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DIFFRACTION, SCATTERING AND IMPEDANCE LOADING

Thomas B. A. Senior, et al

Michigan University

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Diffraction, Scattering and Impedance Loading

By
THOMAS B. A. SENIOR and VALDIS V. LIEPA

Contract No. F19628-68-C-0071
Project No. 5635
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Final Report

September 1967 – September 1972

October 1972

Contract Monitor: JOHN K. SCHINDLER
MICROWAVE PHYSICS LABORATORY

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1 INTRODUCTION

This is the final report on Contract F 19628-68-C-0071, summarizing the work carried out during the period September 1967 through September 1972. At its inception, the main goals of the Contract were the investigation of the reactive (or impedance) loading method for cross section modification, with particular emphasis on increasing the bandwidth of this technique, and the investigation of selected scattering and diffraction problems. Nevertheless, as time progressed the number of specific topics monotonically increased and at least some of these had their origins in other contracts held with the Air Force Cambridge Research Laboratories. A brief comment about these earlier and (in one case) concurrent contracts is therefore necessary to appreciate the genesis and growth of the present work.

Contract AF 19(604)6655 spanning the period 1960-1965 (Kleinman, 1965) was concerned only with diffraction and scattering. Both high and low frequency techniques were investigated but one of the objectives of the contract was the preparation of a series of reports summarizing all available information about the scattering properties of certain geometrically simple (regular) bodies. Unfortunately the breadth and depth aimed at in these reports made it almost inevitable that the earlier ones would be out-dated before the sequence could be completed, and under the successor contract, AF 19(628)4328 (1965-70), it was decided to concentrate on the preparation of a single document covering a variety of separable shapes. This task was carried out with the virtual exclusion of all other topics and culminated in the publication of a book (Bowman et al, 1969) which served as the final report.

In parallel with these studies, the reactive loading method for cross section modification was being explored under Contract AF 19(628)2374. Conceptually at least the method is an attractive one and is well suited to the resonance region where other means of cross section reduction are less effective. It can be used either to increase or decrease the scattering, and during the period 1962-67 the potentiality of this technique was examined in great detail and a number of specific applications were investigated (Senior and Liepa, 1968). For practical purposes, however, the method has a serious drawback: for every geometry considered, the load required for maximum cross section reduction is such that any simple realisation of this loading would provide a frequency coverage of a few percent at most.

The present contract was the successor to the above and it is natural that the initial focus should be on the development of techniques for overcoming the bandwidth limitation of the reactive loading method. Even at this stage, however, some attention was being given to diffraction and scattering problems, and when, in late 1970, the reactive loading work had been brought to a point beyond which it seemed unprofitable to go, the scattering work became dominant. At least some of the tasks which were now embraced were ones which had been initiated under the earlier contract but had been held in abeyance during the creation of "the book".

Since the work which has been carried out has been fully documented in the technical reports and journal articles which have been published (a complete listing is given in the Appendix), we shall here content ourselves with a survey of the contract as a whole in which many of the individual investigations rate only passing mention. For reporting purposes it is convenient to group the topics under different headings, but it should be realised that in many cases the division is somewhat artificial and there are instances, for example, the diffraction by an aperture in a spherical shell, where the description could have been included in any one of several groups.

2 IMPEDANCE LOADING STUDIES

2.1 Background

The impedance (or reactive) loading is a potentially powerful technique for modifying the scattering behavior of a body and, in particular, for reducing the back scattering in the resonance region where other methods such as shaping and the application of absorbers are less effective. Using impedance loading, it is theoretically possible to modify the scattering in almost any desired manner provided the loading has the necessary sophistication. The loading which is required to do this depends on the shape and the size of the body, the location of the load, the frequency and, in general, the direction of the incidence.

In essence, the technique is to introduce an impedance over a small portion of the surface of a conducting body by using cavity-backed slots, slots shunted by lumped elements, or slots loaded by both cavities and lumped elements. Alternatively, one can modify the scattering by attaching dipoles or other stub antennas to the surface of the body, and although such a method may appear more like a cancellation or interference procedure, it can still be classified as a form of impedance or reactive loading.

The application of the impedance loading technique to the cross section modification of such specific target shapes as dipoles, cylinders and spheres was intensively studied under Contract AF 19(628)2374. The sphere, in particular was analyzed in great detail since this is a shape for which a quasi-rigorous solution is possible. The loading impedance and other pertinent quantities could therefore be computed accurately, but in spite of the initial feeling that the geometry would profoundly affect the nature of the impedance, this did not prove to be the case. Indeed, for all of the geometries considered, the loading impedances required for some particular form of cross section control were remarkably similar, and varied with frequency in a manner that was just the opposite of that provided by a passive RLC network, microwave cavity, or terminated transmission line. If one of these devices is used to supply the desired loading, the exact impedance is then produced only at one or more discrete and (usually) widely-spaced frequencies, leading to a narrow band performance. Thus, to reduce the back scattering cross section of a sphere having ka = 4.28, Liepa and Senior (1966) showed that a circumferential slot placed at the shadow boundary and backed by a radial cavity had a bandwidth of 6.5 percent for a 10 dB reduction in cross section and only 2 percent for a 20 dB reduction.

2.2 Quest for Wider Bandwidth

In view of the small bandwidths that can be achieved using simple cavity-backed slots, most of the effort under the present Contract has been directed toward the realisation of the desired impedances using distributed, lumped, and even active elements. Attention was focussed on the problem of cross section reduction, and as typical of the loading to be obtained, the optimum loading vs. frequency curve computed by Chang and Senior (1967) for a sphere loaded with an azimuthal slot was selected. The objective was to realise this over a 2:1 bandwidth in the 50-100 MHz range.

Three different methods of realisation were investigated: (a) passive (discrete) element synthesis, (b) active synthesis and (c) the use of frequency-dependent loading materials inside cavities. Although there was some indication at the beginning that discrete RLC components could provide a bandwidth of (perhaps) 20 percent, all attempts to achieve this in practice proved unsuccessful. Nevertheless, in the course of this investigation, some interesting theoretical problems relating to the continuation of driving point impedances were uncovered. One such problem concerns the specification of the real and imaginary parts of a driving point impedance in a band $\omega_1 \leq \omega \leq \omega_2$, leaving its continuations on to $0 \leq \omega < \omega_1$ and $\omega_2 < \omega \leq \infty$ unstated. By manipulating the Hilbert transforms relating the real and imaginary parts of a function having no poles on and to the right of the $j\omega$ axis, it was shown (1-T) that if the continuations exist, they are unique and readily obtainable. Three necessary conditions were given for the existence of the continuations, and if these are satisfied, the continuations can be found using Fourier series. As examples, the continuations of four known impedances were determined, and the agreement between the Fourier series solutions (using the first six terms at most) and the exact expressions were excellent.

In view of the discouraging results of attempting to synthesize the desired loading by passive means, the subsequent effort was directed more at active devices and the possibility of using a suitable material in radial cavities and coaxial lines. The results, both positive and negative, have been detailed in the Technical Reports 7-T and 8-T. Active devices that were considered included tunnel diodes, circulators and various kinds of negative impedance converters (NIC's). The use of tunnel diodes was soon discounted due to difficulties in biasing and the instability of the circuit. It was also shown theoretically that circulators in conjunction with passive loads could not realise the impedance, so that any hope of using them had to be abandoned. NIC's, however, held out some promise of success, and of the many that were studied, the Yanagisawa NIC looked most hopeful. A circuit for use in the 5-10 MHz range was eventually constructed embodying this design, and measured values of its performance showed it able to produce a loading that would yield a 13 dB (or more) reduction in the back scattering cross section of a sphere over a 2:1 bandwidth (from $ka = 0.5$ to $ka = 1.0$).

To assess the possibility of using materials placed inside radial or coaxial cavities, the permittivity and permeability necessary to give the required load impedance were computed as functions of frequency. Unfortunately, none of the curves generated were compatible with any known real-life material. This was hardly a surprise, since the fact (McMahon et al, 1968) that the desired impedance cannot be obtained using passive lumped elements suggests that the same is true for passive distributed networks as well.

From the results obtained under this Contract it would appear that neither lumped nor distributed passive elements can provide the impedance required for broadband cross section control. The only alternative is to use active devices, and of these the Yanagisawa NIC circuit was most successful. It was shown capable of a 2:1 bandwidth in the 5-10 MHz range and could almost certainly be made to operate at higher frequencies using transistors with higher f_T's. Stability would present some difficulties, but with circuit techniques more sophisticated than those employed (e.g., using strip lines), it might be possible to produce an order of magnitude increase in center frequency. The requirements are stringent, however; a transistor with $\beta = 100$ and $f_T = 2$ GHz, for example, has a beta cut-off frequency of 20 MHz, and exhibits significant phase shift at frequencies as low as 2 MHz. Compensation techniques might make such a transistor usable at 20 or 30 MHz, but it is obvious that any substantial improvement in our capability must await the development of transistors with f_T's of 10 GHz or more, with reasonably large betas.

3 DIFFRACTION AND SCATTERING

3.1 Some Rigorous Studies

One of the objections that can be levelled at most of the theoretical investigations of reactive loading is the assumption of an infinitesimal gap across which a constant (arbitrary) voltage is assumed. If the slot is backed by a cavity, the coupling to the interior modes and, hence, the calculation of the loading presented, is achieved by individually matching the interior and exterior fields to this voltage. For most bodies this seems to be the only practical way of tackling the problem, but because of the uncertainty inherent in the approximations, it is impossible to determine the effect of slot size on the loading required.

Unfortunately there are very few problems indeed where the coupling to an interior cavity can be treated in a mathematically rigorous manner, but one that is amenable to analysis is a thin spherical shell with a circular aperture. For a plane electromagnetic wave at symmetrical incidence, Chang and Senior (5-T) expanded the interior and exterior fields in spherical modes and matched directly across the aperture. In practice, the matching was achieved in a least squares sense and to improve the convergence of the process, the field singularities at the edges of the aperture were taken into account explicitly. The resulting surface and far fields were computed for a number of aperture angles and for $0.8 \leq ka < 4.85$ where a is the radius of the sphere. In general it was found that the presence of the aperture increases the back scattering cross section except in the immediate vicinity of the resonant frequencies of the interior, where marked reductions occur. The results were confirmed by experiment.

A second problem that was considered is concerned with the effect of a very thin layer of highly conducting material on the scattering from a dielectric.

The particular model chosen was a sphere composed of a pure (lossless) homogeneous isotropic dielectric covered with a uniform metallic layer and illuminated by a plane electromagnetic wave (Senior and Desjardins: 11-T). The analysis is rather trivial and a computer program was written to calculate the back and forward scattering for sphere diameters comparable to a wavelength or less. Initially at least the results obtained were rather surprising in showing the irrelevance of the penetration depth in the metal as a criterion for estimating the transition between the dielectric and metallic sphere behaviors. It was found, for example, that the metallic sphere behavior persisted until the layer thickness had been reduced by at least 4 orders of magnitude below the penetration depth, and a further two orders of magnitude reduction was necessary to recover the dielectric sphere behavior. The results were confirmed analytically by a low frequency expansion which suggested that the extreme mismatch which occurs at the surface of the metal for all except the most infinitesimal thicknesses is the dominating factor rather than the attenuation in the metal.

3.2 Low Frequency Expansions

Under the earlier Contract AF 19(604)6655, a method was developed for obtaining the complete low frequency expansion of the far field scattered by a finite acoustically soft or hard body when illuminated by a plane wave. The method is based on the iteration of the appropriate Green's function for Laplace's equation and therefore requires the solution of only one potential problem for the body in question, in contrast to prior methods in which each term in the expansion involves the solution of a new potential problem. Although the technique had been applied to a sphere, its efficacy for a non-trivial body had not been demonstrated.

A convenient vehicle for this demonstration is the spheroid and the method has now been applied to soft and hard prolate and oblate spheroids (Asvestas and Kleinman, 1969 a, b; 1970). In each case the entire low frequency expansions was explicitly determined and recurrence relations were obtained relating the coefficients in these expansions.

It is natural to ask whether a similar method can be developed for the solution of electromagnetic scattering problems at low frequencies. This is indeed the case, though the extension is by no means trivial. Nevertheless, for a finite, perfectly conducting body Asvestas (2-r; see also Asvestas and Kleinman, 1971) succeeded in deriving two coupled integral equations for the field vectors, the kernels of which are dyadics obtainable from potential functions associated with the surface in question, i.e. solutions of Laplace's equation satisfying particular boundary conditions. At low frequencies the solution to these equations can be found by a Neumann series expansion, from which the successive terms in the low frequency expansion can be deduced. Formal recurrence relations connecting the coefficients of these terms were presented, and to illustrate the procedure the leading term in the low frequency expansion for a sphere was derived.

Theoretically, the above method is significant in establishing a systematic procedure with which all terms in the low frequency expansion can, in principle, be obtained. This holds out the lure of penetrating into the resonance region from below, but unfortunately the generality of the method is purchased at some cost: to calculate even the leading term for a body as simple as a sphere is a considerable undertaking with this method, and there is little hope of obtaining explicit values for higher order terms.

As regards the leading (or Rayleigh) term in the low frequency expansion, there are other and simpler methods for deriving it. For practical purposes, this is the term of most interest and attention was now focussed on it. As is well known, this term is attributable to the induced electric and magnetic dipoles, and for a finite perfectly conducting body illuminated by an arbitrary plane wave, a compact representation of the Rayleigh term is afforded by the electric and magnetic polarizability tensors which are functions only of the geometry of the body. Moreover, for a rotationally symmetric shape, all but 6 of the 18 tensor elements are zero, and only 3 are independent (Keller et al, 1972). Each of these can be expressed as a weighted integral of a potential function which can be obtained from the solution of an integral equation. The numerical solution of these equations was investigated (Senior and Ahlgren: 9-T) and their connection with acoustical problems explored. A computer program was written to solve the equations by the moment method, and to compute the tensor elements, the electrostatic capacity and a further quantity related to the capacity (see also Senior and Ahlgren, 1973).

3.3 High Frequency Approximations

The work that was carried out in this area divides naturally into two categories: an analysis of the properties of creeping waves, and the development of equivalent current representations for edge diffraction.

When a plane electromagnetic wave is incident on a perfectly conducting sphere or circular cylinder of large radius, a disturbance is created in the vicinity of the shadow boundary and the resulting waves propagate around the body. These waves are called creeping waves and, for these two particular geometries, their characteristics have been determined from an analysis of the exact solutions of the problems. The work of Fock and others indicates that any smooth convex body will also support these waves which now follow geodesics and have properties which, to a first order, are functions only of the local geometry. A more detailed examination of the surface field description with particular reference to the currents near to any caustic on the surface was carried out by Larson (4-T).

The integral equation for the surface field was first expressed in terms of geodesic coordinates and the azimuthal integration performed to leave a one dimensional (singular) equation with integration along the geodesic through the observation point. A variety of approximate solutions and interpretations of the homogeneous equation were presented; the source/sink character of the caustic was explored and evidence given suggesting that the field near to the caustic is similar to that on a sphere.

The second creeping wave study was of a very different nature. When a thin circular disk is illuminated by a plane electromagnetic wave at glancing incidence with its electric vector parallel to the plane of the disk, the back scattered field shows a marked oscillation as a function of frequency, and the period of this is consistent with the interference between a wave reflected from the front edge and one which has travelled around the rim. The latter appears similar to a creeping wave in spite of the nominally zero transverse radius of the rim and has been termed a 'planar creeping wave' (Senior, 1969 a). To explore this wave and determine its characteristics, the surface fields were probed on a number of disks having radii ranging from λ to 2.5λ. These showed that the current is concentrated near the rim and is exponentially attenuated away from it. Over the near portion the wave proceeds with a phase velocity which is almost that of light and with an attenuation proportional to the distance travelled. The phase velocity and the attenuation factor were deduced as functions of ka. From the resulting surface field description the back scattered field was computed and shown to be in excellent agreement with measured data (Senior, 1969b).

A more recent study has been directed at the high frequency diffraction by edges and other surface singularities. Although the geometrical theory of diffraction has proved remarkably effective for estimating this type of scattering, and is a technique which is well suited for both analytical and diagnostic purposes, it is much less convenient numerically. Indeed, it suffers the disadvantages common to all ray techniques, one of which is the identification of ray paths from transmitter to receiver and the location of flash points. The divergence factors specifying the decay in field strength along a ray must then be calculated, and at points where an infinity of rays come together, the resulting field infinity must be corrected by incorporating caustic matching functions in the analysis.

These difficulties could be overcome were it possible to find the currents existing in a neighborhood of a surface singularity. Integration would then yield directly the scattered field and in practice it is only necessary that the current be equivalent in the sense that it produces the same far field scattering as, say, first order GTD. This concept of equivalent currents was used by Ross (1967) in seeking the caustic matching functions and bears the same relationship to GTD as physical optics does to geometrical optics. It was subsequently developed by Ryan and Peters (1969) who gave explicit expressions for the equivalent ring currents at the base of a cone. However, they considered only directions of incidence which were very close to axial and the currents they obtained do not provide an adequate means for estimating the back scattered field at oblique angles.

We therefore examined anew (Knott and Senior, 1972) the problem of diffraction by a ring discontinuity in slope. For plane wave illumination at arbitrary incidence and arbitrary polarization, first order GTD was reformulated to yield a simple expression for the field scattered in an arbitrary direction in terms of electric and magnetic Hertz vectors. Equivalent (filamentary) currents were then deduced having the property that a stationary phase evaluation of the integral gives precisely the first order, wide angle GTD expression. An approximate analytic evaluation of the integral leads to the same caustic matching functions postulated by Senior and Uslenghi (1971 a) in their treatment of back scattering, and computations based on this analytical expression are in excellent agreement with values obtained by direct numerical evaluation of the integral for all angles of incidence and scattering. Comparisons were also made with measurements of the bistatic fields diffracted by a cone.

The practical and conceptual simplifications afforded by these currents are quite considerable, but there are many features of them which still have to be explored. For example, it is obvious that the currents must be similar to those implied by Ufimtsev's fringe theory (Ufimtsev, 1962), but that they are not identical is evident from the fact that the present currents permit a trivial derivation (Senior, 1972) of the correct second order (multiple) diffraction contribution, whereas Ufimtsev's theory does not (Senior and Uslenghi, 1971b).

3.4 Inhomogeneous Dielectrics

The imaging and scattering of electromagnetic fields by radially inhomogeneous dielectric regions have been studied off and on throughout the Contract. Such lenses have many interesting imaging properties, and since the refractive index is matched to unity (that of free space) at the outer surface, even the back scattered field can behave in a rather unusual manner.

Alexopoulos (3-T, 1969) considered two types of refractive index variation:

$$N(\xi) = \frac{1-\gamma}{\xi-\gamma}, \qquad \gamma \text{ arbitrary}$$

and

$$N(\xi) = \xi^p, \qquad p > -1$$

where $\xi = r/a$ with a = outer radius of the lens. The first of these is such that both radial eigenvalues satisfy the same hypergeometric equation and had not previously been explored. For a metallic sphere coated with a layer of either dielectric, the optics and creeping wave contributions to the back scattered field are determined from the known characteristics of the radial eigenvalues. Computed data are presented.

The admissible refractive index variations for which the radial eigenfunctions $S_n(\xi)$ and $T_n(\xi)$ are proportional to the same hypergeometric function were spelled out by Uslenghi (1969 b), and the explicit forms for the eigenfunctions were then given (Uslenghi, 1969 a) for two general families of lenses which include, as special cases, the Luneburg, Maxwell fish-eye, Eaton and metal-like lenses. The metal-like lens was examined in detail by Uslenghi and Weston (1970) who obtained the leading terms in the high frequency expansion of the back scattered field by application of a modified Watson transformation to the eigenfunction expansion.

A class of generalized Luneburg lenses having the property that concentric spheres are imaged on to one another has been considered by Uslenghi (1969 c). For given pairs of spheres, the refractive index variations are determined and specimen results computed (Daniele et al, 1970).

3.5 Periodic and Rough Surfaces

The study of the scattering of a plane electromagnetic wave by a two-dimensional periodic surface has been a major feature of the Contract, but though the results obtained have proved valuable in their own right, the original motivation for this work was the need for a more accurate method of estimating the back scattering from a rough surface when illuminated obliquely.

There is a wealth of papers in the published literature dealing with scattering from rough surfaces, but if there is one feature that almost all of the theoretical treatments have in common, it is their reliance on the physical optics approximation which, in essence, reduces the determination of the scattered field to quadratures. This is not to deny that there are many differences of detail, both conceptual and analytical, depending, for example, on whether the perturbed surface is defined specifically or statistically, the nature of the statistical variations assumed, the stage at which the averaging is performed, the method of evaluating the remaining surface integral, whether shadowing is taken into account (and if so, how it is approximated) etc. Still and all, the results obtained are still limited by the physical optics approximation, which takes no account of any multiple scattering, is invalid for surfaces of curvature small compared with the wavelength (small scale roughness), and provides a false estimate of shadowing.

If the surface is illuminated near normal incidence, these deficiencies are often of little consequence, primarily because the base surface (a plane) provides a strong return. As we depart from normal incidence, the surface concentrates the return in the forward (specular) direction, where the estimated scattering from the perturbed surface may remain valid, but in other directions (e. g. back scattering), all of the observed return is a consequence of the roughness, and any perturbation based on physical optics is of very doubtful validity.

In order to adequately treat the case of oblique angles of incidence on a rough surface, it appears necessary to postulate a base surface which will itself generate a back scattered return at these angles; to devise a means for accurately estimating this scattering; and then to handle by a perturbation or other technique such small scale roughness as it may be desirable to include. This is the essence of our original concept and since the most simple form of base surface having the required property is a periodic (or even a sinusoidal) one, we were naturally led to a study of scattering by a two-dimensional perfectly conducting periodic surface.

The actual work that was performed is described in Technical Reports 6-T and 10-T. For each of the two principal polarizations, the integral equations for the surface fields were cast into forms suitable for numerical solution, and the solutions found using the moment method with an interpolation scheme. Numerical data were obtained for both the surface and far fields for a variety of surface profiles. The roles played by the polarization and direction of the incident field were examined and the results compared with the predictions of physical optics. Such physical phenomena as the P- and S-type Wood anomalies were also explored.

Nevertheless, our original objective was not achieved. Although the shortcomings of the physical optics approximation were fully demonstrated, we were not successful in developing an improved analytical/empirical approximation to the surface field on the periodic surface which could then serve as a basis for treating a class of rough surfaces. Moreover, the computer program, though superior in several (small) respects to those previously available, was still so enormously expensive to run for all surfaces except those of small electrical scale that it was impractical to regard a numerical solution for the field on a periodic surface as an adequate tool for treating rough surfaces in general.

In spite of this rather negative conclusion, which should not detract from the intrinsic worth of the results for periodic surfaces that were actually obtained, we are still of the opinion that the approach suggested is the only theoretically justifiable one for treating back scattering from rough surfaces at very oblique angles of incidence; and the manner in which it might be implemented is discussed in the last chapter of Technical Report 10-T. We also investigated the affect of limiting the beamwidth of the illumination and developed a computer program for calculating the scattering from a periodic dielectric interface.

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APPENDIX

The following Technical Reports have emanated from this Contract.

1363-1-T (AFCRL-68-0349): "Network Function Determination from Partial Specification," by A. R. Braun and E. L. McMahon (June 1968).

Abstract: In certain problems of Network Theory the real and imaginary parts of a driving-point impedance function may be independently given in a band of interest ($\omega_1 \leq \omega \leq \omega_2$), leaving its continuations onto ($0 \leq \omega \leq \omega_1$) and ($\omega_2 \leq \omega \leq \infty$) completely unspecified.

By manipulating the Hilbert Transforms, relating the real and imaginary parts of a function of a complex variable ($p = \sigma + j\omega$) having no poles on the $j\omega$ axis or in the right-half plane, this report shows that if the continuations exist they are unique and readily obtained.

Three necessary conditions for the existence of the continuations to the given parts (of the driving-point impedance function) are obtained. Further, if these three conditions are satisfied the continuations may be obtained as a Fourier series.

Four known impedances were used as examples and their continuations determined. The results obtained were excellent. The agreement between the Fourier series solution (using the first six terms at most) and the exact expression was good up to the second significant figure.

In the appendix a computer program which obtains the Fourier coefficients of the unknown continuations, from the given real and imaginary parts, is furnished.

1363-2-T (AFCRL-68-0495): "Iterative Solutions of Maxwell's Equations," by J. S. Asvestas (October 1968).

Abstract: The problem of scattering of electromagnetic waves by a closed, bounded, smooth, perfectly conducting surface immersed in vacuum is considered and a method for determining the scattered electric and magnetic field vectors (solutions of the homogeneous Maxwell equations satisfying well known boundary conditions on the surface and the Silver-Muller radiation condition at infinity) everywhere exterior to the surface is presented. Specifically, two integral equations are derived, one for each scattered field vector. These equations are coupled. The kernels of the equations are dyadic functions of

position and can be derived from the solutions of standard interior and exterior potential problems. Once these dyadic kernels are determined for a particular surface geometry the integral equations can be solved by iteration for the wave number k being sufficiently small. Alternatively, the scattered fields in the integral equations may be expanded in a power series of the wave number k and recursion formulas be found for the unknown coefficients in the expansions by equating equal powers of k. As a check, the method is applied to the problem of scattering of a plane electromagnetic wave by a perfectly conducting sphere. The first two terms in the low frequency expansions of the electric and magnetic scattered fields are found and are shown to be in complete agreement with known results.

1363-3-T (AFCRL-68-0617): "Electromagnetic Scattering from Certain Radially Inhomogeneous Dielectrics," by N. G. Alexopoulos (November 1968).

Abstract: In this research, the phenomenon of electromagnetic wave propagation through, and scattering from, radially inhomogeneous dielectrics is studied for very high frequencies. The dielectrics are considered lossless, radially inhomogeneous in the spherical coordinates system, and of the converging or of the diverging type. The lens problem is studied by the geometrical optics technique and the radar cross-section of perfectly oonducting spheres coated with radially inhomogeneous dielectrics is investigated. By assuming a plane wave as the incident electromagnetic field, the contribution in the backscattering direction due to the reflected field and the creeping waves is determined by applying asymptotic theory. This necessitates the use of the WKB and/or Langer's method for the solution of the pertinent differential equations, depending on whether there exist transition points in the range for which the solutions are required. Also the integrals of Scott (1949) are needed in order to determine the reflected portion of the field.

Such a study is interesting not only from the theoretical but also from the practical point of view, in that it lends itself useful to the understanding of radio wave propagation in radially inhomogeneous dielectrics and of the effect of coating perfectly conducting spheres with radially inhomogeneous media. It also has applications to problems of wave propagation in the ionosphere and around the earth.

To begin with, a general outline of the problem and the methods of solution is given. Then, a new class of radially inhomogeneous dielectrics is introduced and it is studied by the ray tracing technique. This new class of radially inhomogeneous dielectrics is also treated as the coating of a perfectly

conducting sphere and the monostatic cross-section is examined when the dielectric is of the converging or diverging kind. Finally another class of radially inhomogeneous media, previously discussed by Nomura and Takaku, is considered and its effect in reducing or enhancing the radar cross-section of a perfectly conducting sphere is determined.

1363-4-T (AFCRL-69-0122): "Asymptotic Theory of Diffraction," by D. G. Larson (March 1969).

Abstract: Given a smooth, convex conducting body of revolution with a plane electromagnetic wave propagating in the direction of the axis of revolution, the problem considered is that of finding an expression, valid for small values of wavelength, which describes the currents in the vicinity of the caustic in the shaded region of the surface.

The problem is formulated in terms of an integral equation obtainable from a three-dimensional Green's function. The integration with respect to the azimuthal variable is carried out by two different schemes and the results discussed in relation to one another. The remaining integration, which is over a geodesic path, defines an integral equation which possesses a singular kernel. This singular equation is then studied in conjunction with a bounded kernel.

The body of revolution under consideration to this point is then specialized to the case of the sphere in order to compare the theory with known results, and some of the physical implications of the theory are discussed.

1363-5-T (AFCRL-69-0203): "Scattering by a Spherical Shell with a Circular Aperture," by S. Chang and T. B. A. Senior (April 1969).

Abstract: The electromagnetic scattering behavior of a spherical shell with a circular aperture is studied. The shell is assumed to be perfectly conducting and infinitesimally thin, and is illuminated by a plane wave symmetrically incident upon the aperture. The application of the method of least square error, as well as of a modified version is fully discussed. The modification consists of the separating out of the appropriate surface field behavior near to the edge of the aperture, and was carried out to overcome the slow convergence and marginal accuracy of the original approach. The marked improvement provided by the modification is clearly evident.

The numerical study is limited to the frequency range corresponding to $0.8 \leq ka \leq 4.85$, where a is the radius of the spherical shell, and numerical

values of the backscattering cross sections for the aperture angle $\theta_o = 30^o$ and 90^o, as well as for the tangential field components over the boundary surface for $\theta_o = 30^o$, are presented. To verify these results and to obtain more physical insight into the scattering behavior, experimental measurements of the backscattering cross sections for $\theta_o = 15^o$, 30^o, 45^o, 60^o and 90^o, and of the current components for $\theta_o = 30^o$, are obtained using two sets of spherical shell models. It is observed that a spherical shell with aperture-on incidence has, in general, a higher backscattering cross section than a solid sphere except at values of ka near to the cavity resonances, where marked reductions occur. A comparison of the numerical and experimental results is made.

1363-6-T (AFCRL-70-0507): "Scattering by a Periodic Surface," by T. C. Tong and T. B. A. Senior (September 1970).

Abstract: Numerical procedures are developed for the digital solution of the integral equations for the currents induced in a perfectly conducting, two dimensional periodic surface when a plane electromagnetic wave is incident. Data are obtained for both the surface and far fields for a variety of sinusoidal surfaces for plane waves of either polarization at oblique as well as normal incidence, and the results are compared with the predictions of physical optics.

1363-7-T (AFCRL-71-0514): "Circuit Realization of Impedance Loading for Cross Section Reduction," by E. L. McMahon (September 1970).

Abstract: Techniques for realizing a reactance which is a decreasing function of frequency are discussed. A Negative Impedance Converter (NIC) circuit is analyzed and techniques given for compensating for imperfections and frequency dependence. An RC realization of the desired impedance is given, and it is demonstrated that this realization can be modified to compensate for phase shift in the NIC. An analytical and numerical analysis of a NIC based on amplifiers with 50Ω input and output impedances is presented.

1363-8-T (AFCRL-71-0500): "Techniques for Broadband Control of Radar Cross Sections," by V. V. Liepa and E. L. McMahon (September 1971).

Abstract: Methods of realizing the load impedance required for radar

cross section control of conducting bodies are discussed. It is shown that passive loading, using frequency-dependent dielectric/magnetic materials in a radial or coaxial line, requires a frequency dependence which is not exhibited by any known material.

A number of active synthesis approaches are examined, with emphasis on those using the Negative Impedance Converter (NIC). Experimental results are given for a particular NIC realization operating in the 5-10 MHz range; the circuit is shown to be capable of producing the load impedance required for a cross-section reduction of 13 dB or more over a 2:1 bandwidth.

1363-9-T (AFCRL-72-0162): "The Numerical Solution of Low Frequency Scattering Problems," by T. B. A. Senior and D. J. Ahlgren (February 1972).

Abstract: The low frequency scattering of electromagnetic and acoustic waves by rotationally symmetric bodies is considered. By concentrating on certain quantities such as the normalised component of the induced electric and magnetic dipole moments, it is shown how the first one or two terms in the far zone scattered fields can be expressed in terms of quantities which are functions only of the geometry of the body. Each of these is the integral of an elementary potential function which can be found by solving an integral equation. A computer program has been written to solve the appropriate equations by the moment method, and for calculating the dipole moments, the electrostatic capacity, and a further quantity related to the capacity. The program is described and related data are presented.

1363-10-T (AFCRL-72-0258): "Scattering of Electromagnetic Waves by a Periodic Surface with Arbitrary Profile," by T. C-H. Tong and T. B. A. Senior (April 1972).

Abstract: Numerical procedures are developed for the digital solution of the integral equations for the current induced on a perfectly conducting, two-dimensional periodic surface of arbitrary profile when a plane electromagnetic wave is incident. By using Floquet's theorem the range of integration is reduced to a single period, and special summation techniques consisting of a Poisson summation and the subtraction of the dc term are used to improve the convergence of the infinite series representation of the Green's function. The integral equations are then solved numerically using the moment method and an interpolation scheme.

Data are obtained for both the surface and far fields for a variety of sinusoidal, full-wave rectified, inverted full-wave rectified and triangular profiles for plane waves of either polarization at oblique as well as normal incidence, and the results are compared with the predictions of physical optics.

The numerical results are used to illustrate some interesting physical phenomena, notably the P-type and S-type Wood anomalies associated with the frequency and angular responses of diffraction gratings, and to develop a scheme to estimate back scattering from a sinusoidal surface at oblique incidence.

The knowledge gained in the study of scattering from periodic surfaces is then applied to the study of rough surfaces by treating the surface as a small scale roughness superimposed upon a periodic base (representing the large scale roughness). The small scale roughness is approximated by a random function with a Gaussian distribution.

1363-11-T: "Minimal Thickness Coatings," by T. B. A. Senior and G. A. Desjardins (May 1972).

Reports 1-T through 5-T and 10-T are the Ph. D. theses of the corresponding authors (or lead authors).

The following Journal articles are based on work supported wholly or in part by the Contract.

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The three papers marked with an asterisk were distributed as Scientific Reports.