Progress In Electromagnetics Research C, Vol. 20, 1–15, 2011

A SIMPLE STRATEGY TO TACKLE MUTUAL COUPLING AND PLATFORM EFFECTS IN SURVEILLANCE SYSTEMS

G. Bernardi, M. Felaco, and M. D'Urso

SELEX Sistemi Integrati
Via Circumvallazione Esterna di Napoli
Zona ASI, Giugliano, Napoli I-80014, Italy

L. Timmoneri and A. Farina

SELEX Sistemi Integrati
Via Tiburtina, km 12.400, Roma I-00131, Italy

E. F. Meliadò

OPTEL, Consorzio Nazionale di Ricerca per le Tecnologie
Optoelettroniche dell'InP
Via Circumvallazione Esterna di Napoli
Zona ASI, Giugliano, Napoli I-80014, Italy

Abstract—This paper presents an optimal power pattern synthesis procedure able to tackle the mutual coupling and platform effects even for electrically large arrays. The novelty of the approach is due to its capability to account in the synthesis procedure for two different aspects at the same time: the coupling between the array radiating elements and the coupling between these elements and the array platform. The mutual coupling evaluation is based on the active element pattern method, and the active element pattern is numerically computed. The kind of synthesis problems here addressed belongs to the class of convex optimization problems. Therefore, the solution is found by means of very efficient convex programming tools, without requiring global optimization schemes, thus saving time and costs. The extension of the overall tool to adaptive arrays is also considered.

Received 30 November 2010, Accepted 9 February 2011, Scheduled 17 February 2011
Corresponding author: Gabriella Bernardi (gbernardi@selex-si.com).

1. INTRODUCTION

Today's radar systems are required to fulfill hard pattern specifications, i.e., extremely high gains in certain directions and accurate jammer rejection. An example of radar systems that require these particular pattern properties is represented by passive surveillance radars [1]. Since the interest in such application is currently increasing, this contribution is focused on the techniques to be used in order to obtain the above mentioned pattern requirements specified for passive radar systems. These properties can be in principle achieved by appropriate array synthesis techniques. In the last years, in fact, a large number of techniques have been investigated, but most of the obtained results miss some desired requirements, as in the following highlighted.

The basic idea of passive radar systems is to conveniently exploit opportunity signals, like analogue FM transmitters or Digital Video Broadcasters to detect and track targets [2–4]. As a consequence, the costs are significantly reduced respect to active radar systems [5, 6], and the environmental impact is minimized.

Such systems require the suppression of the signal coming from the illuminator of opportunity, because this is stronger than the signal scattered from the target in the passive radar direction. The incident wave, in fact, is usually scattered in all the directions but it is received only in the direction of the radar respect to the target. This means that *ad hoc* designed patterns have to be synthesized, able to maximize the gain in the target direction and to reject both the transmitter signal (always present, also in the *quiescent* scenario) and eventual dynamic jamming sources that can rapidly affect the environment noise characterization [7].

The formulation of the synthesis problem requires to determine the antenna structure and the excitations such that the obtained pattern satisfies the desired assigned specifications. This problem has been widely studied and it has been modeled as an optimization problem. Among the approaches most used to solve this class of problems, global algorithms have become particularly popular, like, for instance, Particle Swarm (PS) and adaptive genetic algorithms [8–10]. At least in principle, these techniques can reach optimal performance, paid by a great computational effort, not always affordable. Other methods, based for example on minimum distance algorithms or the alternate projection method or some variants of the traditional synthesis techniques [11, 12], are also available in literature; these methods are less time-consuming then the previous ones but do not reach the best achievable performance. In this paper, instead, the quiescent pattern synthesis problem has been recast as the solution of a

Convex Programming (CP) [13–15] problem, thus completely avoiding the usage of global optimization schemes. The convexity property, in fact, assures that the optimum is unique and the solution, found with the more efficient local search algorithms, is certainly the global optimum.

Since the goal of this work is to provide useful tools able to give optimal and, at the same time, practical solutions for the passive radar beamforming, it is also crucial to consider, in the synthesis procedure, some non-ideal effects that significantly change the radiating system properties: the mutual coupling between the array elements [16] and the coupling with the array platform.

The most of the efforts have been made so far to compensate the mutual coupling effects between the array elements. They have been included in the synthesis procedure by means of different mutual coupling evaluation methods: the *pattern multiplication* [17]; *fully numerical* techniques; *active element patterns* approach [18–21].

The *pattern multiplication* method can be applied to radiating element that are affected by mutual coupling only on their active input impedance but not on the shape of their current distributions. In this case the complete pattern can be computed starting from the knowledge of the active element input impedances. An array of half-wave dipoles is one example of such an array. In fact, it is possible to predict accurately the array performance by introducing the coupling matrix [22, 23]. Unfortunately, the computation of the coupling matrix is not easy when the half-wave dipoles are mounted on complex platforms. In this case, in fact, *fully numerical* techniques can be used for mutual coupling evaluation. Again, if the platform is very complex, or electrically large, fully numerical techniques also fail, because of the too intensive computational approach [22]. The *active element patterns* method, instead, uses measured or numerically computed patterns of the individual elements in presence of the array and platform and stores these quantities for the subsequent overall pattern computation. This approach is often preferable, and is in fact adopted also in this contribution, because it is less time consuming then the fully numerical techniques and not approximated [22] (there is still an approximation due to the numerical technique employed to compute the active individual element pattern, but it is the same of the fully numerical techniques). Today, several commercial solvers are available that can help to carry out numerical computations as much accurately as possible even when electrically large structures [24, 25] are involved. Up to now, in fact, the platform effects have been usually neglected [26]. In few cases this problem has been dealt with [27–29], but the adopted synthesis techniques are questionable since, as before explained, make usage of global schemes for the optimum research thus not exploiting the convexity properties and increasing, without need, the computational burden.

Finally, the above mentioned considerations are also included in an adaptive null synthesis procedure, in order to show the potentiality of the proposed approach for all the realistic operation modes of a passive radar.

The paper is organized as follows: in the second section the mathematical formulation of the synthesis problem is explained. In particular, the standard CP problem and adaptive procedure are briefly presented together with their variants based on the active element pattern method. The third section provides some numerical results of presented tool as applied to a realistic study case. Conclusions are finally drawn.

2. MATHEMATICAL FORMULATION

The mathematical formulation of the problem is discussed in this section. The synthesis problem has been divided into two sub-problems: the synthesis of the quiescent pattern, and the adaptive null synthesis. These two problems have been faced by means of different algorithms that are discussed in the following two subsections respectively.

2.1. Synthesis of the Quiescent Pattern

In this subsection the mathematical formulation of the quiescent pattern synthesis technique is formally defined. The quiescent pattern is the pattern required to a passive radar system when no jamming sources are present in the environment. This means that the scenario is deterministic, because only the interference of the transmitter of opportunity (whose direction is well-known) is present and has to be suppressed. Therefore, the requirement is to maximize the power received in the spatial region where the target can be (the surveillance region) and to contain it under a desired threshold in the direction of the transmitter. Such a problem can be classified like a masked power pattern synthesis problem [15, 30]. This belongs, in particular, to the class of *convex problems*; this class of problems have been so far addressed without accounting for the mutual coupling effects. In the following, instead, a novel convex synthesis is presented that includes the coupling effects compensation.

For a fixed array geometry, synthesizing the sum power pattern means finding the (complex) excitations that maximize the radiated power in a desired direction (target direction) assuring, at the same time, specified low level of radiated power in the other directions. Since the objective function is represented by the radiated power, the field phase in the target direction is a degree of freedom of the synthesis problem that can be used to make the objective function convex, as specified in the following.

Assumed that a reference system is chosen (see [13, 14, 30] for details), the array pattern can be introduced:

$$E(\theta,\phi)=\sum_n E_n(\theta,\phi)=\sum_n l_n I_n; \tag{1}$$

the objective function, to be maximized in the target direction (θ_0,ϕ_0), is:

$$f_{obj}=|E(\theta,\phi)|^2_{(\theta=\theta_0,\phi=\phi_0)}; \tag{2}$$

where

- E_n is the field radiated by the nth element
- l_n is the n-th unit-excitation active element pattern, that contains all the effects of the platform and mutual coupling [22];
- I_n is the complex excitation of the n-th radiating element;

As above mentioned, the objective function (2) can be appropriately modified to be considered a convex function. In fact, since the radiated power in a given direction is not affected by the phase of the array pattern in the same direction, the pattern in the target direction can be considered a real quantity. In this hypothesis the objective function exhibits a linear dependence on the unknowns (the complex excitations of the radiating elements) thus being a convex function; the optimization is subject to constraints that define a convex set too,

$$\begin{cases} G_1(X)\le C_1, \\ \dots \\ G_m(X)\le C_m. \end{cases} \tag{3}$$

Therefore the complete mathematical formulation of the problem can be finally written as follows:

$$\mathrm{Max}_{(I_1,\dots,I_n)}\mathrm{Re}\big(E(\theta_0,\phi_0)\big) \tag{4}$$

subject to the constraints:

$$\mathrm{Im}(E(\theta_0,\phi_0))=0, \tag{5}$$

$$|E(\theta_i,\phi_i)|^2\le \mathrm{UB}(\theta_i,\phi_i)\quad i=1\dots M. \tag{6}$$

where:

- $((\theta_0, \phi_0), \ldots, (\theta_M, \phi_M))$ are the directions of the discretized space.
- $\mathrm{UB}(\theta_i, \phi_i)$ is the desired power threshold in the i-th direction.

As anticipated, this synthesis procedure accounts for the electromagnetic coupling between the radiating elements and the platform by means of the active element pattern approach. The core of the presented procedure lies in the role played by the pattern of each radiating element appearing in the array factor defined by Eq. (1). In fact, by feeding one antenna of the array with unitary excitation it is possible to evaluate the effect of the platform and radiative mutual coupling [22] on each array antenna and then, by simple superposition, on the whole array. In this work the active element pattern evaluation has been made by using a commercial numerical solver, CST [24], that allows to compute the field even for electrically large structures. This obviously requires the CAD modeling of the specific structure and an appropriate tradeoff between the desired accuracy and the available computation time.

2.2. Adaptive Nulling

An adaptive array is capable to detect the direction of arrival of a jamming source and to suppress the interference realizing a spatial filtering based on the synthesis of a retrodirective receive beam in the jammer direction to be substracted from the original pattern [31]. In this paper the quiescent scenario, given from the sole interference of the illuminator of opportunity, is obtained by the pattern synthesis technique explained in the previous subsection. In this subsection, instead, the procedure to suppress additional dynamic interference sources is briefly recalled. In particular, for a narrowband array the scalar output s_k is given by the linear combination of the sampled inputs c_k multiplied by the complex weights w_k, as follows:

$$s_k = c_k^H \cdot w_k \tag{7}$$

with:

$$c_k = [c_{0,k}, c_{1,k}, c_{2,k}, \ldots, c_{N-1,k}]^T, \tag{8}$$

$$w_k = [w_{0,k}, w_{1,k}, w_{2,k}, \ldots, w_{N-1,k}]^T \tag{9}$$

where H denotes the Hermitian transpose.

The vector of the optimal weights can be found as [7]:

$$w_k = R_{cc}^{-1} \cdot r_{cp} \tag{10}$$

where R_{cc} is the input correlation or covariance matrix and r_{cp} is the cross correlation matrix between the desired signal and the received signal.

In the case of interest of this paper the jamming sources are stationary and uncorrelated; the process, therefore, only needs enough time to allow the estimation of R_{cc} and r_{cp}. Then R_{cc}^{-1} is computed, and the optimum weight vector is found [32].

In order to obtain the suppression of the added dynamic sources without loosing the quiescent pattern performance (that is the desired side lobe level and the transmitter signal suppression), the optimal weights found in Eq. (10), have to be combined with the optimal weights found for the quiescent pattern. In this case the estimation of R_{cc} and r_{cp} has to consider at each element of the array, the amplitude and phase of the incident wave weighted by the excitation set found by *CP* programming, as before explained. There are in literature significant adaptive nulling scheme that guarantee reduced computational costs [33–35]; in this work, anyway, the focal point is not the particular adaptive scheme, but the possibility to insert the *active element CP-based synthesis* previously explained in the framework of the PCL application, where it is used to obtain the starting point of the dynamic jamming suppression, that is the optimum quiescent scenario.

3. NUMERICAL EXAMPLES

In this section a quantitative example relative to the described procedure is reported. The geometry of the system is described in Subsection 1. Two different results are reported in Subsection 2: the first does not account for the coupling effect, i.e., it has been obtained by means of the standard convex programming procedure; the second one, instead, has been obtained by means of the proposed active element pattern synthesis, thus highlighting the difference between the performance achievable with or without the presented method. This is also included into the adaptive nulling technique, and the results are finally showed.

3.1. Geometry Description

In this subsection the method above presented is applied, as mentioned in the introduction, to meet the requirements of a circular passive radar. The antennas are half-wavelength dipoles positioned on a circle, see Figure 1, supported by steel arms of a lattice steel structure 2.5 meters high displayed in Figure 2.

In this configuration, the mathematical expression of the array pattern on the azimuthal plane becomes:

$$AP\left(\theta=\frac{\pi}{2},\phi\right)=\sum_{n} I_n l_n \exp(-j\beta R\cos(\phi-\phi_n)), \tag{11}$$

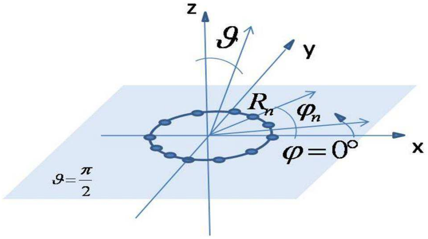

Figure 1. Circular array scheme.

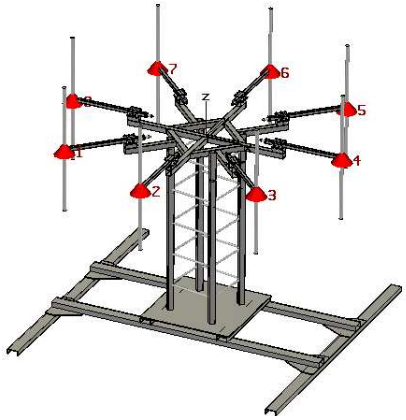

Figure 2. Circular array mounted on its platform.

where:

- R is the distance of each radiating element from the origin of the reference system, i.e., the circle radius.
- ϕ_n is the angular position of the n-th radiating element.

It is worth to note that the array platform has not a circular symmetry; this means, as it can be read in the next section, that the structure affects differently each radiating element pattern.

3.2. Synthesis Results

In this subsection a practical example of passive radar beamforming is here reported. In particular, the requirements are related to the plane $\theta = \pi/2$. The target is expected in a sector 80 deg wide; as a consequence in this region of the space the received power has to be maximized. The transmitter is positioned at 180 deg respect to the center of the surveillance region. Summarizing, the quiescent pattern, i.e., the time-invariant pattern, presents the maximum between −40 deg and 40 deg and a deep null at −180 deg. In addition to these static pattern properties, appropriate nulls are dynamically realized, depending on the presence of interference jamming sources, by means of the adaptive nulling technique above presented. In order to highlight the strength of the proposed method, the results of its application to a case of interest are in this subsection showed and compared to the ones obtained applying the traditional convex synthesis procedure (i.e., without accounting for the coupling effects).

To this aim, the isolated dipole far-field is used in the standard synthesis procedure, and is depicted in Figure 3. The results of the standard convex synthesis of the ideal array without any coupling effect are showed in Figure 4. These results, however, are not applicable because the effects of the structure are not negligible and can change significantly the achievable performance; this is visible clearly by looking at the single element far-field pattern, as affected by the presence of the other antennas and the platform, showed in Figure 5. What would be measured applying to the actual structure the weights found at the previous step, is showed in the Figure 6. As it can be seen, there is a strong difference and loss of performance respect to the ideal case. Therefore, it appears obvious that taking into account of the coupling effects in the beamforming is crucial. What can be in fact

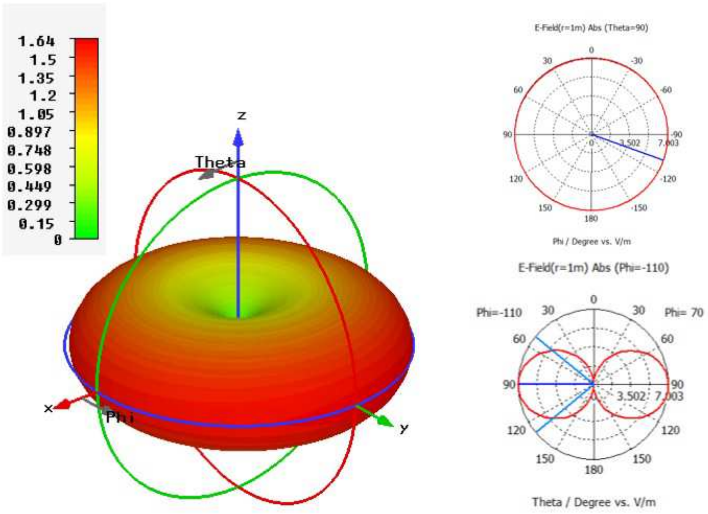

Figure 3. One half-wavelength isolated dipole.

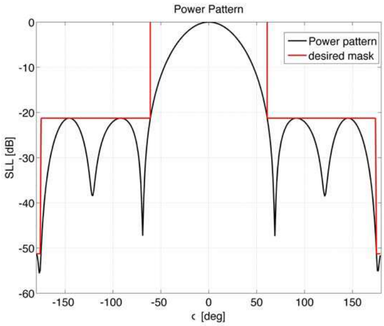

Figure 4. Standard convex synthesis of the ideal array without any coupling effect.

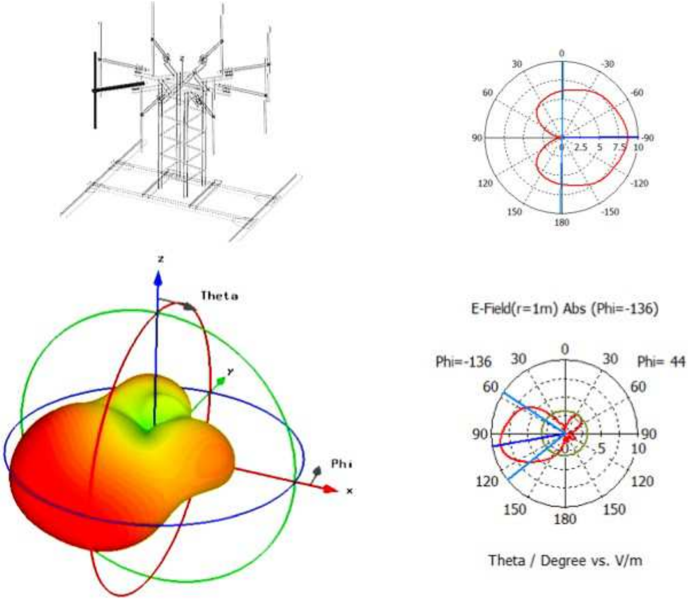

Figure 5. One half-wavelength dipole (the dark element) mounted on the platform (transparent).

obtained by means of the proposed procedure is showed in Figure 7, where an improvement respect to the ideal case in the performance can be also observed. It is worth to note that the active element patterns have to be evaluated once the radar installation configuration has been designed. This operation can be really time-consuming, depending on the array dimension, but it has to be done only one time. Then, the synthesis procedures (both quiescent and adaptive) use the evaluated patterns and reach the goals in few seconds (~ 0.5 sec for the quiescent pattern and less then 0.05 sec for the adaptive nulling) in a MATLAB environment, on a dual quad-core 64 bit Intel processor, 2.5 GHz, 8 GB RAM.

These encouraging results have been included successfully in the adaptive nulling framework as clearly visible in Figure 8. It is worth to note that the adapted pattern does not respect the mask, i.e., the graphic representation of the constraints set in the convex problem defined in Section 2.1. This is not surprising because, differently from the CP procedure, the weights found by the adaptive processing represent the solution of an unconstrained problem. However, as visible

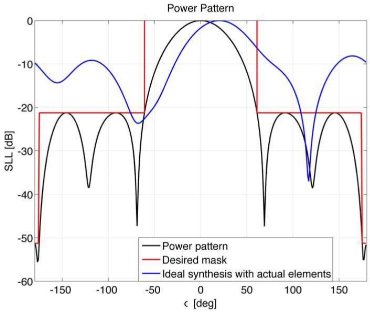

Figure 6. Results of the standard convex synthesis applied to the actual structure.

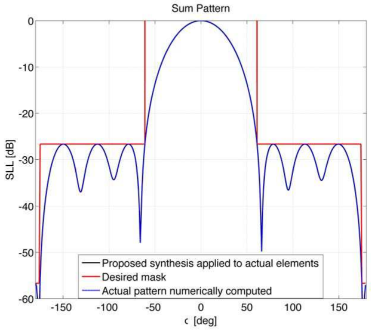

Figure 7. Results of the active element pattern synthesis applied to the actual structure.

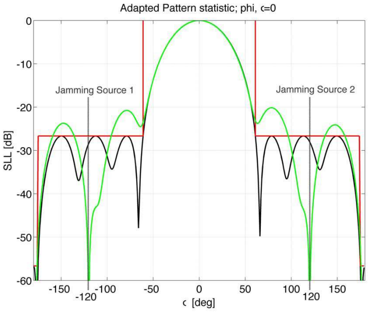

Figure 8. Results of the active element pattern synthesis applied to the actual structure included in the adaptive nulling framework.

in the picture, this effect is not particularly critical. In fact, the performance of a PCL has to be evaluated considering at the same time several aspects, such as the maximization of the radiated power in the direction of interest, the maximization of the jammer rejections and, of course, the capability to process in real time the received signals. The strategy here proposed is derived from a trade-off among the cited aspects. In particular, the adapted pattern is not too far from the mask, mainly in the null regions, and the CP based synthesis method takes more time than the adaptive procedure. Therefore, it is convenient, to not compromise the real time processing, using for the jammer rejection the faster adaptive procedure accepting the slight degradation of the quiescent pattern.

4. CONCLUSIONS

This paper shows the effectiveness of a power pattern synthesis method based on convex programming theory. Several kinds of array synthesis problems such as narrow beams, scanned single and multiple beams, interferences rejection have been faced, and some of them have been applied to the case of interest here proposed. The good results achieved are shown. The strength of the used method is its flexibility respect to the array geometry. In this work a circular array has been considered but the method can be easily extended to arbitrary geometries and can be therefore applied to the case of conformal array. The model takes into account the mutual coupling effects between the radiators of the array and the array platform in a convex programming framework. These effects have been evaluated by means of a 3D full wave simulator and compensated with a convex synthesis procedure, that guarantees to reach the global optimum in a very short time.

REFERENCES

1. Fabrizio, G., F. Colone, P. Lombardo, and A. Farina, "Passive radar in the high frequency band," *2008 IEEE Radar Conference*, Rome, Italy, May 26–30, 2008.
2. Malanowski, M. and K. Kulpa, "Digital beamforming for passive coherent location radar," *2008 IEEE Radar Conference*, 1–6, Rome, May 26–30, 2008.
3. Griffiths, H. D. and C. J. Baker, "Passive coherent location radar systems, part 1: performance prediction," *IEEE Proceedings — Radar, Sonar and Navigation*, Vol. 152, 153–159, June 3, 2005.
4. Poullin, D. and M. Flecheux, "Recent progress in passive coherent

location (PCL) concepts and technique in France using DAB or FM broadcasters," *2008 IEEE Radar Conference*, 1–5, Rome, May 26–30, 2008.

5. Skolnik, M. I., *Introduction to Radar Systems*, 3rd edition, McGraw-Hill Science Engineering, 2003.
6. Skolnik, M. I., *Radar Handbook*, 3rd edition, McGraw-Hill Professional, 2008.
7. Farina, A., *Antenna-Based Signal Processing Techniques for Radar Systems*, Artech House, Boston, London, 1992.
8. Brooker, E., *Practical Phased Array Antenna Systems, Part 2, Antenna Array Fundamentals*, Artech House Inc., Norwood, MA, 1991.
9. Demarcke, P., H. Rogier, R. Goossens, and P. De Jaeger, "Beamforming in the presence of the mutual coupling based on constrained particle swarm optimization," *IEEE Transactions on Antennas and Propagation*, Vol. 57, 1655–1666, 2009.
10. Hill, D. A., "A numerical method for near-field synthesis," *IEEE Trans. Electromgnetic Compatibility*, Vol. 27, No. 4, 201–211, November 1985.
11. Fenn, A. J., C. J. Diederich, and P. R. Stauffer, "An adaptive-focusing algorithm for a microwave planar phased-array hyperthermia system," *Lincoln Lab. J.*, Vol. 6, No. 2, 269–288, 1993.
12. Fenn, A. J., "Evaluation of adaptive phased array antenna far field nulling performances in the near field region," *IEEE Transactions on Antennas and Propagation*, Vol. 38, No. 2, 173–185, November 1990.
13. Isernia, T. and G. Panariello, "Optimal focusing of scalar fields subject to arbitrary upper bounds," *Electronic Letter*, Vol. 34, No. 2, 162–164, January 1998.
14. Bucci, O. M., L. Caccavale, and T. Isernia, "Optimal focusing of uniformly spaced arrays subject to arbitrary upper bounds in nontarget directions", *IEEE Transactions on Antennas and Propagation*, Vol. 50, No. 11, 1539–1554, November 2002.
15. D'Urso, M. and T. Isernia, "Solving some array synthesis problem by means of an effective hybrid approach," *IEEE Transactions on Antennas and Propagation*, Vol. 55, No. 3, 750–759, March 2007.
16. Balanis, A.C., J. Glen, and P. Jameson, *Antenna Theory: Analysis and Design*, J. Wiley & Sons, New York, Chichester, Brisbane, Toronto, Singapore, 1997.
17. Oliner, A. A. and R. G. Malech, "Mutual coupling in infinite

scanning arrays," *Microwave Scanning Antennas*, 195–335, R. C. Hansen, Academic Press, New York, 1996.

18. Allen, J. L., "Gain and impedance variation in scanned dipole arrays," *IEEE Transactions on Antennas and Propagation*, Vol. 10, 556–573, September 1962.
19. Aumann, H. M., A. J. Fenn, and F. G. Willwerth, "Phased array antenna calibration and pattern prediction using mutual coupling measurements," *IEEE Transactions on Antennas and Propagation*, Vol. 37, 844–850, July 1989.
20. Parad, L., "Some mutual impedance effects in phased array," *Microwave J.*, Vol. 5, 87–89, June 1962.
21. Wasyikiwsyj, W. and K. Kahn, "Element patterns and active reflection coefficient in uniform phased arrays," *IEEE Transactions on Antennas and Propagation*, Vol. 22, 207–212, March 1974.
22. Kelley, D. F. and W. L. Stutzman, "Array antenna pattern modeling methods that include mutual coupling effects," *IEEE Transactions on Antennas and Propagation*, Vol. 41, No. 12, 1625–1632, December 1993.
23. Huang, Z., C. A. Balanis, and C. R. Birtcher, "Mutual coupling compensation in UCAs: Simulations and experiment," *IEEE Transactions on Antennas and Propagation*, Vol. 54, No. 11, 3082–3086, November 2006.
24. CST Microwave — website: http://www.cst.com
25. HFSS Ansoft — website: http://www.ansoft.com
26. Caccavale, L., T. Isernia, and F. Soldovieri, "Methods for optimal focusing of microstrip array antennas including mutual coupling," *Microwave Antennas and Propagation, IEE Proceedings*, Vol. 147, No. 3, 1350–2417, June 2000.
27. Su, T. and H. Ling, "Array beamforming in the presence of a mounting tower using genetic algorithms," *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 6, 2011–2019, June 2005.
28. Su, T. and H. Ling, "A model for the active element pattern of array elements including both mutual coupling and platform effects," *IEEE International Symposium on Antennas and Propagation Society*, Vol. 4, 2130–2133, 2000.
29. Obelleiro, F., L. Landesa, J. M. Taboada, and J. L. Rodriguez, "Synthesis of onboard array antennas including interaction with the mounting platform and mutual coupling effects," *Antennas and Propagation Magazine*, Vol. 43, No. 2, 76–82, April 2001.
30. Bucci, O., M. D'Urso, and T. Isernia, "Some facts and challenges in array antenna synthesis problems," *Journal for Control,*

Measurement, Electronics, Computing and Communications, Vol. 49, 13–20, Dubrovnik, May 2008.

31. Gabriel, W. F., "Adaptive arrays — An introduction," *Proc. of the IEEE*, Vol. 64, No. 2, February 1976.
32. Widrow, B., "Adaptive antenna systems," *Proc. of the IEEE*, Vol. 55, 2143–2159, December 1967.
33. Ellingson, S. W. and G. A. Hampson, "A subspace-tracking approach to interference nulling for phased array-based radio telescopes," *IEEE Transactions on Antennas and Propagation*, Vol. 50, No. 1, 25–30, January 2002.
34. Ellingson, S. W. and W. Cazemier, "Efficient multibeam synthesis with interferencing for large arrays," *IEEE Transactions on Antennas and Propagation*, Vol. 51, No. 3, 503–511, March 2003.
35. Ellingson, S. W., "Beamforming and interference canceling with very large wideband arrays," *IEEE Transactions on Antennas and Propagation*, Vol. 51, No. 6, 1338–1346, June 2003.