Radar Cross Section of Dipole Phased Array with Parallel Feed Network using Approximate Method

Hema Singh and Harish Singh Rawat
Centre for Electromagnetics (CEM)
CSIR-National Aerospace Laboratories
Bangalore 560017, India

***Abstract*— Radar cross section (RCS) of a parallel-fed dipole array depends on the signal path within the array system. The overall array RCS is derived using approximate method. The impinging signal travels through the antenna elements, phase shifters, and couplers before arriving at the receive port. It undergoes reflection and transmission at each impedance mismatch within the feed network. The array RCS is analytically derived in terms of array factor, neglecting the phase terms. The mutual coupling effect is taken into account. The parametric study of the RCS pattern of linear and planar dipole array is presented. The design parameters of array include dimension of dipole antenna element, geometric configuration, inter-element spacing, beam scan angle, and terminating impedance.**

I. INTRODUCTION

The reflection and the scattering of the impinging signal within the array system decide the radar cross section (RCS) of phased array. The reflection and transmission coefficients for an incident signal depend on the impedance mismatch and the design parameters of the phased array. Moreover the mutual coupling effect in between the antenna elements is an important factor in scattering analysis [1]. A phased array system comprises of radiating elements followed by phase shifters, couplers, and terminating load impedance. These components pose respective impedance towards the incoming signal that travels through the components before reaching receive port of the array system [2].

This paper aims at the estimation and control of in-band RCS of phased arrays considering only the antenna mode scattering, which is dominant as compared to that of structural mode for an in-band operating stand-alone phased array. In this paper, the RCS of parallel-fed linear and planar dipole array is analytically obtained using approximate model. The scattering of the impinging signal till the second level of couplers is considered. The overall RCS of dipole array is analytically derived from the scattering contributions at different component level in terms of array factors, neglecting the phase terms. The array RCS depends on the array design parameters, viz. antenna elements, geometric configuration, inter-element spacing, components such as phase shifters, couplers, terminating impedance, and the feed configuration. The high order reflections and transmissions and edge effect are ignored. The proposed approximate method has less computational burden and its provides accurate results for an arbitrary dipole phased array.

II. FORMULATION

The signal path is followed as it enters into the array aperture and travels through the feed network. The total scattered field of linear dipole array obtained by summing over N_x antenna elements, is given by [3]

$$\vec{E}^s(\theta,\phi) = \sum_{m=1}^{N_x} \vec{E}_m^s(\theta,\phi) = \sum_{m=1}^{N_x} \left[\left\{ \begin{array}{l} \dfrac{j\eta_o}{4\lambda(R_{r_m} + jX_{a_m})} \\ \times h^2.\cos\theta.\vec{E}_m^r(\theta,\phi) \end{array} \right\} \frac{e^{-j\vec{k}\vec{R}}}{R}\hat{x} \right]. \tag{1}$$

where h is the effective height of antenna element, l being the dipole length. $\vec{E}_m^r(\theta,\phi)$ is the field scattered at each component of feed network. A planar array is modeled as stack of linear dipole array along x-direction. The half-wavelength dipoles are placed along x and y directions.

The backscattered RCS due to individual elements *viz.* reflector, phase shifter, coupler and beyond the coupler level in the feed network are expressed as

$$\sigma_r(\theta,\phi)\Big|_{normalized} = \frac{4\pi}{\lambda^2}\left| F\frac{\sin(N_x\alpha_x)}{N_x\sin\alpha_x}\sum_{m=1}^{N_x}\Gamma_{r_m}\right|^2. \tag{2}$$

$$\sigma_p(\theta,\phi)\Big|_{normalized} = \frac{4\pi}{\lambda^2}\left| F\frac{\sin(N_x\alpha_x)}{N_x\sin\alpha_x}\sum_{m=1}^{N_x}T_{r_m}^2\Gamma_{p_m}\right|^2. \tag{3}$$

$$\sigma_c(\theta,\phi)\Big|_{normalized} = \frac{4\pi}{\lambda^2}\left| F\frac{\sin(N_x\xi_x)}{N_x\sin\xi_x}\sum_{m=1}^{N_x}T_{r_m}^2\Gamma_{cp_m}T_{p_m}^2\right|^2. \tag{4}$$

$$\sigma_{beyond\,coupler}(\theta,\phi)_m\Big|_{normalized} = \frac{4\pi}{\lambda^2}\left| F\sum_{m=1}^{N_x}\vec{E}_{m_1}^r(\theta,\phi)\right|^2. \tag{5}$$

where N_x is the number of elements in linear array

$$F = \frac{j\eta_o}{4\lambda Z_{a_m}} \left(\int_{\Delta l} \cos(kl)\,dl \right)^2 \cos\theta. \tag{6}$$

$$\Gamma_{r_m} = \left| \frac{Z_{a_m} - Z_o}{Z_{a_m} + Z_o} \right|. \tag{7}$$

$$\left|T_{r_m}\right|^2 = 1 - \left|\Gamma_{r_m}\right|^2 \tag{8}$$

The magnitude of reflected field, at any junction, depends on the impedance mismatch experienced by the signal during its path from the aperture to the receive port.

$$\vec{E}_m^r(\theta,\phi) = \Gamma_m^r(\theta,\phi).1.e^{j(m-1)\alpha}\,\hat{\theta}. \tag{9}$$

$$\alpha = kd_x \sin\theta\cos\phi. \tag{10}$$

$\vec{E}_m^r(\theta,\phi)$ is the reflected field at the m^{th} antenna element, and α is the inter-element delay with all other symbols having their usual meanings.

The total RCS of dipole array with parallel feed network due to the mismatches in the feed network is expressed as

$$\sigma(\theta,\phi) = \sigma_r(\theta,\phi) + \sigma_p(\theta,\phi) + \sigma_c(\theta,\phi) + \sigma_{beyond\,coupler}(\theta,\phi). \tag{11}$$

The sub-array size required for the RCS estimation depends on the coupler level and is given by 2^q, q is the coupler level [4].

III. Results and Discussion

A systematic step-by-step approach has been followed to compute array RCS based on design parameters and mutual coupling effect. The phased arrays consisting of half-wavelength dipole antennas with low gain in their out-band region are considered. This assumption serves to neglect scattering in wide angles and thus nullifies the effect of structural mode RCS of phased array. Further low-gain in out-band region eliminates the antenna mode scattering when there is perfect matching between the dipole elements. This is because antenna mode scattering no more remain dominant in perfect match case, even with large reflection coefficient. However, mismatches within the feed network during hardware fabrication are almost unavoidable and thus antenna mode remains to be a dominant RCS contributor in case of a phased antenna array operating within its frequency band.

Figure 1 shows the RCS of 64-element parallel-in-echelon parallel-fed dipole array. The length and radius of the dipole are taken as 0.5λ and 0.001λ respectively. The inter-element spacing is 0.5λ; the offset height from the reference plane is taken as 0.25λ. The specular lobe and the lobes due to mismatches at couplers are clearly visible in the RCS pattern. Next, a contour plot of broadside RCS of 64 element parallel-fed side-by-side dipole array is shown in Figure 2. The color of the contours represents the RCS level. It is apparent that the RCS pattern consists of a specular lobe and the lobes due to input load mismatches. Figure 3 demonstrates the role of array configuration on RCS pattern of 64-element linear dipole array. The load impedance and characteristic impedance are 75Ω and 50Ω respectively. Three configurations, viz., side-by-side, collinear, parallel-in-echelon are considered. It is apparent that the RCS of the parallel-in-echelon dipole array is lowest while the collinear array has highest RCS.

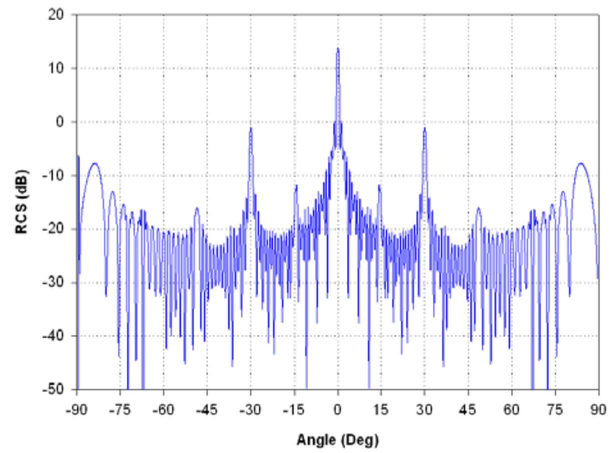


Fig. 1. Broadside RCS of 64-element linear parallel-in-echelon dipole array.

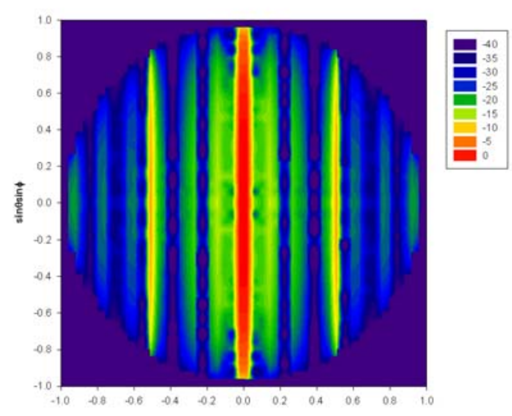


Fig. 2. Contour plot of 64 element parallel-fed linear side-by-side dipole array

The role of terminating load impedance in the RCS pattern of dipole array is significant [5]. Figure 4 shows the broadside RCS pattern of a 16×16 side-by-side dipole array with different terminating load impedances. It is apparent that the array RCS is highest when the coupler is terminated by 0Ω (i.e. short circuited). If the terminating load impedance is increased to 100Ω, the RCS value decreases at specular lobe, lobes due to coupler mismatches, and Bragg's lobes. However this trend in RCS pattern has limiting value.

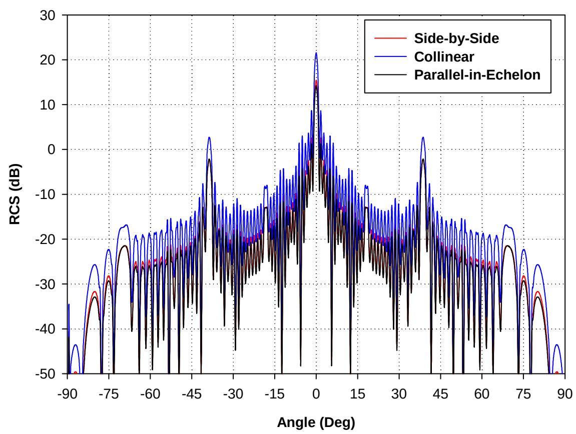


Fig. 3. Effect of array configuration on the RCS pattern of 64-element linear parallel-fed dipole array.

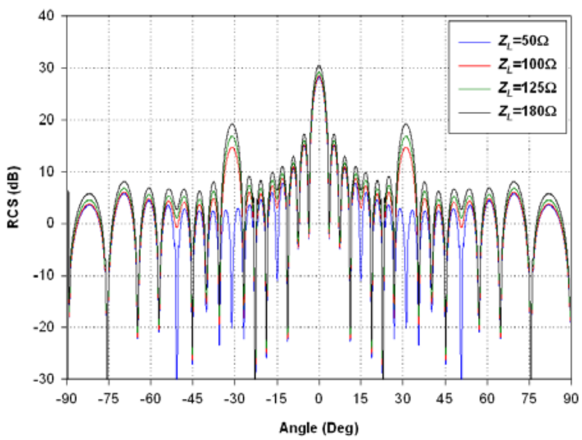


Fig. 4. Effect of terminating load impedance on RCS pattern of 16x16 planar side-by-side dipole array.

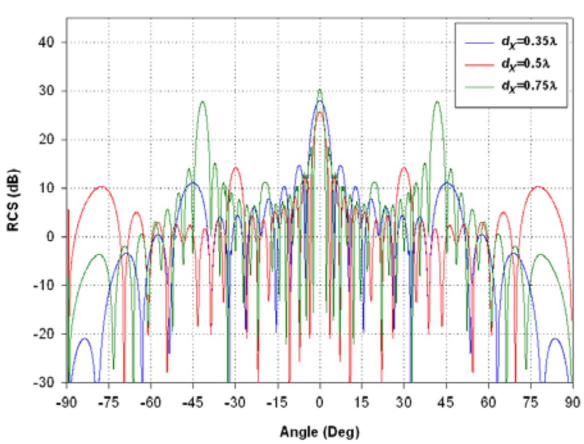
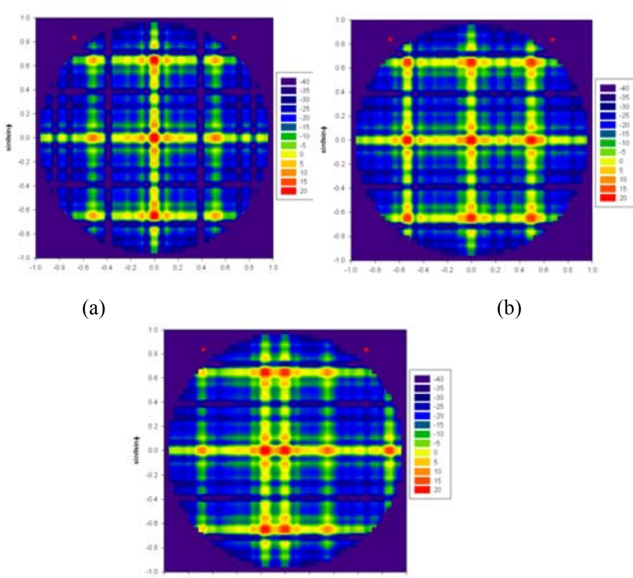


Fig. 5. Effect of inter-element spacing on RCS of 16x10 planar side-by-side dipole array.

On further increase in load impedance i.e. to 125Ω and 180Ω, the RCS increases. This makes the terminating load as an important design parameter towards the RCS optimization.

Next, the role of inter-element spacing in RCS pattern of planar dipole array is analyzed. Figure 5 presents the broadside RCS pattern of 16×10 dipole array for different inter-element spacing along *x*-axis. As the inter-element distance along the *x*-axis is increased from 0.35λ to 0.75λ, both main lobe width and the specular lobe level reduce. The position of specular lobe and lobes due to coupler mismatches remains same. However the RCS level of the lobes in case of d_x=0.5λ is minimum complexity as compared to the conventional method of tracing signal as it travels through the antenna system. This makes it a preferred choice of inter-element spacing for optimum RCS pattern.

Figure 6 shows the contour plots for a 16×10 dipole array with inter-element spacing of 0.484λ and 0.77λ along *x*- and *y*- directions respectively. Here effect of beam scanning on specular lobe intensity is shown. Three cases are shown as per the variation of scan angle and RCS patterns are compared. As scan angle is varied from 0^o to 45^o, it may be seen that the specular lobe level decreases with increase in the level of side lobes. This is in accordance with the law of conservation of energy. Moreover as beam scan angle is again varied from 45^o to 60^o, one can notice that one extra beam arises near to specular lobe with decrease in the energy of both specular and input impedance lobes.



(a) (b)

(c)

Fig. 6. Effect of beam scanning on RCS pattern of 16x10 planar parallel-fed dipole array (a) θ_s= 0^o (b) θ_s= 45^o (c) θ_s= 60^o RCS pattern of 16x10

IV. CONCLUSION

This paper presents the analytical closed form expression of the RCS of parallel-fed uniform linear and planar dipole array in the presence of mutual coupling effect. An approximate method is used to derive the RCS of dipole array in terms of array factors. The phase terms are neglected. The scattered field at each level of the feed network is expressed in terms of the reflection and the transmission coefficients, owing to the impedance mismatches at various junctions of feed network. These individual scattered fields are coherently summed to obtain the total RCS of planar dipole array. The approximate model employed proves to be an efficient method for RCS estimation of dipole phased array. It is a simple method with low computational cost.

V. REFERENCES

[1] D.C. Jenn, *Radar and Laser Cross Section Engineering.* AIAA Education Series, Washington, DC, ISBN: 1-56347-105-1, 476p., 1995.

[2] H.L. Sneha, Hema Singh, R.M. Jha, "Scattering analysis of unequal length dipole array in the presence of mutual coupling," *IEEE Antennas and Propagation Magazine,* vol. 55, no. 4, pp. 333-351, August 2013.

[3] H.L. Sneha, Hema Singh, R.M. Jha, "Scattering analysis of a compact dipole array with series and parallel feed network including mutual coupling effect", *International Journal of Antennas and Propagation*, USA, Article Id: 516946, 12p., 2013.

[4] R.S. Elliot, Antenna *Theory and Design.* IEEE Press, John Wiley & Sons (Asia), Singapore, ISBN: 981-253-1947, 594p., 2005.

[5] Sneha H.L., Hema Singh, and R.M. Jha, "Analytical estimation of radar crosssection of arbitrary compact dipole array," *The Applied Computational Electromagnetics Society Journal*, vol. 29, no. 9, pp. 726-734, Sep. 2014.

Dr. Hema Singh is a Senior Scientist at the Centre for Electromagnetics of CSIR-National Aerospace Laboratories, Bangalore, India. Earlier, she was Lecturer in EEE, BITS, Pilani, India during 2001-2004.

She obtained her Ph.D. degree in Electronics Engineering from IIT-BHU, Varanasi India in 2000. Her active area of research is computational electromagnetics for aerospace applications. More specifically, the topics she has contributed to, are EM analysis of propagation in an indoor environment, Phased Arrays, Conformal Antennas, Radar Cross Section (RCS) Studies including Active RCS Reduction. She received Best Woman Scientist Award in CSIR-NAL, Bangalore for period of 2007-2008 for her contribution in area of phased antenna array, adaptive arrays, and active RCS reduction. Dr. Singh has co-authored one book, one book chapter, and over 120 scientific research papers and technical reports.

Mr. Harish Singh Rawat obtained M.Sc. (Electronics) in 2013 from Department of Engineering and Technology, Jamia Millia Islamia, New Delhi, India. He is currently a Project Graduate Trainee at the Centre for Electromagnetics (CEM) of CSIR-National Aerospace Laboratories, Bangalore, India. His research interests include radar cross section (RCS) of simple canonical shapes and phased arrays mounted on planar and non-planar surfaces.