CHAPTER ONE

Introduction

1.1 ARRAY BACKGROUND

Discovery of the first works on array antennas is a task best left to historians, but the two decades before 1940 contained much activity on array theory and experimentation. Some of the researchers were G. H. Brown, E. Bruce, P. S. Carter, C. W. Hansell, A. W. Ladner, N. E. Lindenblad, A. A. Pistolkors, S. A. Schelkunoff, G. C. Southworth, E. J. Sterba, and T. Walmsley. Primary journals were *Proc. IRE*, *Proc. IEE*, *BSTJ*, *RCA Review*, and *Marconi Review*. During World War II, much array work was performed in the United States and Britain. Interest in arrays returned in the early 1960s, with research projects at Lincoln Laboratories, General Electric, RCA, Hughes and others. Some of the array conferences are mentioned in the annotated reference list in Section 1.3.

A salient event was the publication by Academic Press of the three-volume book *Microwave Scanning Antennas* (*MSA*), with volume 1 appearing in 1964, and volumes 2 and 3 in 1966. This work was the first extensive coverage of phased arrays, with emphasis on mutual coupling theory, which is the basis of all array characteristics. After 30 years, *MSA* is still in print, through Peninsula Publishing.

It is the purpose of this book to present a thorough and extensive treatment of phased arrays, adding to and updating the array portions of *MSA*. The scope of the book is all types of arrays except adaptive, for which several excellent books exist; see references at the end of the chapter. Multiple-beam arrays are included. Because most arrays operate at frequencies that allow spacing above ground to be sufficiently large to preclude the ground affecting the array internal parameters, all arrays are presumed to be in free space. Active arrays, that is, those containing active devices, are not treated, nor are array-related circuit components, except for phasers, which are discussed briefly. It is also assumed that all array elements are identical, although the impedance matching may vary with the element position. A semantic difficulty

Phased Array Antennas, Second Edition. By R. C. Hansen

arises with the phrase “phased array”. For some people, this implies beam steering or scanning. But for others all arrays are phased; fixed beam broadside arrays are also phased. There are more important questions of terminology; these are addressed next.

1.2 SYSTEMS FACTORS

Important array factors for the systems designer are broadside pattern, gain versus angles, element input impedance, and efficiency. For all regular arrays, the pattern is given by the product of the element pattern and the pattern of the isotropic array, where the array elements are replaced by isotropes. However, the element excitations must be those of the real array; as discussed later, these are found by solving equations associated with a self-impedance and mutual-impedance or admittance matrix. In general, each element of an array will have a different input impedance. For a fixed beam array these are called “embedded impedances”; the obsolete and misleading term “active impedance” is deprecated. A scanning array not only has different element impedances, but each of them varies with scan angle. These element input impedances are called *scan impedances*.

The pattern of array gain versus angles is called *scan element pattern*; this term replaces *active element pattern*. The *scan element pattern* (SEP) is an extremely useful design factor. The element pattern and mutual coupling effects are subsumed into the *scan element pattern*; the overall radiated pattern is the product of the *scan element pattern* and the pattern of an isotropic array of elements scanned to the proper angle. The isotropic array factor incorporates the effects of array size and lattice, while the *scan element pattern*, as mentioned, incorporates element pattern, backscreen if used, and mutual coupling. Since the *scan element pattern* is an envelope of array gain versus scan angles, it tells the communications system or radar designer exactly how the array performs with scan, whether blind angles exist, and whether matching at a particular scan angle is advantageous. *Scan element pattern* is used for antenna gain in the conventional range equations. For an infinite array, the SEP is the same for all elements, but for a finite array each element sees a different environment, so that the SEP is an overall array factor. Use of infinite array *scan element patterns* allows array performance to be separated into this SEP and edge effects. Formulas for both finite array and infinite array *scan element pattern* are derived later; edge effects are also discussed later.

A similar parameter, appropriate for backscattering from antenna arrays, is the *scattering scan element pattern* (SSEP). This parameter gives the backscattered field intensity from an array element, when the array is excited by an incident plane wave. This then is different from the SEP, which relates radiated field intensity to total radiated power. The radar cross section (RCS) relates reradiated field intensity to incident field intensity, with a $4\pi R^2$ factor. The SSEP is this ratio of reradiated to incident intensity; a convenient normalization is to the broadside value. Just as in the case of a radiating array, the scattering array finite size and edge effects have been separated, so that the SSEP relates the effects of element design and array lattice. It can then be used to make design trades for type of element and lattice; the features due to the array size are included simply by multiplying by the isotropic array factor. Of course, SSEP is related to the RCS pattern. It can be considered as the RCS pattern of one unit cell of the array.

System factors also arise in arrays used for wideband baseband (no carrier) applications. The one-way (communications) range equation, written without explicit wavelength dependence, is

$$P_r = \frac{P_t G A_e}{4\pi R^2} \tag{1.1}$$

where as usual P_r and P_t are received and transmitted powers, R is the range, and G and A_e are the gain of one antenna and the effective area of the other. Both gain and effective area include an impedance mismatch factor:[1] $(1-|\Gamma|^2)$. It is assumed that P_t is fixed, independent of frequency. If the GA_e product is relatively constant over the frequency band of interest, then the signal is transferred without significant dispersion, providing that the antenna and matching unit phase are well behaved also (Hansen and Libelo, 1995). Otherwise significant dispersion can occur.

From a casual look at array antennas, one might assume a planar array to be a constant effective area antenna. However, for a regularly spaced array of low-gain elements, as the frequency increases from nominal half-wave spacing, the gain increases until the first grating lobe appears, with the gain then dropping back to the original level. Further increases in frequency produce additional rises in gain followed by drops as grating lobes appear. The net result is that over a wide bandwidth the gain of an array is at best roughly constant and equal to the half-wave spaced value (Hansen, 1972). This does not include effects of embedded element impedance mismatch with frequency, a phenomenon that further greatly reduces gain. Thus the regularly spaced array is not a candidate for compensation of dispersion. An array with pseudorandom spacing does not experience the appearance of regular grating lobes as frequency is increased. The fraction of power in the sidelobes is roughly constant in a well-designed nonuniformly spaced array, and thus the gain is roughly constant with frequency. Of more importance, however, is the fact that very large numbers of elements are needed to achieve even moderately low sidelobe levels. Thus these types of arrays are not suitable for dispersion compensation either. Arrays of higher gain elements experience, in addition, the dispersion introduced by the elements themselves and are even less suitable.

1.3 ANNOTATED REFERENCE SOURCES

Many textbooks discuss arrays, but the books and digests listed here provide in-depth resources on phased arrays.

[1] Note that “effective length”, which is defined as open circuit voltage divided by incident electric field, does not include impedance mismatch, and is therefore useless by itself.

Microwave Scanning Antennas, R. C. Hansen, Ed., 3 vols., Academic Press, 1964, 1966 [Peninsula Publishing, 1985, 442 pp., 400 pp., 422 pp. (Peninsula combined volumes)].

This, the first extensive work on phased arrays, is still quite useful. Volume 1 has a chapter on aperture distributions. Volume 2 includes array theory, and infinite and finite array analysis; probably the first development of the spectral domain analysis technique for arrays. Feeds, frequency scanning, and multiple beams are covered in vol. 3; multiple beams by Butler of matrix fame.

Proceedings of the 1964 RADC Symposium on Electronically Scanned Array Techniques and Applications, report RADC-TDR-64-225, AD-448 481.

Contained here are early papers on phase quantization errors, ferrite and semiconductor phasers, and beam forming matrices.

The Theory and Design of Circular Antenna Arrays, James D. Tillman, University of Tennessee Engineering Experiment Station, 1966, 235 pp.

This treatise on ring arrays and concentric ring arrays applies sequence theory of azimuthal modes, called symmetrical components in electric power work, to the analysis of impedance and pattern. Array scanning is also discussed.

Proceedings of the 1970 NELC Conformal Array Conference, TD-95, Naval Electronics Lab. Center, AD-875 378.

Both ring arrays and cylindrical arrays are treated in papers, both theoretically and for applications.

Phased Array Antennas, A. A. Oliner and G. H. Knittel, Artech, 1972, 381 pp.

This book is a record of the 1970 Phased Array Antenna Symposium held at Polytechnic Institute of Brooklyn. Included are many papers on impedance calculations, blind angles, and so on, and also on practical aspects, such as scan compensation and feeding and phasing.

Theory and Analysis of Phased Array Antennas, N. Amitay, V. Galindo, and C. P. Wu, Wiley–Interscience, 1972, 443 pp.

Arrays of waveguide radiators are the subject here. The spectral domain method is used extensively. Small finite arrays are solved via equations over the modes and elements. This work is one of the first using multimode spectral analysis.

Proceedings of the 1972 NELC Array Antenna Conference, TD-155, 2 Parts, Naval Electronics Lab. Center, AD-744 629, AD-744 630.

Many papers cover array techniques and components; adaptive arrays, and conformal arrays.

Theory and Application of Antenna Arrays, M. T. Ma, Wiley–Interscience, 1974, 413 pp.

Transform analysis and synthesis of fixed beam arrays is covered, along with many general array examples. The effect of ground on arrays represents a significant part of this book.

Conformal Antenna Array Design Handbook, R. C. Hansen, Ed., Naval Air Systems Command, 1982, AD-A110 091.

This report summarizes a decade of Navair-supported work on cylindrical and conical slot arrays, including mutual impedance algorithms.

Antenna Theory and Design, R. S. Elliott, Prentice-Hall, 1981, 594 pp.

This text is an excellent source for waveguide slot array analysis and synthesis. Sidelobe envelope shaping is treated in detail.

The Handbook of Antenna Design, A. W. Rudge, K. Milne, A. D. Olver, and P. Knight, Eds., IEE/Peregrinus, 1983, vol. 2, 945 pp.

This handbook contains chapters on linear arrays, planar arrays, conformal arrays, ring arrays, and array signal processing. Extensive data are included on array analysis and synthesis, including mutual coupling effects.

Proceedings of the 1985 RADC Phased Array Symposium, H. Steyskal, Ed., report RADC-TR-85-171, AD-A169 316.

This symposium record contains papers on microstrip arrays, adaptive arrays, and scan impedance, among others. A second volume has restricted distribution.

Antenna Handbook, Y. T. Lo and S. W. Lee, Van Nostrand Reinhold, 1988.

This handbook contains chapters on array theory, slot arrays, periodic and aperiodic arrays, practical aspects, and multiple-beam arrays.

Antenna Engineering Handbook, R. C. Johnson and H. Jasik, McGraw-Hill, 1993.

This updated edition of an old classic contains chapters on array theory, slot arrays, frequency scan and phased arrays, and conformal arrays.

Phased Array Antenna Handbook, R. J. Mailloux, Artech, 1994, 534 pp.

This specialized handbook covers most array topics, with emphasis on analysis and synthesis. A chapter covers limited scan arrays and time delayed arrays.

Phased Array-Based Systems and Applications, N. Fourikis, Wiley–Interscience, 1997.

This book emphasizes systems aspects of arrays.

1.3.1 Adaptive Antenna Reference Books

Compton, R. T., Jr., *Adaptive Antennas*, Prentice-Hall, 1988.

Hudson, J. E., *Adaptive Array Principles*, IEE/Peregrinus, 1981.

Monzingo, R. A. and Miller, T. W., *Introduction to Adaptive Arrays*, Wiley, 1980.

Widrow, B. and Stearns, S. D., *Adaptive Signal Processing*, Prentice-Hall, 1985.

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Hansen, R. C., “Comparison of Square Array Directivity Formulas”, *Trans. IEEE*, Vol. AP-20, Jan. 1972, pp. 100–102.

Hansen, R. C. and Libelo, L. F., “Wideband Dispersion in Baseband Systems”, *Trans. IEEE*, Vol. AES-31, July 1995, pp. 881–890.