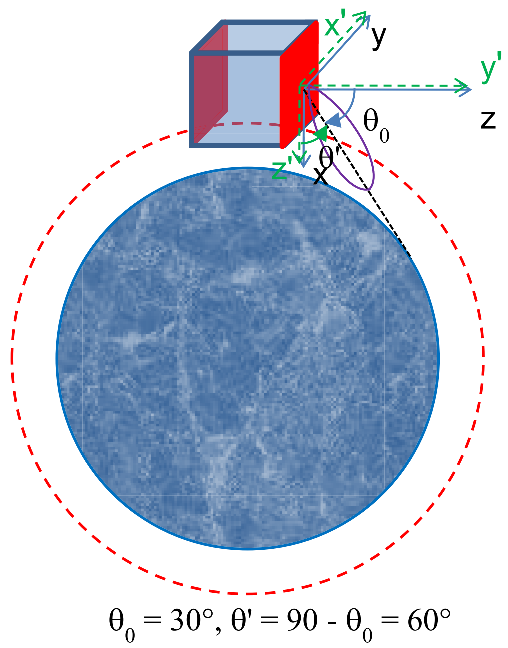


Figure 5 – Coordinate system and coverage angles in orbit.

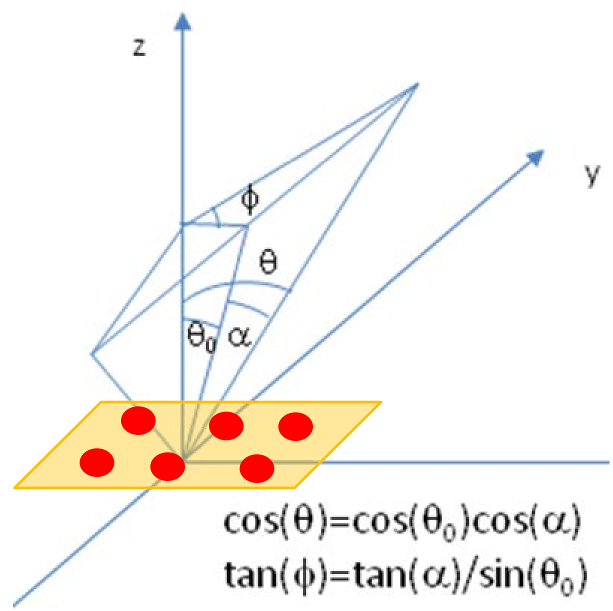


Figure 6 – Coordinate system and coverage angles.

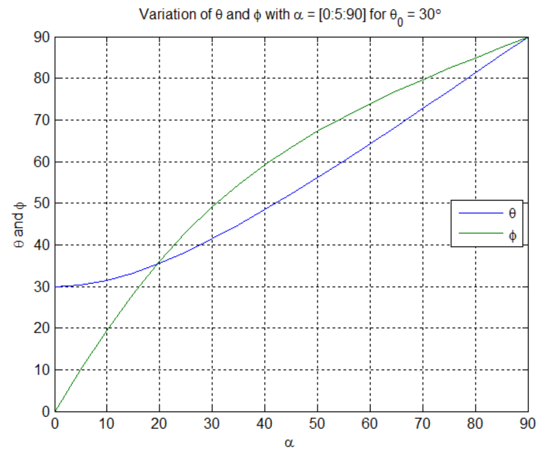


Figure 7(a) – Variations of θ and ϕ, for α=0-90° and θ_0=30°

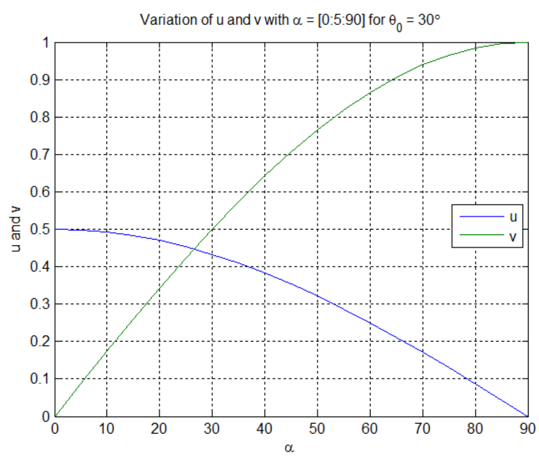


Figure 7(b) – Variations of u and v, for α=0-90° and θ_0=30°

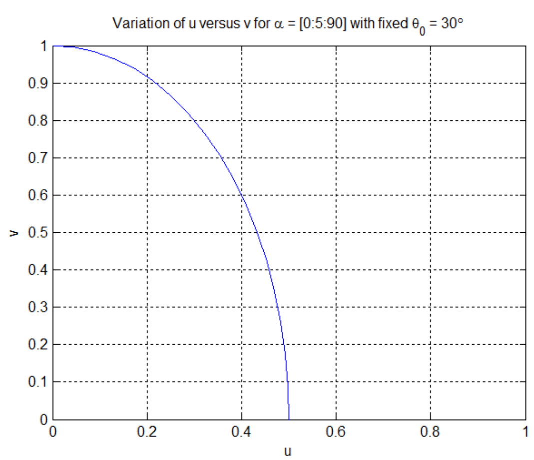


Figure 7(c) – Variations of u vs v for α=0-90° and θ_0=30°

4. The Array Synthesis

The study is performed on a spatial array of 6 identical elements which can in general vary in location, orientation, direction, amplitude and phase. Thus, in general, there are 6x7=42 parameters that can be varied in the synthesis procedure. However, in this study we dictate the elements to be located on a plane with fixed center positions but individually tiltable, and use symmetry considerations for a 2x3 arrangement of the elements with a fixed inter-element spacing of about half a wavelength, and spatial mirror symmetry of 3 elements with the other three (see fig. 6). Furthermore, we use a single electrical tilt angle for the phasing of the array which decides the phase of each element, and two identical mechanical angles (rotation and tilt) for three elements and their mirror images for the other mirror-symmetric elements. Thus, the total number of variable parameters is reduced to 3.

Analytic design procedure

Now, it would seem that a good point for getting the proper array pattern is to start with electrical phase scan of the array with a phase steering angle of 30°, and mechanical scanning of the elements by two positions (a subgroup of three using positive angle values and the other three using the negative values) defined by

θ_0=30° and α=±45°

Thus

θ = 52.24° and ϕ=±63.435°

Or

u=0.3535, v=±0.707

However, this turns out not to provide optimum values. In general, a thorough optimization will be needed to achieve the best results. However, by minor tweaking around these values we have been able to achieve two configurations that provide near optimum gain values for the range of θ_0=30° and α=±45°. Below, we provide the data and corresponding array patterns for two cases.

The two cases provide similar results. Case I emphasized higher gain at the central region at the expense of the loss of a few tenth of dB at the edges, while case II provides a more uniform gain across the region of interest.

Initially, the analysis was performed primarily for the 1.2 GHz (L2) band. However, subsequently, by minor adjustments, we were able to provide similarly good results at L2 as well as the L1 frequency (1.575GHz), by simply keeping the same fixed delay lines for each of the elements.

Note that we have added a 0.8 (0.97 dB) loss factor to all the gain values to account for the beam-forming loss, etc.

Case I - Near Optimum, symmetric case at L2=1.2 GHz

For θ_0=20° and α=±20° we get θ = 28.00° and ϕ=±46.78° ; array scan angle: 20.3°. The location of the elements and their orientation together with their phase and amplitude are given in the following Table.

x(cm)	y(cm)	z(cm)	ϕ	θ	γ	amplitude	phase
0.00	-7.500	0.00	-46.78	28.00	0.00	1.00	-0.00
0.00	7.500	0.00	46.78	28.00	0.00	1.00	-0.00
-15.00	-7.500	0.00	-46.78	28.00	0.00	1.00	-75.00
-15.00	7.500	0.00	46.78	28.00	0.00	1.00	-75.00
15.00	-7.500	0.00	-46.78	28.00	0.00	1.00	75.00
15.00	7.500	0.00	46.78	28.00	0.00	1.00	75.00

The graphic results are provided in Figures 8(a-e).

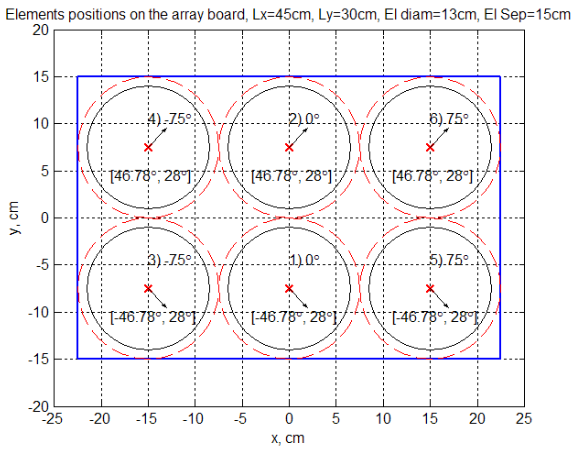


Figure 8(a) – Array elements parameter specification

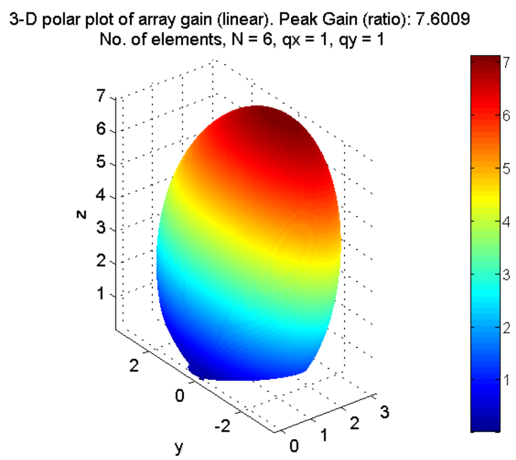


Figure 8(b) – 3D color representation of array gain pattern

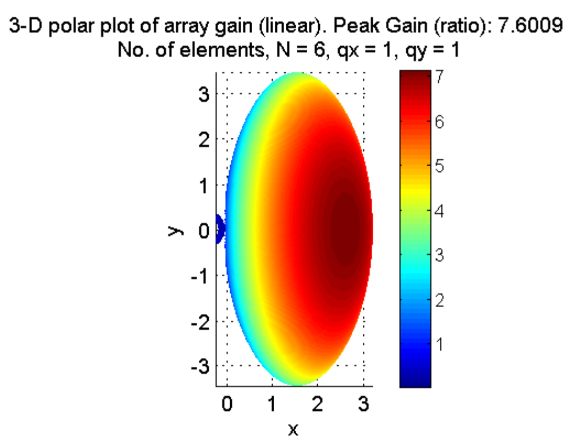


Figure 8(c) – Projection of array gain pattern on x-y plane

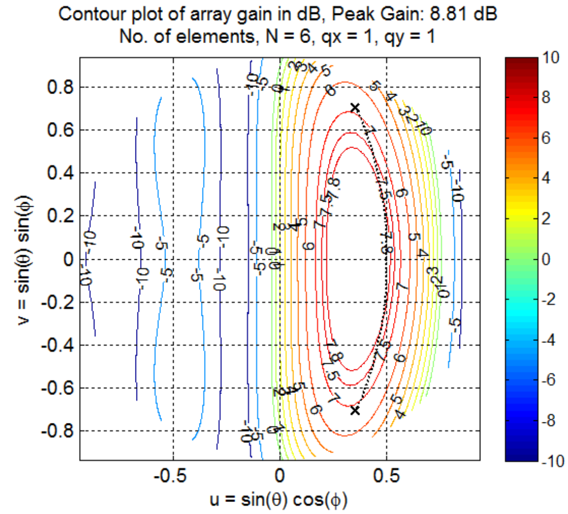


Figure 8(d) – [u, v] contour representation of array gain in upper hemisphere. Dotted curved line is for the scan direction

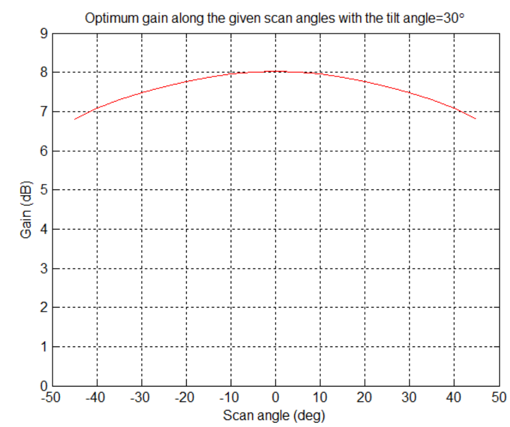


Figure 8(e) – Plot of gain values along the scan direction ($\theta = 30°$ and $-45.00° \le \phi \le +45.00°$)

.

Case II - Near Optimum, symmetric case at L2=1.2 GHz

For $\theta_0=30°$ and $\alpha=\pm 35°$ we get $\theta = 44.81°$ and $\phi=\pm 54.47°$; array scan angle: 20.3°. The location of the elements and their orientation together with their phase and amplitude are given in the following Table.

x(cm)	y(cm)	z(cm)	ϕ	θ	γ	amplitude	phase
0.00	-7.500	0.00	-54.47	44.81	0.00	1.00	-0.00
0.00	7.500	0.00	54.47	44.81	0.00	1.00	-0.00
-15.00	-7.500	0.00	-54.47	44.81	0.00	1.00	-75.00
-15.00	7.500	0.00	54.47	44.81	0.00	1.00	-75.00
15.00	-7.500	0.00	-54.47	44.81	0.00	1.00	75.00
15.00	7.500	0.00	54.47	44.81	0.00	1.00	75.00

Graphic results in this case are provided in Figures 9(a-e).

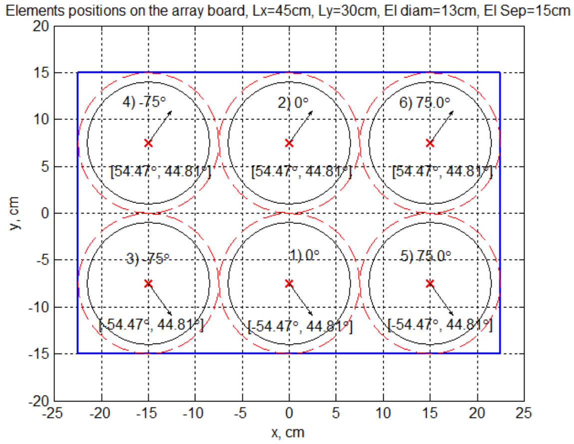


Figure 9(a) – Array elements parameter specification

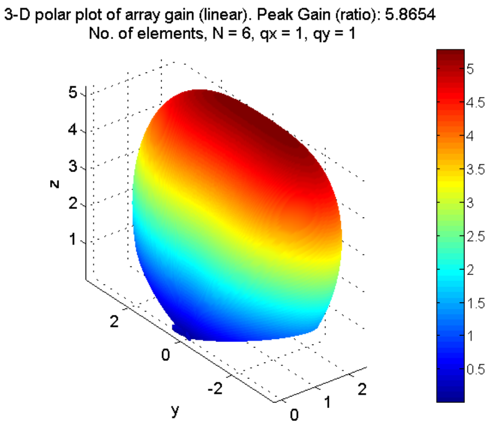


Figure 9(b) – 3D color representation of array gain pattern

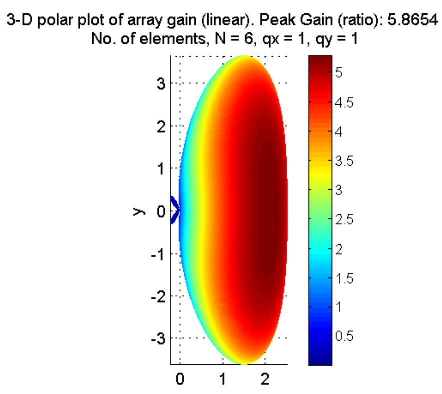


Figure 9(c) – Projection of array gain pattern on x-y plane.

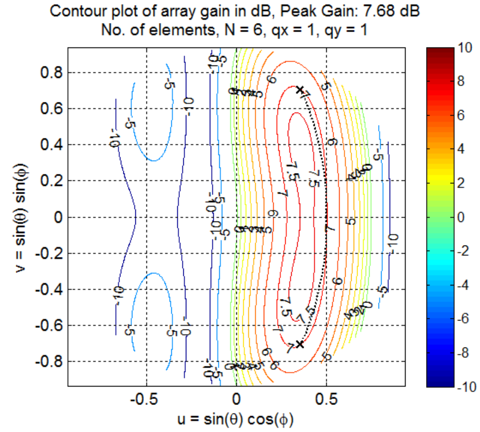


Figure 9(d) – uv contour representation of array gain in upper hemisphere. Dotted curved line is for scan direction.

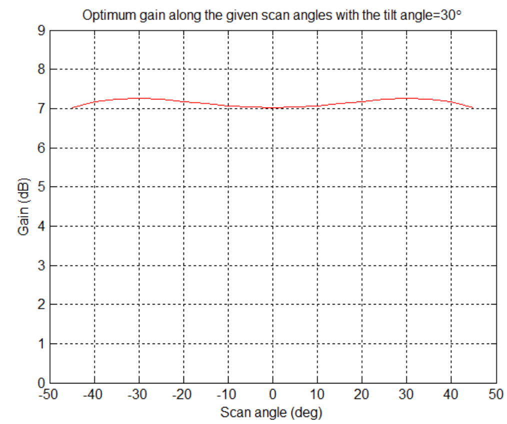


Figure 9(e) – Plot of gain values along the scan direction ($\theta = 30°$ and $-45.00° \leq \phi \leq +45.00°$)

A comparison of the gain results along the region of interest (θ_0=30° and α=-45° to 45°) is given in Figure 10. It includes results from another study with asymmetrically positioned elements.

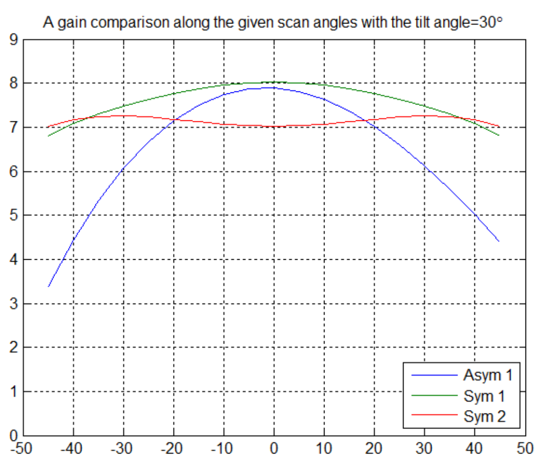


Figure 10 – A gain comparison along the scan region (θ = 30° and $-45.00° \leq \phi \leq +45.00°$) for the two symmetric cases and an asymmetric case from a previous study.

5. The Array optimization

Although near optimum results were obtained by observation and analytic tweaking, a formal optimization technique, such as, Monte Carlo method (MC), genetic algorithm (GA), or evolutionary programming (EP) can be applied to the problem to obtain possibly better results.

Here we use a new evolutionary algorithm based on Tukey-Lambda Probability Distribution. The methodology and details of this new optimization technique are discussed in other papers [3-5].

Here, we provide the data and corresponding array patterns for two symmetric configurations. Again, note that we have added a 0.8 (0.97 dB) loss factor to all the gain values to account for the beam-forming loss, etc.

A number of cases were considered including optimizing separately for L1 and L2 frequencies. If the elements are designed for one frequency, the results are better for the other frequency if the phase shifter is provided with delay lines such that the actual phase shift for the two cases are different. Still using optimization at one frequency and obtaining the results with the same parameters and delay line still do not provide as much improvement as simultaneous optimization at both frequencies. Here, we provide the results only for this case of simultaneous optimization.

In the optimization problems, the fitness function to be minimized is defined as:

$$Fitness = \sqrt{[G_{ave} - G(1)]^2 + [G_{ave} - G(2)]^2 + [G_{ave} - G(3)]^2} - G_{ave}$$

$$G_{ave} = [G(1) + G(2) + G(3)]/3$$

In which indices 1,2, and 3 refer to the start, middle and end points of the line of pattern coverage.

The optimization program is written in MATLAB and the run results are as follows:

- 4 runs at 50 generations each, requiring 49*36+1*42=1806 sample function evaluations
- The best Fitness Value is = -7.0617 obtained at run2
- The best average gain, Gave, is = 6.9818
- The best final 2 set(s) of gains are = 7.278 7.502 7.278 at L2 and 6.993 6.959 6.993 at L1
- The element tilt azimuth angle, ϕ_e, is = 52.5638°
- The element tilt polar angle, θ_e, is = 25.9189°
- The array wavefront scan angle, is = 23.5806°
- The total elapsed time of all runs is 36176.8503 seconds

Figure 11 shows the variation of fitness values versus number of evaluations, while figure 12 shows the total time of each of the four runs. The array parameters configuration and results for L2 (1.2 GHz) are shown in Figure 13(a-e), while the corresponding results for L1 (1.575) are shown in Figures 14(a-e). These results are by no means unique as is usually the case with global optimization techniques. But, as can be seen from Figures 13(e) and 14(e), they provide a very good optimized solution for this array problem.

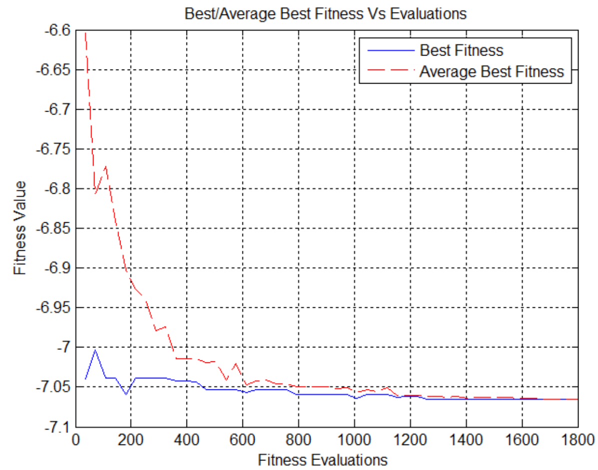


Figure 11 – Variation of fitness values versus number of evaluations

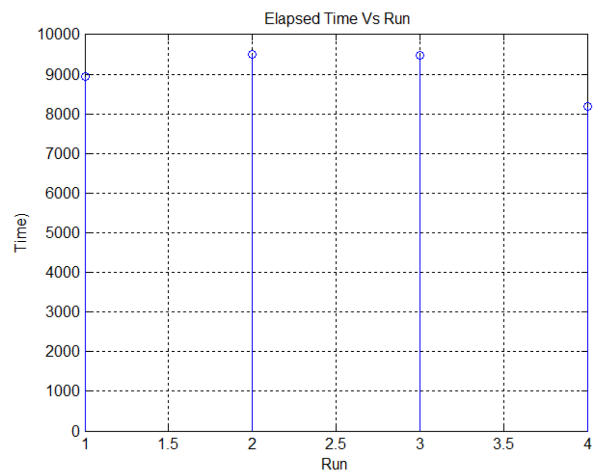


Figure 12– Computation times for different runs

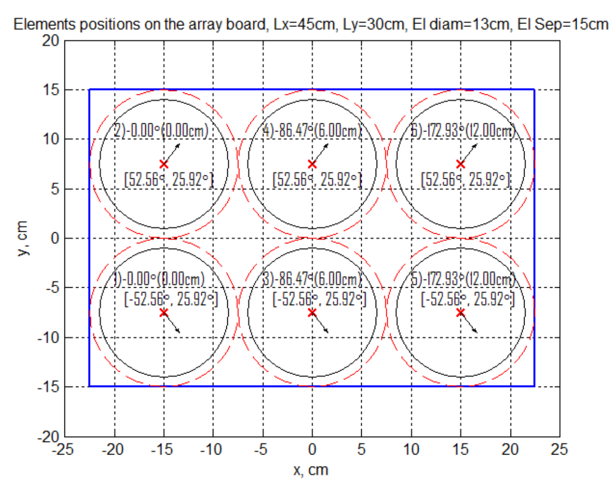


Figure 13(a) – Array elements parameter specification. Black circles indicates the size of the elements, Red circles indicate element separation. Both element phase shifts and delay lengths are given. Also shown are tilt azimuth and polar angles. For L2 (1.2 GHz)

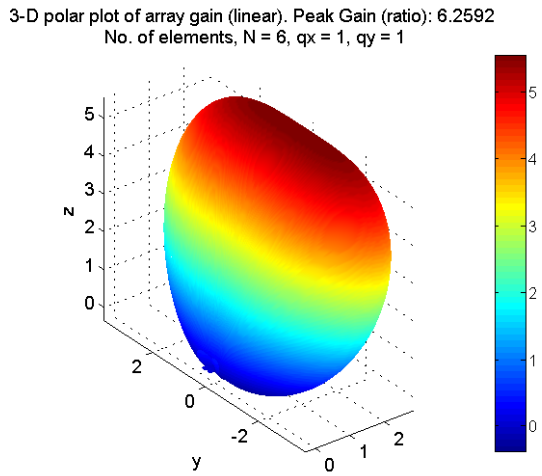


Figure 13(b) – 3D color representation of array gain pattern.

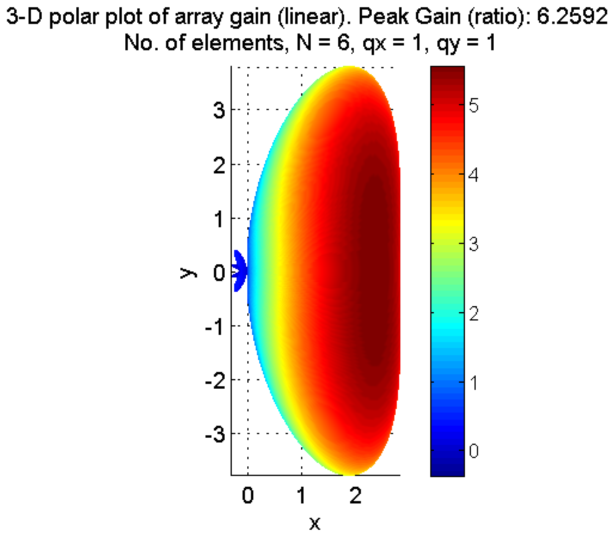


Figure 13(c) – Projection of array gain pattern on x-y plane

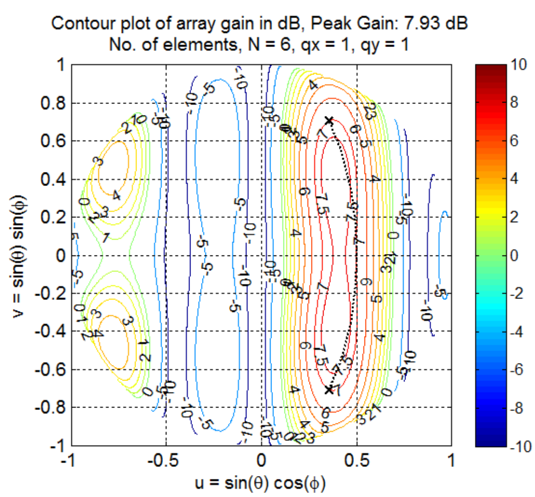


Figure 13(d) – The [u, v] contour representation of array gain in upper hemisphere. Dotted curved line is for scan direction

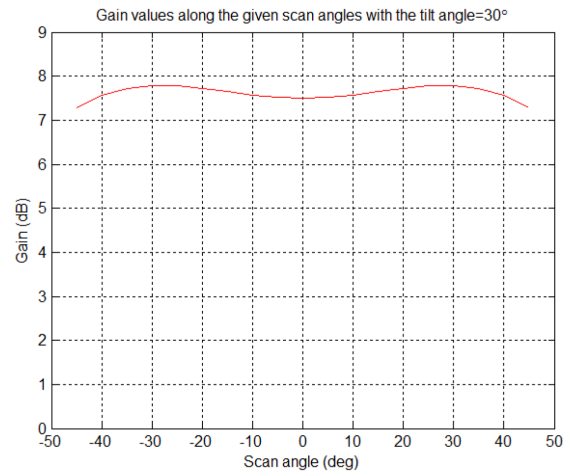


Figure 13(e) – Plot of gain values along the scan direction For L2 (1.2 GHz) (θ = 30° and -45.00° ≤ ϕ ≤ +45.00°).

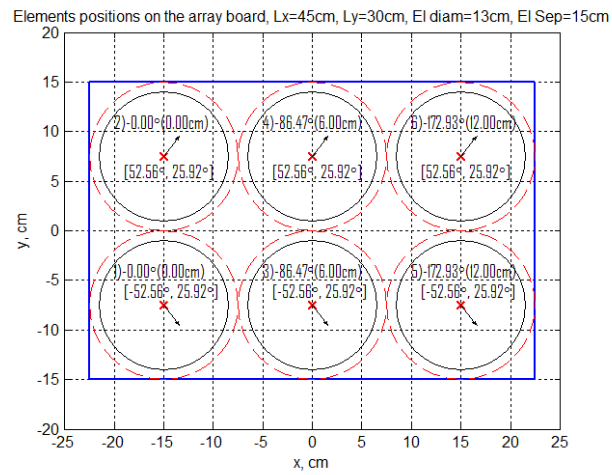


Figure 14(a) – Array elements parameter specification. Black circles indicates the size of the elements, Red circles indicate element separation. Both element phase shifts and delay lengths are given. Also shown are tilt azimuth and polar angles. For L1 (1.575 GHz)

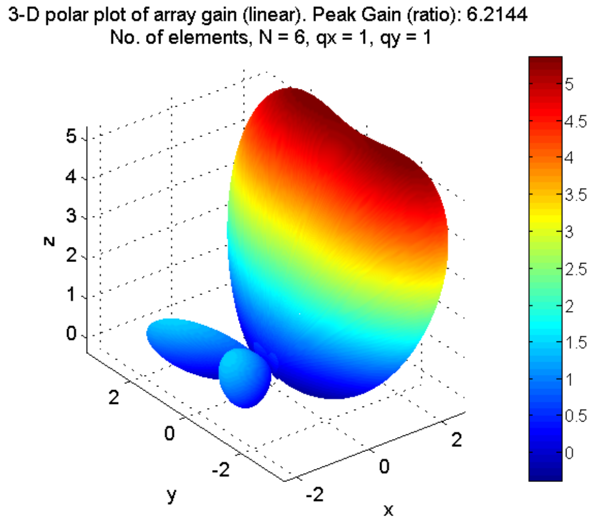


Figure 14(b) – 3D color representation of array gain pattern

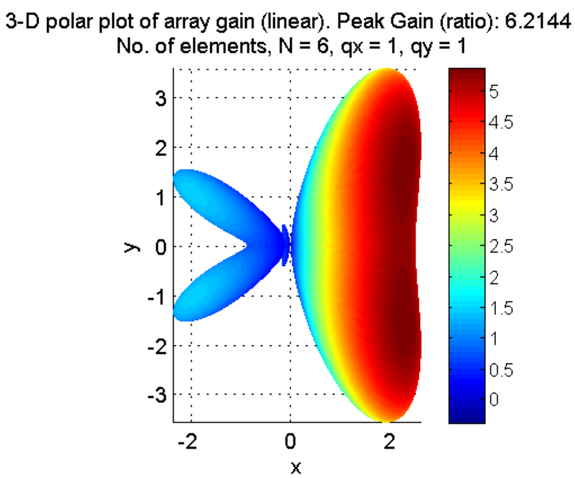


Figure 14(c) – Projection of array gain pattern on x-y plane

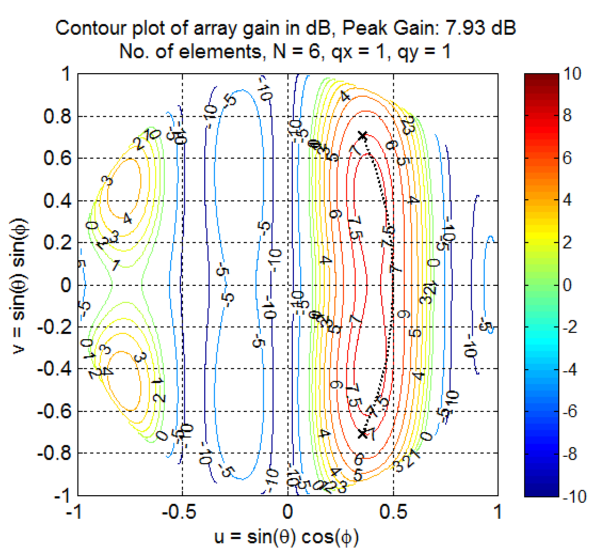


Figure 14(d) – [u, v] contour representation of array gain in upper hemisphere. Dotted curved line is for scan direction

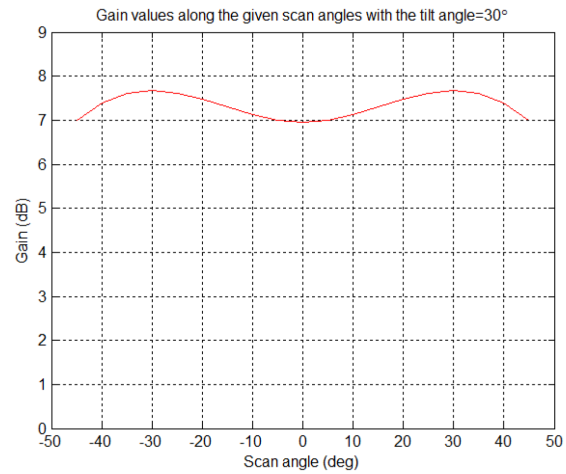


Figure 14(e) – Plot of gain values along the scan direction For L1 (1.575 GHz) (θ = 30° and -45.00° ≤ ϕ ≤ +45.00°).

6. SUMMARY AND CONCLUSIONS

We have shown in this work that it is possible to provide good solutions to some complicated beam-shaping problems of antenna arrays by utilizing all the parameters of interest, including the location and orientation of the array elements in addition to the customary phase and amplitude variations on planar array antennas. These additional degrees of freedom do provide means of accomplishing much better results. Specifically, we have provided a set of good solutions for the 6-element tilted-beam array meeting the requirements of the CLARREO project by allowing for simple tilt of the elements.

Furthermore, even though it is possible to take advantage of various analytic methods to tailor a good solution to array problems, the use of a good global optimization scheme can and does provide a better way for obtaining optimum or near-optimum results, albeit at a computational cost. However, these days with the advent of superfast multiprocessing desktop computers, the computational time and effort is relatively insignificant and are worth the additional improvements that can be obtained.

ACKNOWLEDGEMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors wish to thank Dr. Steve Lowe of JPL for helpful discussions and Dr. Larry Young of JPL for his valuable support.

REFERENCES

[1] Website, http://science.jpl.nasa.gov/projects/CLARREO

[2] V. Jamnejad, "Analysis of a general 3D array of antennas," JPL internal document, soon to be published.

[3] A. Hoorfar, "Evolutionary Programming in Electromagnetic Optimization: A review," IEEE Trans. on Antennas and Propagation, Vol. 55, No. 3, pp. 523-537, March 2007.

[4] V. Jamnejad, A. Hoorfar, "A New Evolutionary Technique Based On Tukey-Lambda Probability Distribution for Electromagnetic Optimization Problems," IEEE AP-S Symposium, Toronto, Canada, July 11-17.

[5] A. Hoorfar, V. Jamnejad, "Advanced Mutation Operator Design in Evolution Strategy Optimization of Electromagnetic Problems," IEEE AP-S Symposium, Spokane, Washington, July 3-8, 2011.

BIOGRAPHIES

Vahraz Jamnejad *is a principal scientist at the Jet Propulsion Laboratory, California Institute of Technology. He received his M.S. and Ph.D. in electrical engineering from the University of Illinois at Urbana-Champaign, specializing in electromagnetics and antennas. At JPL, he has been engaged in research and software and hardware development in various areas of spacecraft antenna technology and satellite communication systems. Among other things, he has been involved in the study, design, and development of ground and spacecraft antennas for future generations of Land Mobile Satellite Systems at L band, Personal Access Satellite Systems at K/Ka band, as well as feed arrays and reflectors for future planetary missions. His latest work on communication satellite systems involved the development of ground mobile antennas for K/Ka band mobile terminal, for use with ACTS satellite system. In the past few years, he has been active in research in parallel computational electromagnetics as well as in developing antennas for MARS sample return orbiter. More recently he has studied the applicability of large arrays of small aperture reflector antennas for the NASA Deep Space Network (DSN). He is also involved in the detailed study and analysis of the near field of large DSN antenna, the design of antennas for various spacecraft and the beam-wave guides and Quai-Optical Transmission Lines for science telescopes as well as ground observation radar antennas, and novel global optimization techniques applied to electromagnetic problems. Over the years, he has received many US patents and NASA certificates of recognition. He is a senior member of IEEE.*

Ahmad Hoorfar *is a professor of electrical and computer engineering at Villanova University, director of its Antenna Research Laboratory, and program director of the electrical engineering's graduate admission and advising. He received his B.S.E.E degree from the University of Tehran, Iran, in 1975 and the M.S. and Ph.D. degrees in electrical engineering from the University of Colorado at Boulder, in 1978 and 1984, respectively. His research contributions over the last twenty years cover areas in electromagnetic field theory, numerical modeling and novel designs of multifunction printed and low-profile antennas, metamaterial media and surfaces, through-wall microwave sensing and imaging, evolutionary computational methods, and antenna measurement techniques. Dr. Hoorfar was the chair of the joint Antennas and Propagation/Microwave Theory and Techniques (AP/MTT) Chapter of the IEEE Philadelphia Section from 1993 to 1996, and was the recipient of the 'IEEE chapter of the year award' for his leadership in chairing the AP/MTT joint chapter. In addition, he was the general chairman of the 12th and 13th Annual Benjamin Franklin Symposiums in Microwave and Antenna Technology held in 1994 and 1995, and co-organizer of the 22nd Antenna Measurement Technique Association (AMTA) Symposium held in Philadelphia in October 2000. Dr. Hoorfar spent his sabbatical leaves in 2002 and 2009 at the NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, where he contributed to the development of various electromagnetic optimization codes for design of feed horns, dual reflector systems, and antenna arrays. He is a senior member of IEEE and a member of the International Union of Radio Science (URSI), Commission B.*