Plane-Wave Scattering-Matrix Theory of Antennas and Antenna-Antenna Interactions

This monograph [1] represents David Kerns's final compilation on the subject of near-field antenna measurements. It was published shortly before he retired, and it remains the best and most exhaustive treatment of planar near-field scanning theory. The author developed much of the material in the course of teaching graduate electrical engineering courses in the University of Colorado.

As outlined in the author's preface, the monograph is distinguished by the use of plane-wave spectra for the representation of fields in space and by the consideration of antenna-antenna (and antenna-scatterer) interactions at arbitrary separation distances. The plane-wave representation is eminently suitable for this purpose as well as for the expression of conventional asymptotic quantities of antenna theory, such as power gain, effective area, and polarization.

The primary objective of the monograph is to facilitate the critical acceptance and proper application of antenna and field measurement techniques deriving more or less directly from the plane-wave scattering-matrix (PWSM) theory of antennas and antenna-antenna interactions. A secondary objective is to present some recent and some new theoretical results based on this theory. To some extent the second objective supports the first one.

The expository plan is based upon experience at NBS in developing, discussing, teaching, and reporting on the PWSM theory and techniques, as well as upon observing at close hand the development of major NBS facilities for practical antenna measurement applications. All field and antenna measurements involve measurements of antenna outputs and inputs. This part of the total process is the approximate dividing line between the domain of antenna theory and the domain of microwave measurement techniques including instrumentation. Or perhaps instead of a dividing line there is a gap or crevice.

Elaborate measurements made on expensive antennas with expensive measuring equipment can be (and have been) vitiated by improper microwave network calculations or by improper adjustments due to improper interpretation of impedance-matching requirements. This is in part a reflection of omitted, inadequate, or even incorrect discussions of relatively simple network calculations in the literature.

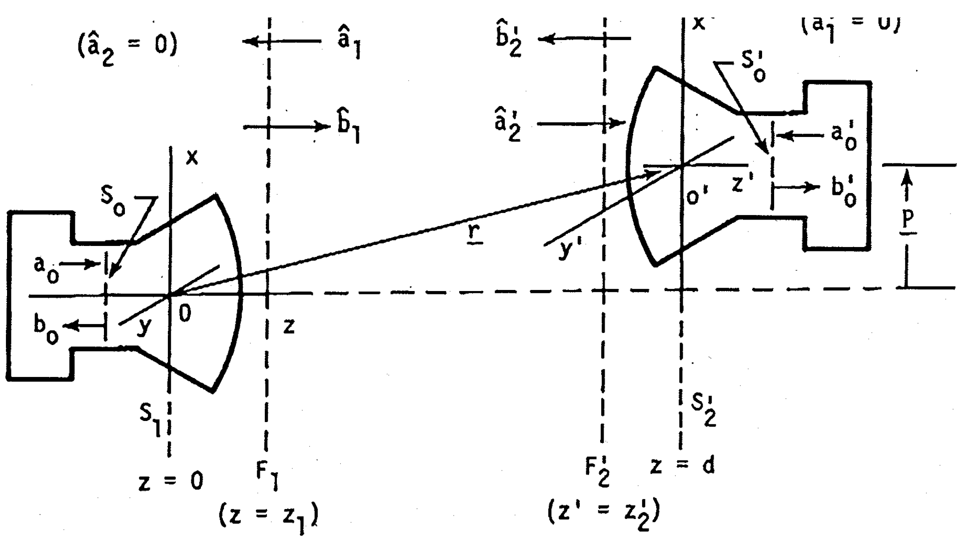

Fig. 1. The figure provides a hint of the complexity of the analyses addressed in the monograph. It represents a pair of antenna systems operating in a homogeneous, isotropic, dissipationless medium; one antenna is transmitting, and the other receiving. The complete treatment of a transmission system must include effects of scattering by both antennas and thus automatically includes treatment of reflection systems, in which one antenna functions in both transmitting and receiving modes and the other antenna represents an arbitrary passive (linear) scattering object.

One quantity, characteristic of the type of antenna measurements of interest here, is the transfer normalization required to obtain the ratio of receiving antenna output to transmitting antenna input correctly in magnitude and relative phase. This normalization, even if done correctly with good instruments and good technique, may represent the single largest contribution to the inaccuracy or uncertainty of the eventually determined antenna or field data. In short, to be able to make good microwave antenna measurements, one must be able to make good microwave measurements. This is true regardless of the brand of antenna theory that one uses.

The theoretical basis and the techniques of microwave network calculations receive little or no emphasis in most books on electromagnetic theory and, apparently, surprisingly little in the training and background of microwave and microwave-antenna engineers. Chapter I of this monograph is intended to supply some of the missing emphasis. It consists of a revision and adaptation of part 1 of the book by Kerns and Beatty [2] with an added section giving basic microwave network equations selected and discussed with antenna measurement applications in mind. The general theoretical foundation provided in this chapter has an additional role in the present monograph.

The use of the plane-wave representation of the spatial fields (as contrasted to the use of spherical or cylindrical waves) simplifies and strengthens the theoretical analogy between an antenna and an ordinary waveguide junction (or N-port) described in terms of a finite number of discrete waveguide input or output modes, and it greatly simplifies the analogy between coupled antennas and coupled waveguide junctions.

Chapter I is intended to be concise as well as elementary, but it is elementary only with respect to its principal subject. The reader is assumed to have a good working acquaintance with Maxwell's equations, vector analysis, and elementary matrix algebra. Transmission-line theory may be underrepresented in the discussion, but the use of the traveling-wave resolution of fields more or less automatically takes care of the need for transmission-line equations.

Chapter II gives a formulation of the PWSM theory of antennas and antenna-antenna interactions together with basic analytical techniques for measurement applications. The formulation is relatively thorough and complete, whereas the measurement techniques are treated briefly. The reason for this imbalance is that the measurement techniques are acquiring their own literature, to which references are given. Chapter II contains all of the material in the previous most complete discussion of the PWSM theory [3] with revisions to improve the exposition. The bias is toward the subject of measurements as an end and not merely as a means, with emphasis on accurate measurements, or at least measurements with controlled approximations. Both generality and detail are required to avoid over-idealization, to permit the framing of precise definitions, and to permit cognizance and the possibility of control of approximations. Less general theorems and simplified formulas might improve appearances of the pages of the monograph, but would tend to be much less convenient and useful to a measurement-oriented person interested in accurate measurements. It is much easier to reduce, than to increase, the generality of a given set of equations.

The generality of the PWSM formulation is such that it is not necessary to single out any particular types or classes of antennas for purposes of discussion of measurement equations. The measurement related theorems and equations are valid for arbitrary types of antennas, such as the so-called linear antennas, aperture antennas, and arrays of antenna elements.

The third and last chapter is in essence a rather lengthy research paper. It relies upon the first three of the four sections of Chapter II for definitions, theorems, and motivation; in turn, the analytical results obtained in Chapter III support and illustrate Chapter II.

The use of examples is a feature of the exposition (38 numbered examples are included, most of them in Chapter III). The examples serve several purposes: the rederivation or restatement of certain well-known results in the PWSM format is expected to lend perspective, establish confidence, and show some of the connections to existing theory. Examples are used to provide extensions of the text material not readily available elsewhere and to form part of the development of the subject. Most of the examples are suitable as material for exercises (but so also are many equations and assertions for which detailed argument is not given).

Kern's ground breaking 1960 paper [4] on the *Theory of diffraction in microwave interferometry* was the seminal work that marks the beginning of modem near-field antenna metrology. Under the leadership of Kerns and other pioneers at NBS, near-field techniques have become the preferred methods for characterizing the radiating properties of microwave antennas. In addition to the well-known NIST antenna group, several universities maintain active near-field measurement research programs. Half a dozen companies market near-field scanning equipment and well over 200 laboratories worldwide routinely perform near-field measurements. The IEEE Antennas and Propagation Society has published a special issue *(IEEE Transactions on Antennas and Propagation, June 1988)* and regularly features sessions on near-field techniques at its conferences.

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Bibliography

[1] David M. Kerns, *Plane-Wave Scattering-Matrix Theory of Antennas and Antenna-Antenna Interactions,* NBS Monograph 162, National Bureau of Standards, Washington, DC (1981).

[2] David M. Kerns and Robert W. Beatty, *Basic Theory of Wave-guide Junctions and Introductory Microwave Network Analysis,* Pergamon Press, Oxford (1967) p. 29 ff.

[3] David M. Kerns, Plane-wave scattering-matrix theory of antennas and antenna-antenna interactions: formulation and applications, *J. Res. Natl. Bur. Stand.* **80B**, 5-51 (1976).

[4] D. M. Kerns and E. S. Dayhoff, Theory of diffraction in microwave interferometry, *J. Res. Natl. Bur. Stand.* **64B**, 1-13 (1960).