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A QUALITATIVE SURVEY OF NEAR-FIELD ANALYSIS AND MEASUREMENT

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PAUL F. WACKER

Abstract--This first paper in a series on a new unified theory of near-field analysis and measurement serves as an introduction to and a summary of some of the forthcoming papers in the series. Further, it describes the advantages and limitations of near-field scanning and compares various techniques, as well as corrects many of the conceptual errors of the literature. Being firmly based upon generalized scattering matrix theory and both relativistic and gauge invariance (Wigner's extended inhomogeneous Lorentz group [1964]), the theory is rigorous and very comprehensive, general, and fundamental, yet it provides the detailed bases of extremely efficient computer programs for reduction of both electromagnetic and acoustic measurements on planar, circular cylindrical, and spherical scanning lattices, as well as provides the basis for the most accurate method of calibrating standard gain horns (described in the series). For both the probe correction and ideal probe cases, the theory yields a series of general-but-explicit formulas which apply to the aforementioned and other lattices (including plane-radial) and to a wide variety of physical systems; plug-in expressions (given by the theory) depend upon the type of lattice and, in the spherical case, parametrically upon the physical system. The efficiency of the spherical EM programs (based upon a paper in the series) is indicated by the fact that probe-corrected least squares values of the complex coefficients of 50,000 exact global solutions of Maxwell's equations in spherical coordinates and the associated far field may be computed in a few minutes.

I. INTRODUCTION AND SUMMARY

During the past 25 years, scanning on planes [9],[8], circular cylinders [10],[26], and spheres [4],[5] has been developed to obtain far-field patterns of antennas. These procedures have many practical advantages and can yield accuracies equalled only in a small number of far field measurements. The currently-used Cartesian-planar data-processing is extremely efficient and cylindrical moderately so. The present series of papers describes highly efficient processing of spherical data ([8], [21], Paper V), plane-radial scanning [22], Paper III), improvements in cylindrical processing (Paper IV), and the (author's) theory of the extrapolation method for gain and effective area ([18], [11], Paper VI). The latter is the most accurate method of calibrating standard gain horns; the values calculated from the horn geometries are usually outside the limits of error of measurements made with this technique at the National Bureau of Standards (NBS) [11].

The planar, cylindrical, and spherical analyses were originally developed in different laboratories and the treatments particularized for each surface. However, due to the complexity of the spherical analysis, it is highly desirable to have a panoramic view of near-field scanning and a common notation for the various scanning surfaces and physical systems. Then both general and detailed comparisons can be made, facilitating (a) the transfer of understanding from one surface or physical system to another, (b) the translation of computer programs from one physical system to another (say EM to acoustic in a gas, liquid, or solid), (c) insurance that all available computational efficiencies are utilized, (d) emphasis upon fundamentals rather than a morass of detail, (e) generalization and extension to other scanning lattices and physical systems, (f) defining the limits of the techniques, (g) eliminating unnecessary repetition in presentation, and (h) clarification of concepts. (Ad hoc studies of particular systems have led to many conceptual errors in the literature; see Section III A.) To achieve these ends, the presentation (Paper II) is in terms of a unified theory in which spherical, Cartesian planar, plane radial, cylindrical, and other types of scanning and both electromagnetic and acoustic systems are treated as mere special cases. Only parts of the unified theory and unified notation are evident from Cartesian planar or cylindrical theory because of their simplified nature; details which are so simple in the Cartesian planar case that they may be barely considered may be extremely complicated in the spherical case, e.g., transformation of the modal coefficients under translation normal to the measurement surface. However, spherical theory does provide such a basis, Cartesian planar and cylindrical being limits of the spherical on the equator and pole, respectively, as the radius becomes infinite [16].

This first paper provides a non-mathematical introduction to and summary of some of the subsequent papers in the series. It first discusses the advantages and limitations of various measurement procedures and compares them. Then it provides a non-mathematical summary of near-field analysis.

In general, the antenna or other transducer is treated as a black box as far as the formal analysis is concerned, with no consideration of its shape or current distribution; however, known or assumed symmetry of the transducer may be used in reducing the measurement and computational effort, and qualitative information concerning the pattern or design is useful in choosing measurement conditions and the modes used to represent the data. Minimal assumptions, idealizations, and approximations are made, leading to highly accurate results, even for systems many wavelengths across. This is to be contrasted with techniques in which various approximations are made (see [6] for some of them); the accuracy and reliability of the results of such treatments of course depend upon the specific problem and approximations made, but are commonly less than satisfying. This series of papers emphasizes rigorous rather than approximate treatments, in particular, exact global solutions of the differential equation(s) (Maxwell's in the EM case), their exact transformations under change of coordinates, and natural orthonormalities of the transformation coefficients with respect to summation on the measurement lattice; it also makes full use (see Papers II-V and VII) of the Discrete Fast Fourier "Transform" (DFFT) (here rigorously exact), even for spherical scanning. (An "exact global solution" here means an exact solution valid everywhere in space for a given infinite medium.) The approximate procedures usually do not use the DFFT and so are usually no faster if as fast; further, many of them break down for large systems (see Paper II). The rigorous theory is very comprehensive, general, and fundamental. The general statements made in these papers apply in particular to Cartesian planar, circular cylindrical, spherical, and some types of plane-radial scanning; various other possible and proposed scanning procedures will be discussed relative to the preceding norms. Apart from obvious exceptions, the statements also apply to the extrapolation method, which involves a linear (one-dimensional) scan as the transducers are separated. Since the analysis and computer programs are in large part independent of the physical system, the statements made also apply to many physical systems, including electromagnetic, heat flow, and acoustic systems, acoustic scanning having been in operation at the NBS since 1975 [7].

The rigorous three-dimensional theory of near field analysis and measurement was pioneered by the National Bureau of Standards, which has been engaged in near-field analysis since 1953, with a definitive paper on Cartesian planar scanning being published by Kerns and Dayhoff in 1960 [9], including full treatment of the probe pattern and multiple reflections to all orders. In 1963, Baird [1] described the operation of the NBS 50 GHz scanner and preliminary measurements of the near field of a horn-lens antenna 100 wavelengths on an edge. Brown and Jull [2] described an azimuthal scanning procedure in 1961, but assumed the pattern to be independent of the z coordinate. Leach and Paris [10] described circular cylindrical scanning in 1973. The author first presented his extrapolation method for gain and effective area in 1969 [17],[18], and Newell and Kerns incorporated his procedure in their description of the three-antenna method in 1971 [13],[11]. Jensen described spherical scanning in 1970 [4],[5], and the author presented the scheme for practical reduction of spherical data with and without correction for the probe pattern in 1974 [19],[21]. The author first described his unified theory in 1974 [20],[21]. The early history of scanning is discussed by Kerns [8].

II. ADVANTAGES, LIMITATIONS, AND COMPARISONS OF MEASUREMENT TECHNIQUES

A. Advantages

The suitability of a given method of determining a transducer pattern of course depends upon the transducer and the use of the data. For a transducer which is small both physically and in terms of wavelength, say a probe, near-field techniques seldom compete with conventional methods. However, for larger transducers, near-field techniques have the following distinct advantages.

First, near-field measurement systems are closely coupled and therefore subject to laboratory-type control, making for high accuracy [11],[12],[14].

Second, the data are expressed as linear combinations of exact global solutions (modes) of the appropriate differential equation(s) (Maxwell's in the EM case) for the given infinite medium; small angle, scalar, or Kirchhoff diffraction theory approximations are not used. Hence, (a) every computed field is consistent with the differential equation(s), (b) measurement and computational efforts are not wasted determining information available from the differential equation(s), etc., and (c) various auxiliary tools become more effective. Thus, complex vector solutions are much more effective for interpolation, statistical tests of significance, and smoothing than are arbitrarily-chosen real scalar polynomial or sinusoidal basis functions. Further, optional application of additional a priori constraints becomes more effective; e.g., (a) rejection (on a priori grounds) of high transverse spatial frequencies in the near field (evanescent and high-order supergain modes), (b) symmetry of the transducer for possible reduction of measurement and computational effort, (c) finite size of the transducer in the extrapolation method, spherical scanning, and (to some extent) circular cylindrical scanning, and (d) frequency dependence of the pattern, related to the Singularity Expansion Method and dispersion (causality, Kronig-Kramers) theory. Hence, many superficially plausible interpretations of measurement errors are rejected, often automatically, and the measurement data effectively used. Far-field amplitude measurements are not subject to such stringent theoretical constraints.

Third, each and every measurement (commonly tens or hundreds of thousands) is used to compute the pattern for each and every direction. Hence, random error and ambient noise are quite unimportant, particularly since the signal-to-noise ratio is high in a closely coupled system.

Fourth, full correction for proximity effects is made, which is especially important for high accuracy measurements. However, minimization of proximity error in conventional measurements can be burdensome; to reduce the proximity error for a typical standard gain horn to 0.05 dB requires a separation of 32 (not 2) a^2/λ, where a is the largest transverse dimension and λ is the wavelength. Further, with contoured pattern antennas, the required measurement distance may be ten times that normally required [24],[25].

Fifth, ground reflections and grazing-incidence reflections of an "anechoic" chamber are eliminated since the test transducer and probe are close together and the absorber can be placed essentially perpendicular to the radiation. In conventional measurements, ground reflections are often significant even for very high towers. Their importance is illustrated by observations with our extrapolation method; we not infrequently observe ground reflections with antennas of 20 dB or more gain, yet the ratio of tower height to antenna separation is never less than 15 percent. (Such reflections cause no error in the extrapolation method at microwave frequencies.)

These observations, combined with the separation required to eliminate proximity error, indicate that very long ranges and especially high towers are required for high-accuracy conventional measurements. (Fifteen percent of 32 a^2/λ yields 4.8 a^2/λ for a desirable tower height.) Reflections in chambers are also larger than is commonly believed. Thus, in a "good" anechoic chamber, the apparent gain may vary by 2 dB (at L band) as the antenna pair is rotated with respect to the chamber walls, and the field in the volume later occupied by the test antenna may vary by as much as 1 or 2 dB, particularly in a rectangular chamber [3]. The low reflections and the lack of problems with random error and ambient noise thus make near-field techniques quite attractive for determining low-level sidelobes and the depth and shape of the "null" of a monopulse antenna operating in the difference mode.

Sixth, near-field scanning gives quite detailed information. The far-field amplitudes and polarizations are commonly given for 10,000 or more directions. Given sufficiently close spacing in the near field, arbitrarily fine spacing in the far-field pattern can be obtained with a minor increase in computational effort in the spherical case (and for the azimuthal dependence in the cylindrical case); the computations are padded with zeros prior to taking the final (inverse) DFFT. A similar technique may be used for planar scanning. Further, the phase and amplitude of each component of the electromagnetic six-vector can be obtained as functions of position in the far, intermediate, and near field. Hence, near-field interactions, say common site interference, can be determined from near-field data [27], but not from far-field amplitude data.

Seventh, assuming that a computer is available, the cost of a near-field range is much less than a far-field range or anechoic chamber capable of giving equal accuracy on comparable antennas. In fact, for an antenna mounted on a model, azimuth-over-elevation, or elevation-over-azimuth mount, no probe transport system is needed for "spherical" scanning; this is of course quite attractive for an inexpensive system and for large steerable dishes.

Eighth, for production line testing and adjustment, the antenna need not be transferred to a tower on a range between adjustments. Further, measurements of satellite antennas can be made in a clean room.

Ninth, the all-weather character of near-field work is an obvious advantage, near-field measurements being independent of moisture in the ground, foliage on trees, and weather conditions. Further, the method may be used to determine the patterns of antennas in atmospheric absorption bands, e.g., in a water absorption band, and has been used for highly accurate measurements in the O_2 band at 60 GHz [11]; these frequencies may, of course, be used for communication between satellites.

Tenth, a complete satellite may be considered as an antenna, automatically including scattering by other parts of the satellite. Similarly, a terrestrial antenna can be measured on site, automatically including the effects of the mount and permitting computation of ground reflection effects.

Note that near-field techniques (a) can give absolute measurements including mismatch corrections, (b) need not involve approximations other than truncation of the infinite set of basis functions, and (c) apply to nonreciprocal transducers (say arrays with ferrite phase shifters or isolators), whether transmitting, receiving, or scattering. Further, an absolute near-field measurement combined with pattern integration can be used to determine the losses in a transducer, e.g., a radiometric antenna. Note further that scanning is useful for moderate accuracy requirements; thus, if the error in the far-field amplitude can be increased by a factor of five, the errors in the real and imaginary parts of the near field can be increased by a factor of five. From a single physical scan, the patterns for many different steering directions may be obtained for an array, or patterns for many different frequencies can be obtained for a broadband antenna; the steering direction or frequency is merely stepped rapidly during the scan, and the data unscrambled in the computer.

B. Limitations

Near-field measurements are somewhat limited by the availability of absorbers, say below a few hundred megahertz for antennas; however, the antenna may be directed toward the zenith and ferrite absorbers used, consistent with their cost. Further, at very high frequencies, measurement of phase as a function of position becomes more difficult, particularly measurement to a small fraction of a cycle over a large area, all referred to a single reference. (This limitation does not apply to the author's extrapolation method, since it does not require phase measurement.) Nevertheless, we have accurately determined the patterns of 60 GHz antennas 100 wavelengths in diameter using only a simple positioner. With our currently used laser fringe-counting technique for measuring probe position, the positional accuracy for planar scanning is limited only by the straightness, parallelism, and planarity of the scan lines; with servo mechanisms, measurements could be made even in the far infrared. Further, servo mechanisms and a fringe-counting system should permit accurate measurements to be made on physically large antennas using a relatively flimsy probe-transport system.

For electrically large antennas, large numbers of measurements and considerable data processing are required. However, near-field measurements and processing appear feasible even for antennas for which accurate far-field terrestrial measurements are impractical, and the near-field range is much less expensive than a large conventional range or anechoic chamber. We have already processed $500^2 \times 2 = 500{,}000$ real values for a single planar scan of given polarization and, in the spherical case, routinely obtain least squares values of the complex coefficients of the 50,000 exact solutions of Maxwell's equations in spherical coordinates, used as basis functions, with full correction for the pattern of the probe. Moreover, symmetry, directional probes, and other techniques may be used to reduce the required data-taking and data-processing.

Transverse scanning provides very detailed pattern information, but (unlike the extrapolation method) it is not very economical for determining gain in a single direction.

C. Comparison of Near-Field Scanning Techniques

Which near-field technique is most appropriate depends upon the nature of the pattern, the physical size of the antenna, the nature of the available mount and/or probe transport system, and the transverse physical size of the near field (where the amplitude is significant).

In mechanical terms, the "spherical" scan is most convenient because no probe transport is required. This is particularly attractive for inexpensive implementation and for physically large transducers mounted on elevation-over-azimuth or azimuth-over-elevation mounts. (If the transducer cannot be tipped, azimuthal rotation and a probe on a gantry arm may be used.) Circular cylindrical and plane-radial scanning are next simplest, requiring only an azimuthal rotator and a linear probe transport. Circular cylindrical is useful for an azimuthally symmetric antenna on a tower. Cartesian planar scanning requires the most complicated probe transport system.

In terms of data processing, Cartesian planar scanning is by far the simplest, circular-cylindrical and plane-radial next, and spherical is the most complicated of the methods being used. The probe correction is almost trivial for the planar case, not trivial for the cylindrical case, and quite complicated for the spherical case, yet commonly needed for a wide-angle scan. If the wide-angle radiation is negligible or of no interest, a directional probe can be used with planar scanning, permitting wider spacing of measurements and truncation of the measurement area, thus reducing both the measurement and data-processing effort.

For a well-collimated pencil beam significantly smaller in cross section than an available scanning system, planar scanning is very well suited. Similarly, cylindrical scanning is quite effective for a fan beam and, with a directional probe, in determining the sidelobes of a transducer. Spherical and plane-polar scanning are well suited to a transducer with simple azimuthal dependence. For a transducer which radiates in (or is steered to) wide off-axis angles, spherical scanning is much better suited. In fact, if there is much radiation making a small angle with the scanning plane or cylindrical axis, planar and cylindrical scanning require unreasonable scanning areas and involve a marked degradation of measurement accuracy. In principle, planar scans may be made on a series of canted planes using a directional probe (with a probe correction), but this tends to be unwieldy.

III. DESCRIPTIVE SURVEY OF NEAR FIELD ANALYSIS

The unified theory is based upon generalized scattering matrix theory and symmetries arising from relativistic and gauge invariance. Hence, the theory is very comprehensive, general, and fundamental and involves few assumptions, idealizations, and approximations. Nevertheless, it provides the detailed bases for extremely efficient computer programs. For simple systems, many data reduction techniques may be used, but for highly accurate results on transducers many wavelengths across, the most efficient available techniques are required. Further, particularly for the latter systems, few approximations can be made because (a) the far field pattern is obtained by (sophisticated) extrapolation of near-field data <u>perpendicular</u> to the measurement surface and (b) good values of high-order modal coefficients are commonly required. For all types of near-field scanning, the data reduction commonly involves tens or hundreds of thousands of (a) complex simultaneous equations (one for each measurement), (b) complex unknowns (one for each exact global solution (mode) used in fitting), and (c), for the probe-pattern correction case, transformations of the set of modal coefficients (one transformation for each probe position and orientation). (This is true for Cartesian planar and cylindrical scanning as well as spherical and plane-radial, although it may not be so evident in the first two cases due to the simplicity of the analysis.) The transformations are carried out, the equations solved, and the complex-vector far field calculated (from the coefficients) for a like number of directions, all in minutes or even seconds; these times apply for the EM case, despite the complexity of the radial transformations for exact global solutions of Maxwell's equations in spherical coordinates. (Conventional techniques for the solution of simultaneous equations are completely avoided in the scalar case; sets of two equations in two unknowns remain in the planar and cylindrical EM cases, but even these may be eliminated in the spherical EM case.)

The assumptions and idealizations are three in number: (i) The system is assumed to be mathematically linear, but the treatment is easily extended to nonlinear transmitting transducers for fixed input levels. (ii) The <u>medium</u> is assumed to be invariant under certain translations, rotations, reflections, <u>and/or</u> inversion(s), depending upon the scanning procedure, but no assumption is made concerning losses. (iii) The appropriate differential equation(s) (Maxwell's in the electromagnetic case) are assumed to be obeyed. Actually, the last two assumptions are expressed in terms of symmetries and much of the analysis, particularly the orthonormalities on the measurement lattice and the DFFT, applies to systems for which the differential equations are unknown. (Except as limited by the properties of the medium and apart from some optional simplifications, all the symmetries used in this series of papers follow from relativistic invariance (Wigner's extended inhomogeneous Lorentz group [23], even for non-linear media and differential equation(s).) The symmetries explain the similarities between different physical systems (including the occurrence of the same special functions) and provide (a) general expressions in which various scanning lattices are mere special cases, (b) the modal transformations, (c) the measurement lattices, (d) the <u>natural</u> orthonormalities with respect to summation on the measurement lattices for <u>both the</u> ideal probe and probe correction cases, and (e) justification for the use of the DFFT; in fact, for mathematically linear systems, the symmetries provide all the (measurement) lattices on planar, circular cylindrical, and spherical surfaces which yield natural orthogonalities with respect to summation of the exact solutions and of the transformation coefficients of their addition theorems (required for efficient processing of the ideal probe and probe-correction cases, respectively) [22]. Although symmetry can be completely avoided for any specific physical system and scanning lattice, it is basic to a unified theory.

There are no approximations in the theory, which includes all the transmitting, receiving, and scattering properties of each transducer and both proximity and multiple reflection effects without approximation. However, two approximations are made in the numerical computations (in addition to those of the complex exponential subroutine and rounding in the computer (say after 48 mantissa bits)): (i) The infinite set of exact global solutions of the differential equation(s) is truncated. However, for spherical scanning, the set of modes actually used in the numerical computations is mathematically complete (for the given differential equation(s) and finite transducers) except for insignificant supergain modes. (ii) In transverse scanning (i.e., for measurements on a surface), multiple reflections between the transducer under test and the probe are minimized experimentally and neglected in the computations. However, they are fully treated in the extrapolation method, as are the reflections between each transducer and its source or load, even in transverse scanning. As used for Cartesian planar, plane radial, circular cylindrical, and spherical scanning, the DFFT involves no approximations beyond the already-mentioned truncation of the solution set, since only the coefficients of a finite Fourier series need be determined.

These techniques give absolute values without physical standards such as standard gain horns. A pair of transducers (transmitting and receiving) is considered to constitute a two-port and substitution measurements are made, yielding the four complex elements of the 2x2 scattering matrix as functions of the separation and relative orientations of the transducers. The patterns of the individual transducers are determined in the absolute sense with the aid of the three antenna method [13],[11], which starts with three transducers of unknown gain and polarization.

The data processing consists primarily of sophisticated curve fitting, ordinarily supplemented by a rigorous form of extrapolation (in computing the far field). Since the basis functions used in fitting the experimental data are confined to exact global solutions of the differential equation(s), pattern measurements may be confined to a surface and (in the EM case) to two vector components [15]. In the extrapolation method, spherical scanning, and the azimuthal part of cylindrical scanning, finite dimensions of the transmitting and receiving transducers are also assumed; this causes the mathematically complete sets to be discrete in these cases. Since the modes are discrete in the spherical case and the higher order modes (with high transverse spatial frequencies) are supergain modes, the finite set actually used is mathematically complete except for insignificant supergain modes. Actually, supergain modes present no special problem beyond the total number of modes, the required spacing of the measurements, and the resulting increase in measurement and computational effort; hence, the pattern of a practical supergain antenna can be accurately determined if desired. The use of exact global solutions means that no effort is wasted in determining information available from the differential equation(s) or (in the aforementioned cases) from the finite size of the transducers. These modes of course make far more effective use of measurements or computations (in a theoretical problem) than segmented ad hoc basis functions such as those used in the moment method or Simpson's rule.

At NBS, full correction is routinely made for the probe pattern, proximity effects, the complex mismatch factor (multiple reflections between each transducer and its source or load), and (for the extrapolation method) multiple reflections between the two transducers. The probe may have arbitrary directivity (even for spherical scanning), be either transmitting or receiving (even if nonreciprocal), and (in a vector field) have arbitrary on-axis polarization (ellipticity). Further, least squares fitting of the data is routine for the spherical and extrapolation methods and is optional for Cartesian planar, plane radial, and circular cylindrical scanning; truncation of the basis set provides a convenient means of rejecting high transverse spatial frequencies (e.g., supergain modes) inconsistent with the transducer design. For spherical scanning and the extrapolation method, there is automatic discrimination against not only random errors but also against some types of consistent (bias) errors; in particular, modes inconsistent with finite transducers are rejected, as are isotropic modes in spherical scanning of electromagnetic systems. Further, in the scanning of EM systems, the use of exact global solutions permits measurements to be confined to two components [15] if the propagation across the surface is only outward or inward.

A. Conceptual Errors

Unfortunately, a considerable number of conceptual errors occur in the existing literature. Some of them are corrected before presenting the mathematical analysis in the next paper. A linear combination of plane waves (or of circular cylindrical or spherical) can represent an arbitrary field, including the near, intermediate, and far zones and supergain, evanescent, and reactive modes, even in a lossy medium, to arbitrary accuracy in the mean, provided that the total energy of the field (or the portion represented) is finite. (The plane wave representation includes evanescent waves which are exponentially damped perpendicular to the scanning plane and therefore inhomogeneous.) Like supergain modes, evanescent and reactive modes present no fundamental problem in representation, but it is usually convenient in the determination of far-field patterns to have the probe far enough from the transducer under test so that the evanescent modes are insignificant, permitting wider spacing of the measurements and reduced computational effort. The far-field wave impedance is not assumed for the near, intermediate, or far zone, except asymptotically in the latter case. Multiple reflections are fully treated in the theory, although (as previously mentioned) those between the two transducers are not included in the computations of transverse scanning (except perhaps to first order). The magnetic pickup of the probe is not neglected; in fact, an ideal electric dipole probe may be used to determine the full pattern of a so-called shielded loop antenna.

According to the literature, planar, cylindrical, and spherical scanning must be based upon reciprocity. On the contrary, unless one wishes to express the receiving properties in terms of the transmitting properties or vice versa, reciprocity of the transducers is completely irrelevant. (Although burying the essential parts of a proof in a maze of familiar-but-irrelevant material may comfort the casual reader, it decreases understanding.) The transducers can be arrays containing ferrite phase shifters and isolators. Moreover, Cartesian-planar and plane-radial scanning theory and computational techniques apply to anisotropic, non-reciprocal, magnetoelectric, biaxial, birefringent, and piezoelectric media; only the mechanical properties of the medium restrict application to a general mathematically-linear perfect crystal. However, with identical probes equally-spaced in a planar surface and time-windowing to avoid multiple reflections, these techniques could be used for geophysical prospecting (EM or acoustic) in an anisotropic medium; further, the analysis and computer programs described in this series would provide for correction for the pattern of the individual probes in both the transmitting and receiving arrays (which may be the same).

In addition to explicit errors, there are erroneous implications in the literature. In processing spherical data, it is not assumed that the probe pattern approximates that of a short dipole; the probe may have arbitrary directivity. According to the literature, an exact solution in the spherical wave case is impractical because the solution of many simultaneous equations is required. In fact, for Cartesian planar, plane radial, circular cylindrical, and other types of scanning, as for spherical, there is a complex simultaneous equation for each probe position and orientation, but in the efficient processing procedures, conventional techniques for the solution of the equations are largely avoided through decoupling based upon symmetry. However, for the electromagnetic problem, only in the spherical case can the decoupling be complete so that conventional techniques can be avoided completely; Cartesian planar, plane radial, and circular cylindrical require ordinary solution of sets of two equations in two unknowns. As for exact solution being impractical in the spherical case, the set of solutions used to express the pattern of the test transducer in numerical computations is mathematically complete (except for insignificant supergain modes), but such a set is impractical for both planar and cylindrical scanning. Conceptual errors concerning reactive and evanescent modes and domains of convergence will be corrected in the forthcoming paper on the General Theory of Near-Field Scanning (Paper II).

B. Data Processing

There are two parallel treatments of scanning data; one assumes an ideal probe and the other corrects for the effect of the probe pattern upon the measured signal. In each case, the computations consist essentially of the DFFT, supplemented by matrix multiplication in the spherical case. (These multiplying matrices are independent of the test transducer, the detailed nature of the probe, the frequency, radius of the sphere, and both the number and angular positions of the measurements.) These computations supplant: evaluation of the point matching matrix and its inverse, matrix inversion, ordinary solution of simultaneous equations (at least in more than two unknowns), ordinary numerical integration, evaluation of functions of direction (even in the computation of the far field), time-consuming orthogonalization, and (in the Cartesian planar, plane radial, and circular cylindrical cases) even matrix multiplication. The procedure may be considered to involve numerical integration in which the basis functions are constrained to be exact global solutions of the differential equation(s) and perhaps otherwise constrained; therefore it is highly efficient in terms of the use of experimental data. All of these data processing schemes may be considered to be techniques of determining the response to synthetic plane waves, but this point of view provides no new computational or experimental techniques.

In a scalar field an ideal probe measures the field at a point, while in a vector field an ideal dipole measures a component (of a given polarization) at a point; thus for the ideal probe case, efficient data reduction requires orthonormalities between solutions on the measurement lattice. However, in the probe correction case, simple expressions are obtained only if the patterns of the two transducers are expressed in the same coordinate system; hence, the set of modal coefficients for one or both of the transducers must be transformed from its coordinate system to another. These transformations occur in each of the simultaneous equations which are solved in fitting the experimental data (one equation and transformation for each probe position and orientation). The transformations are the main source of the algebraic complexities, the radial transformation being particularly complicated in the spherical case. Efficient data reduction is then obtained if the transformation coefficients are orthonormal with respect to summation on the measurement lattice (weighted summation in the spherical case). For transverse scanning, the nominal axis of the probe is ordinarily kept perpendicular to the scanning surface, simplifying the transformations and mechanical design. The transformations are split into two parts, one perpendicular to the measurement surface and the other on or parallel to the surface. The former is carried out once and for all for a given probe, surface, and frequency, greatly simplifying the computations in the spherical case and increasing the efficiency in the cylindrical case beyond that of the published [10] program. The transformations on or parallel to the surface are supplanted by orthonormalities with respect to summation on the measurement lattice (see Paper II on the general theory of near-field scanning); in the Cartesian planar, circular cylindrical, and spherical cases by DFFTs, supplemented by a matrix multiplication in the spherical case.

C. Unified Theory

As previously mentioned, the unified theory is based upon symmetry analysis (theory of group representations) and generalized scattering theory. It yields explicit formulas valid for a wide range of physical systems and for various coordinate systems and scanning lattices. It also yields explicit functions which are plugged in the general formulas and which vary according to the the type of scanning lattice and, in the spherical case, parametrically according to the physical system. These formulas of course facilitate both general and detailed comparisions between various scanning and physical systems, facilitating transfer of understanding and translation of computer programs from one physical system to another.

Given enough symmetry operations (translations, rotations, reflections, and/or inversion), symmetry alone gives all the familiar modal indices for rectangular, circular cylindrical, and spherical coordinates. These are symmetry indices, like even and odd, and include: the propagation constants k_x, k_y, and k_z; the cylindrical and spherical radial constants k_R and k_r; m and n of $P_n^m(\cos\theta)\exp(im\phi)$; the angular frequency ω; and the TE,TM designation. Further, symmetry gives the explicit modal expressions including the special functions and their definitions. Moreover, symmetry gives explicit expressions for the transformations of the modal coefficients under coordinate change, during both the scanning operations and motion perpendicular to the scanning surface; determination of f(-x) from f(+x) for f even or odd is a familiar example of this process. Furthermore, symmetry specifies the measurement lattices and gives the orthonormalities of both the solutions and transformation coefficients with respect to summation on the lattice, as well as justifying the approximation-free use of the DFFT. (The author knows of no general constructive procedure which is not based upon symmetry, yet provides orthogonality of the transformation coefficients.)

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The discussion of advantages, limitations, and comparisons of various measurement techniques distils decades of experience in the NBS Antenna System Metrology group and various predecessor units; it is quite impossible to determine the origin of many conclusions of Section II and quite possible that some of them were either suggested or independently arrived at by others such as Dr. David M. Kerns, Dr. Ramon C. Baird, or Allen C. Newell.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This first paper in a series on a new unified theory of near-field analysis and measurement serves as an introduction to and a summary of some of the forthcoming papers in the series. Further, it describes the advantages and limitations of near-field scanning and compares various techniques, as well as corrects many of the conceptual errors of the literature. Being firmly based upon generalized scattering matrix theory and both relativistic and gauge invariance (Wigner's extended inhomogeneous Lorentz group [1964]), the theory is rigorous and very comprehensive, general, and fundamental, yet it provides the detailed bases of extremely efficient computer programs for reduction of both electromagnetic and acoustic measurements on planar, circular cylindrical, and spherical scanning lattices, as well as provides the basis for the most accurate method of calibrating standard gain horns (described in the series). For both the probe correction and ideal probe cases, the theory yields a series of general-but-explicit formulas which apply to the aforementioned and other lattices (including plane-radial) and to a wide variety of physical systems; plug-in expressions (given by the theory) depend upon the type of lattice and, in the spherical case, parametrically upon the physical system. The efficiency of the spherical EM programs (based upon a paper in the series) is indicated by the fact that probe-corrected least squares values of the complex coefficients of 50,000 exact global solutions of Maxwell's equations in spherical coordinates and the associated far field may be computed in a few minutes.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Acoustics; antenna gain; antenna patterns; computer programs; cylindrical scanning; electromagnetic theory; group representations; near-field analysis; near-field measurement; plane-radial scanning; spherical scanning; symmetry.

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