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14. ABSTRACT
A hybrid surface and volume integral equation approach is implemented for the calculation of electromagnetic scattering from dielectric material coated complex targets. The implementation includes three sets of mesh types: triangle/tetrahedron, quadrangle/hexahedron of first order, and quadrangle/hexahedron of second order (curvilinear). The solver is accelerated by the multilevel fast multipole algorithm so that electrically large sized targets can be analyzed. The program can be used for RCS analysis of complex targets, antenna-platform interaction calculation, wave propagation simulation, and microwave circuit analysis.

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TECHNICAL REPORT (FY02)

Project name:

Full-wave Modeling Using Curvilinear Surface and Volume Meshes for the Calculation of Radar Scattering from Material Coated Targets (Sponsor ID: N00014-00-1-0605)

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Date	Fund Received	Fund to be received	Total
04/10/00	$40,478		$40,478
08/06/01	$88,326		$88,326
?		$76,182	$76,182
?		$95,014	$95,014
Total	$128,804	$171,196	$300,000

Objective of the project

1. Overall technical object of the project.

    The objective of this project is to investigate a coupled integral equation technique for the accurate and efficient prediction of electromagnetic wave scattering from complex radar targets that are coated or partially coated by radar absorbing materials.

2. Specific objectives of the project in FY02.

    (a) Formulation and Implementation of curvilinear mesh.

    In order to represent the CAD mesh of a complex target, the mesh size are made very small, usually on the scale of one tenth of a wavelength. This is necessary to accurately represent the target geometry with fine and small details. If the target surface contains small and curved structures, flat patch cannot model the surface curvature. As a result, the curvilinear mesh will be included in the formulation and the program.

    (b) Verification of MLFMA for curvilinear mesh.

    The multilevel fast multiple algorithm (MLFMA) has been verified for flat quad and triangle patches. When curvilinear mesh is implemented, the accuracy and the efficiency need to be verified with exact solution.

    (c) Evaluation of the convergence in CG iteration by comparing with SIE solver.

    The high efficiency of MLFMA relies on the reduction of the matrix-vector multiplication needed in the conjugate gradient (CG) solver. However the overall solution time consists of three part: the matrix filling, the time for each iteration, and the number of iterations. In order to demonstrate the advantage of the hybrid IE solver in this project, the rate of convergence for the hybrid IE are compared with that of the SIE solver.

Quantitative impact on the Navy/DoD of meeting the technical objective

The theory and the computer program resulted from this project will provide an accurate and efficient tool for researchers and design engineers to simulate radar scattering from three-dimensional complex targets. The research results from this project can directly and indirectly benefit the following applications of Navy and DoD: Low observable vehicle analysis and design, radar antenna placement on complex platform, radar signature prediction of complex vehicle for target recognition, and virtual electronic combat simulation.

1. It is well known in stealth technology that two important means for reducing radar scattering of a vehicle are by choosing a special shape and by material coating. A reliable and efficient computer software that can simulate radar scattering from complex targets can greatly speed up the process for searching the optimum shape and optimum material coating.

2. Based on the principle investigator's knowledge and the publicly available literatures, today's design engineers rely on experiments as well as on approximate numerical methods in the design of modern low observable vehicles. Experimental methods take long time and cost more than numerical simulation. Moreover, experimental methods usually cannot give out optimum design. The program from this project provides high solution accuracy compared to the approximate methods.

3. The currently available computer programs that can accurately predict the radar scattering of realistic size are only for conducting objects. Stealth target often have partial coating by absorbing material. Two important approaches that can handle material coating are: (a) the hybrid finite-element method and boundary integral equation method, (b) the hybrid surface and volume integral equation method. The latter method is investigated in this project.

4. The radar scattering signature of a vehicle is the most important characterization in target recognition. Often a target's signature is stored in a data base that is used for target recognition. The radar signature of a vehicle can be obtained via: (a) Measurement, (b) Numerical computation. The measurement is not always possible beside the high cost involved. An example is that when the vehicle is in design process, one cannot do any measurement to get the signature. Another important example is that we cannot do any experiment to get the signature of a foreign/enemy vehicle. However, by numerical method, we only need the CAD mesh of the vehicle to predict its signature. The computer program resulted from this project can be used for this purpose.

5. The radar, communication, and navigation of a vehicle rely heavily on RF and microwave antennas. Mounting an antenna on a vehicle will generally: (a) affect the performance of the antenna itself, (b) affect the performance of other antenna and electronic systems. This is due to the interference between the antenna and the mounting platform. It is not always possible to actually mounting an antenna on the vehicle to determine the optimum location of mounting. In addition, when the location of mounting cannot be changed, we need to know the degree by which the performance is degraded. The computer program from this project has the potential to predict the performance of antennas when mounted on a complex vehicle. The program is accurate and efficient over previous computer programs that are either not accurate or not efficient.

6. In virtual electronic combat simulation, radar beam pattern and target signature pattern are very important parameters for modeling realistic radar and targets. These data are retrieved from a data base that is prepared before the simulation. There is no way, except by numerical calculation, to get signature for a vehicle that does not exist or for a foreign vehicle. The accuracy of these data is important to ensure a realistic simulation. Again the computer program from this project can be used for this purpose.

Technical issue description of the project

1. Technical issues that are resolved and/ or remaining in order to achieve the technical objective.

The major technical issues that have been resolved:

(a) The hybridization of the surface and volume integral equation.
(b) The selection of unknown function for the volume current.
(c) Curvilinear implementation
(d) Convergence rate evaluation for the hybrid operators

In the following, we present the details of each issue and the approaches applied to resolve them.

(a) The hybridization of the surface and volume integral equation.

Previous studies by other researchers were mostly focused on either the volume integral equation (VIE) or the surface integral equation (SIE). The VIE study are mainly to investigate the scattering characteristics of dielectric material. The SIE research has a long history because most conventional radar targets are made of conductors and the scattering properties can be obtained by solving the surface integral equation. For low observable vehicle design or for vehicle with antenna radome, both material and conductor present in a vehicle. A natural way is to combine the SIE and VIE. One problem for this direct combination is the poor conditioning of the matrix resulted. We have introduced a normalized basis function to expand the surface current and volume current to make the matrix elements balanced so that the condition of the impedance matrix is improved.

To show how this is resolved, consider the hybrid surface-volume integral equations,

$$\text{SIE: } \vec{L}(\vec{r},\vec{r}\,')\cdot\vec{J}_S(\vec{r}\,')+\vec{L}(\vec{r},\vec{r}\,')\cdot\vec{J}_V(\vec{r}\,')=-\vec{E}^{inc}(\vec{r}), \quad \vec{r}\in S$$
$$\text{VIE: } \vec{L}(\vec{r},\vec{r}\,')\cdot\vec{J}_S(\vec{r}\,')+\vec{L}(\vec{r},\vec{r}\,')\cdot\vec{J}_V(\vec{r}\,')-\vec{E}=-\vec{E}^{inc}(\vec{r}), \quad \vec{r}\in V$$

In the above, $\vec{L}(\vec{r},\vec{r}\,')$ is the integral operator that maps the current into electric field intensity. In the SIE, the tangent component for each term is implied. Consider the expansion of the unknown functions by two sets of basis functions, one set is for the surface current $\vec{J}_S$, and the other set is for the volume current $\vec{J}_V$:

$$\vec{J}_S(\vec{r})=\sum_{n=1}^{N_s} a_n^S \vec{f}_n^S(\vec{r}), \qquad \vec{r}\in S$$
$$\vec{J}_V(\vec{r})=\sum_{n=N_S+1}^{N_S+N_V} a_n^V \vec{f}_n^V(\vec{r}), \qquad \vec{r}\in V$$

Note that the unit of $\vec{J}_S$ is A/m, and the unit of $\vec{J}_V$ is A/m^2. Since both basis functions, $\vec{f}_n^S$ and $\vec{f}_n^V$, are unitless, then the expansion coefficients, a_n^S and a_n^V, will carry units of A/m and A/m^2, respectively. The difference in the unit of the expansion coefficient is balanced by the impedance elements. In other words, the matrix elements will have different units which is not desired for matrix solvers, as the unbalanced matrix element tend to high condition number. Eventually this leads to more iterations (more CPU time) for a convergent solution.

To overcome this difficulty, we modified the basis function to absorb the unit difference in the surface and volume currents so that the expansion coefficients carry the same unit, and so do the matrix elements. This is done by dividing the surface basis function by its edge length and the volume basis function by the area of the common face. The modified basis functions are related to the original basis functions by the following two equatins:

$$\tilde{\vec{f}}_n^S(\vec{r}) = \frac{1}{l_n}\vec{f}_n^S(\vec{r}), \qquad \tilde{\vec{f}}_n^V(\vec{r}) = \frac{1}{S_n}\vec{f}_n^V(\vec{r})$$

Note that now the modified basis function for surface current has a unit of 1/m and that for the volume current has a unit of $1/\text{m}^2$.

(b) The selection of unknown function for the volume current.
Even though there are many studies previously on the volume integral equation, however few researchers realized the importance of selecting the correct unknown function. The reason is that earlier studies used the simplest basis function (the pulse basis function) to approximate the unknowns, hence either the current or the total electric field can be used as the unknown function and the other is a derivable. To increase the solution accuracy, linear basis functions are used in this project; hence we face an issue of selecting the basis function in the formulation. According to the properties of the basis functions used (the extended RWG basis function), we choose to use the displacement current as the unknown function and derive the total field from this current.

From Maxwell's equation (Ampere's law), we derive the equivalent volume current to be

$$\vec{J}_V(\vec{r}) = i\omega\left[\varepsilon_b - \varepsilon(\vec{r})\right]\vec{E}(\vec{r}),$$

here, ε_b is the dielectric permittivity of the background media in which the target resides. For example, if the target is in air, then $\varepsilon_b \approx \varepsilon_0$, the value in free-space. If the target is under water, then ε_b is that of the sea water. The permittivity for the coated material on the target is indicated by $\varepsilon(\vec{r})$ which is a function of position, meaning the coatings are different from place to place. Since $\vec{J}_V$ and $\vec{E}$ are related by this equation, a straight forward approach is to choose either $\vec{J}_V$ or $\vec{E}$ as the unknown function inside the material. However it turns out that when basis function for continuous vector functions are used to represent the unknown functions, we encounter a problem of violating the boundary condition for $\vec{J}_V$. This problem happened when $\varepsilon(\vec{r})$ has discontinuities from cell to cell. It is known that the boundary condition across the interface of two dielectric materials is that the normal component of the electric flux density vector $\vec{D}$ is continuous.

Hence we choose the displacement current $\vec{J}_d = i\omega\varepsilon(\vec{r})\vec{E}(\vec{r})$, that is proportional to $\vec{D}$, as the unknown function. Since $\vec{J}_d$ is proportional to the flux density, the boundary condition is satisfied when the basis functions that are continuous across two cells are used to expand the unknown function. From the solution to $\vec{J}_d$, the equivalent volume current $\vec{J}_V$ and the total electric field intensity $\vec{E}$ can be derived.

(c) Curvilinear implementation

In FY01, the formulation and the program are completed for the first order mesh, i.e., the flat quadrangle and the flat faced hexahedron. The preliminary implementation used the triangle and tetrahedron cells. Accepting two types of mesh gives the users flexibility in solving real world problems, because sometimes, triangle/tetrahedron mesh are more appropriate to model a target that than using other meshes.

To model small and fine details of a target with curvatures, it is necessary to use curvilinear mesh. It is known that the solution accuracy depends on two parts: one part is the accuracy on geometry modeling, and the other is the accuracy on the representation of the induced currents. Sometimes, the geometry modeling error will dominate. For example, it is difficult to model a sphere of radius less than one tenth of a wavelength by flat patches whose sizes are of the same order as the radius of the sphere. This is easily done by using curvilinear patches.

With the addition of curvilinear mesh, the program will include the follow pairs of mesh types:

Triangle/Tetrahedron (first order)
Quadrilateral/Hexahedron (first order)
Quadrilateral/Hexahedron (second order, the curvilinear mesh)

A problem with different geometry meshes in one program is that multiple subroutines of similar function are needed. This is not desired in program because it increases the debugging time, and most importantly, it is difficult for maintaining. This issue is resolved by writing the basis functions for all the geometry meshes into a uniform type. The uniform basis function that applicable for surface meshes, as well as for volume meshes, are given by

$$\vec{f}_n(\vec{r}) = \frac{\vec{b}_n(\vec{r})}{\sqrt{g}} , \qquad \nabla\cdot\vec{f}_n(\vec{r}) = \frac{D_n}{\sqrt{g}}$$

In the above two equations, $\vec{b}_n$ is a vector and D_n is a scalar, $\sqrt{g}$ is the Jacobian of the transform which maps a cell of arbitrary shape in x-y-z space into a unit cell in u-v-w space. A unit surface quad-cell is a square of unit side-length, and a unit volume cell is the cube with side-length equal to unit. The introduction of the uniform basis function not only solved the problem of adding the curvilinear mesh into the program, but also opens the door for other basis functions. With the addition of the curvilinear quad-patch mesh, the program now is expanded to include three pairs of meshes as shown in Table 1.

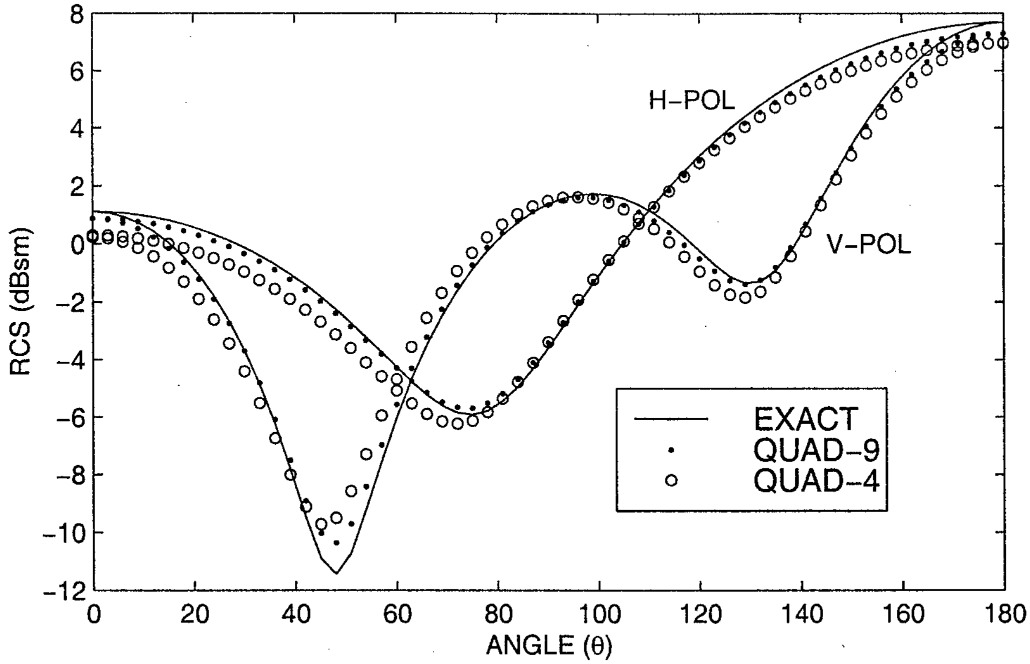


Figure 1. The bi-static radar cross section of a conducting sphere with radius 0.3 m at the frequency of 300 MHz. The caption "QUAD-9" stands for curvilinear mesh (second order), and the "QUAD-4" stands for the flat-shaped mesh (first order). In both models, the number of patches used is 96.

Table 1. A list of mesh types that has been implemented in the hybrid IE program for mixed material and conducting surface modeling

Mesh order	Surface model	Volume model
First	Triangle (specified by 3 pointes on vertex)	Tetrahedron (specified by 4 points on vertex)
First	Quadrilateral (specified by 4 points on vertex)	Hexahedron (specified by 8 points on vertex)
Second	Quadrilateral (specified by 9 points on vertex)	Hexahedron (specified by 27 points on vertex and center of cell

(d). Convergence rate evaluation

Three important hypotheses behind the hybrid volume-surface integral equation algorithm are:

- Better conditioned matrix equation (which means fast convergence rate)
- Easy to integrate with multilevel fast multipole algorithm (which means efficient in memory and CPU time for iterative solvers).
- Capable of handling position dependent dielectric permittivity (which means the program can handle non-uniform coatings).

The first hypothesis, the better conditioned matrix equation, is based on the argument that the volume integral operator is more smooth than the surface integral operator, and hence it produces a bettered conditioned matrix. To verify this, we implemented a SIE program to solve the scattering from mixed conducting and material objects. The SIE is based on the combined field equation formulation and is valid for uniform materials only. Using the same mesh size and comparable number of unknowns, we compare the number of iterations needed to reach the same residue error for a same problem for: (i) the hybrid surface volume integral equation approach (the VSIE in this project), and (ii) the SIE approach. It is found that the VSIE needs significantly less number of iterations to converge compared to SIE approach. This has important impact on the overall solution time because for multiple excitations, the CPU time is proportional to the number of iterations.

As an example, consider a conducting plate of triangular shape that is coated on its three sides by dielectric material, as shown in Figure 2. The VSIE and SIE are used to calculate the mono-static radar cross section (RCS) on the horizontal plane. Figure 3 shows the comparison of the solutions which indicates that the two solutions are close to each other. However the SIE approach needs much more iterations than VSIE to reduce the residue error from 1.0 to 0.001. Table 2 shows the details of the comparison for the triangle objects as well as for a number of other types of objects.

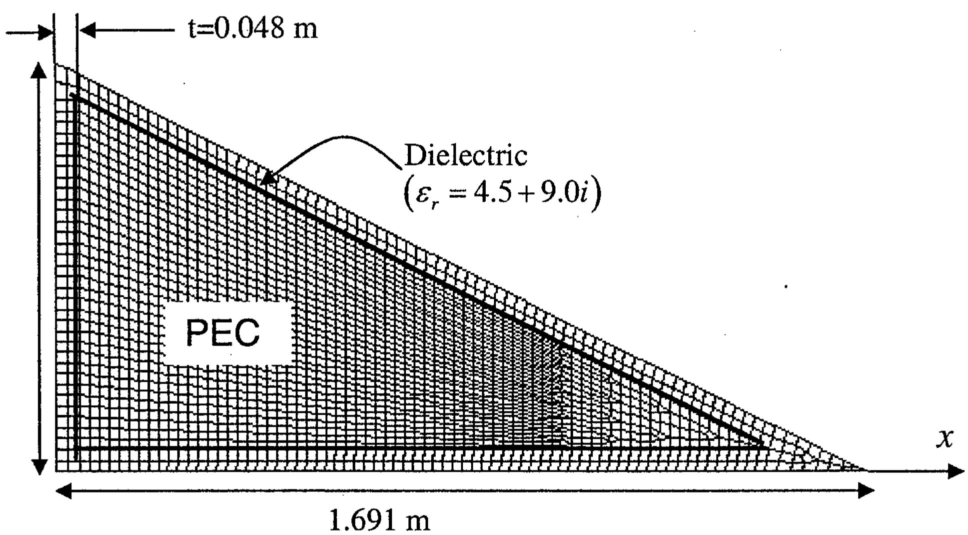


Figure 2. The mesh of the coated triangular plate. The coating material has the same thickness as the conducting plate and is uniformly coated on the three sides.

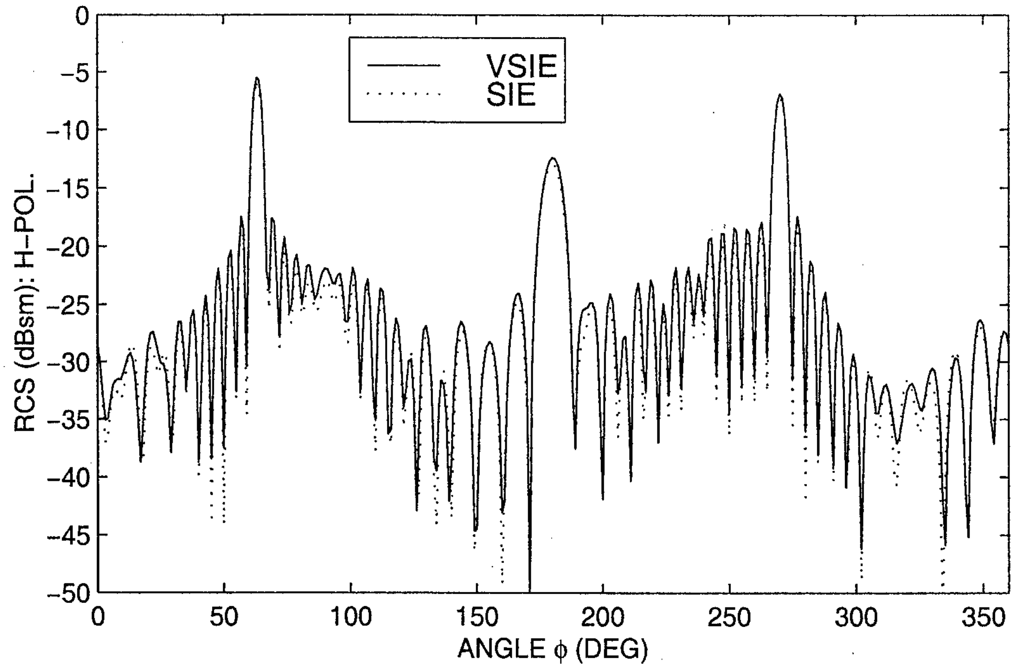


Figure 3. The mono-static RCS of a triangle PEC plate of finite thickness that is coated by dielectric material on its three sides. CFIE with combination constant of 0.7 is used in both SIE and VSIE programs.

Table 2. The comparison of the run-time parameters for the SIE and VSIE programs using the same CG solver (the number of iterations are the average for all mono-static incident angles except for the Bi-static sphere case for which the iteration number is for the first incident angle).

Examples	Residue Error	Number of Unknowns		Average Iteration Number		RCS Error (rms) dB	
		SIE	VSIE	SIE(V/H)	VSIE(V/H)	V-Pol	H-Pol
Cylinder	0.001	4368	7920	65/66	22/25	0.42	0.29
Box (mesh 1)	0.005	1512	1884	324/117	22/21	3.05*	4.26*
Box (mesh 2)	0.005	3240	3772	146/89	10/10	0.91*	2.36*
Box (mesh 3)	0.005	5964	6672	112/77	7/7	0.25	0.88
Sphere	0.001	5184	5184	161/160	94/97	0.48	0.66
Triangle Plate	0.002	11840	10610	128/83	9/10	2.75†	1.75†

*The mesh size for SIE and VIE are different (the mesh for SIE is too coarse). †The large error in this case is caused by the rapid oscillation in the RCS because the target size is large.

From table 2, for triangle plate, the average number of iteration per angle is 128 for SIE and 9 for VSIE (V-Pol). If both algorithms consume the same amount of CPU time for the matrix-vector multiply (this is a reasonable assumption for most coated objects), this means the SIE will need about 10 times more CPU to converge for solving the same problem than the VSIE. From table 2, we find that the iteration numbers for VSIE in generally are much smaller than that of the SIE. This verifies that the hypothesis about the iteration advantage of VSIE over SIE is true.

2. Technical issues that are remaining in order to achieve the technical objective.

The technical issues that are remaining can be cast into two categories: The issues that are predicted (mentioned) in the original proposal for which procedures have been proposed to resolve them, and the issues that are not predicted, but emerged during the implementation process. The issues in the first categories will be resolved in the remaining year of the project, i.e., FY03. The issues in the second category will not affect the achievement of the proposed objective, but rather they are mostly enhancement to the program for even wider applications. Remaining issues that will be resolved in FY03 and the procedures to resolve them are listed below.

(i) The matrix filling program is not optimized

The overall CPU time for the VSIE program depends on three factors: the preparation (mesh process and matrix filling), the time for each matrix-vector multiplication, and the number of iterations. The application of multilevel fast multipole algorithm has reduced the time for matrix-vector multiplication by orders of magnitude, hence this part has been optimized. Using the VSIE operators, the number of iterations is usually smaller than that of the SIE operators. To further reduce CPU time for the program, it is necessary to optimize the matrix filling part. This is even important for bi-static or multi-frequency applications.

The matrix filling time may be comparable in some problems to the time consumed by the rest of the solvers. It is estimated that by optimization, the matrix filling time can be reduced by a factor of 2 to 4. The procedure of optimization is to perform the integration using the cell-based loop. The current program used the basis-to-basis loop, leading to redundant calculations. This redundancy is more significant in the volume integrals.

(ii) The continuous dielectric permittivity

Currently we have assumed that the permittivity is piece-wise continuous between cells for the coating material. This is ideal for modeling layered coatings. However to model materials with continuous permittivity, it is necessary to include continuous permittivity into the program. For this purpose, we propose to describe the permittivity by curvilinear interpolation: $\varepsilon(\vec{r}) = \sum_{k=1}^{M} \varepsilon_k P_k(u,v,w)$. Here M is the number of vertices of the cell (4 points for the flat quadrilateral, and 27 points for the curvilinear hexahedron), $P_k(u,v,w)$, $k = 1,2,\cdots,M$ are the interpolation polynomials.

(iii) Magnetic material

The current formulation and program assumed that $\mu = \mu_b$ (a constant that is equal to that of the background media). This satisfies the condition for most applications. However in some special cases, magnetic material may present (for example, radar absorbing material). Hence it is necessary to include magnetic material into the program. This can be done by introducing a new unknown function, the magnetic current, and a new operator, the K-operator, into the formulation and program.

The above issues will be resolved in FY03. To make the program even more powerful, it is possible to hybridize the line integral into the VSIE program so that it can handle line source and wire/surface/volume scattering and radiation problems. In addition, our preliminary experiments showed that the number of iterations can be reduced further by implementing proper pre-conditioners in the CG solver. These are the issues that we found important during the implementation, but they are not proposed. The implementation of these features will depend on Navy/DoD interests and funding.

Milestones and timeframes across the life of the project by which progress and potential of success can be assessed

	Month 1-6	Month 7-12	Month 13-18	Month 19-24	Month 25-30	Month 31-36
Theory & formulation						
Implementation Flat mesh						
Implementation MLFAM						
Implementation Curvilinear						
Optimization of program						
Validation & Simulation						
Documentation And reporting						

The progress and major accomplishments made during the last year

During the last year (April 1, 2001 to March 31, 2002), we have performed the following tasks:

(a) Evaluated the convergence rate of the hybrid VISE program and concluded that the matrix condition for the VSIE algorithm is smaller than that using the SIE alone. Some examples on this progress are shown in Figures 2, 3, and Table 2.
(b) Implemented the curvilinear mesh in the program. This allows the user to use curvilinear mesh to model complex targets to very fine details. A test example on the advantage of the curvilinear mesh is shown in Figure 1 on the previous pages.
(c) We did some testing cases for the VSIE program. For example we have applied this program to evaluate the effect of radome on antenna radiation.
(d) We add input impedance calculation feature. This will transit the program for applications other than RCS calculation.

The major accomplishments of the results obtained over the life of the project

Major accomplishments:

(a) We have completed most of the theoretical formulation of the program, and verified that the hybrid volume-surface integral equation approach possesses a number of advantages, which includes better conditioned matrix system, easier to implement the fast solvers, and capable of handling non-uniform dielectric materials. Hence this approach has the potential to be developed into a powerful and useful computer simulation tool for electromagnetics, antennas, and microwave applications.
(b) We have successfully implemented the hybrid VSIE algorithm into a working program that can be used for a number of applications, including (but not limited to) radar cross section calculation, antenna-platform interaction analysis, wave propagation simulation, microwave circuit analysis.
(c) We have solved the mesh truncation problem in solving the volume integral equations.
(d) We have implemented the program with multiple mesh types. This gives the user of the program flexibility to model targets with different types of meshes. The implementation of the curvilinear mesh in the program is especially important in that complex structures can be modeled in very fine details; this removes the error due to geometry modeling to minimum.

Application examples

To demonstrate the achievements from this project, and to show the status of the program, the following shows two examples that are generated by the computer program from this project.

Example 1: the effect of coating on radar cross section. In this example we calculate and compare the RCSs a conducting plate with and without material coating (Figure 4). This example shows how the program can be applied to low observable vehicle design.

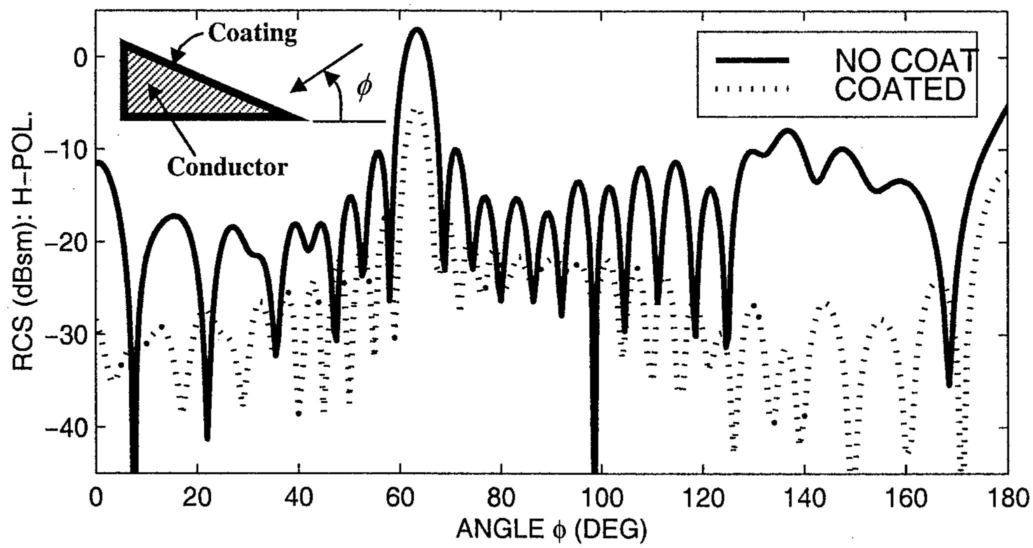


Figure 4. The Mono-Static RCSs of a PEC plate with and without material coating. The coating has reduced radar cross section significantly for all incident angles.

Example 2: The effect of radome on antenna array radiation. In this example we compare the effects of various radome shapes on the radiation pattern and pointing error of a dipole array (Figure 5). This example shows how the program can be applied for antenna-platform interaction calculation and analysis.

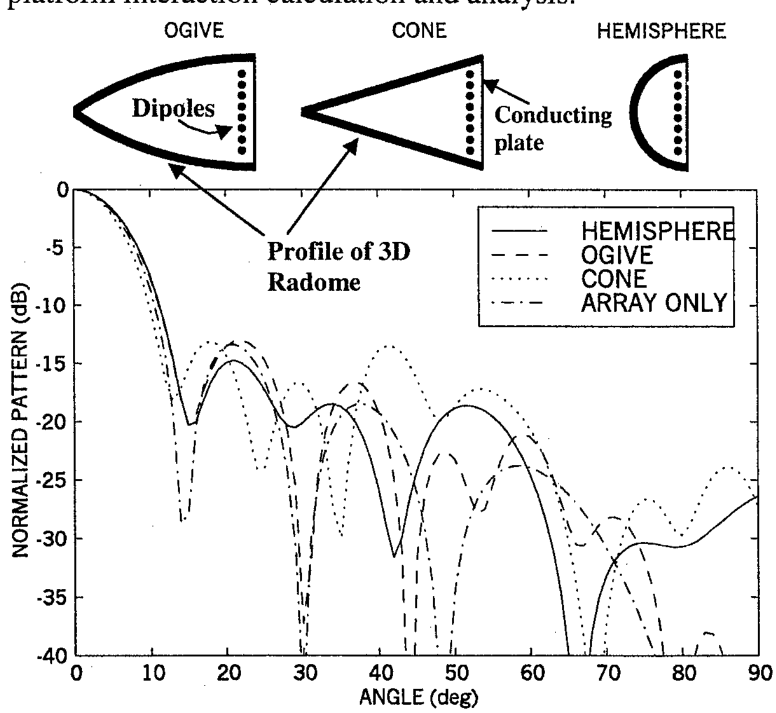


Figure 5. The comparison of the normalized radiation of a dipole array in the presence of three types of radome shapes: (a) ogive shape (dash line), (b) straight cone shape (dotted line), and (c) hemisphere shape (dots). The radiation of the same dipole array in free-space is also plotted for reference (The cross view of the radome profiles are shown on top of the plot, in which the small solid dots stand for the dipole elements. Dipoles are oriented in z-direction).

Example 3: The input impedance calculation for printed antennas. In this example, we calculate the input impedance of a printed patch antenna on a finite and curved substrate (Figure 6, 7). Most current commercial software assumes flat and infinitely large substrate and ground plane. The program from this project is able to handle substrate/ground plane with finite size and arbitrary shapes. This example shows how the program can be applied for dual DoD and commercial problems.

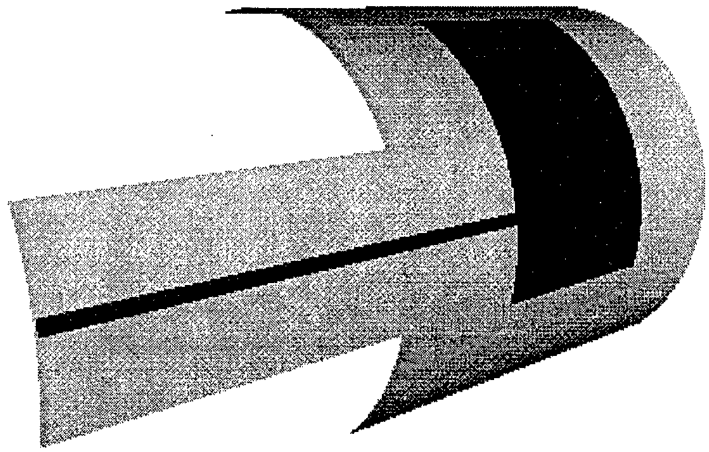
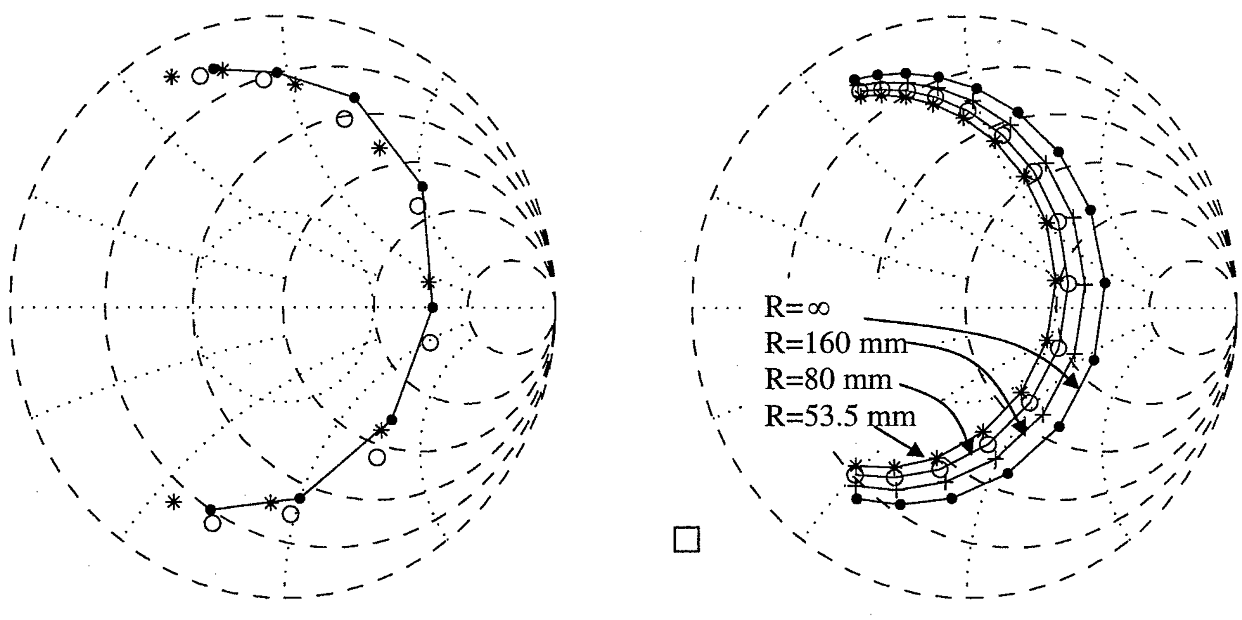


Figure 6. The printed patch conformal antenna on a curved substrate and ground plane that simulates curved vehicle surface.



(a) (b)

Figure 7. *(a)* The input impedance of a flat rectangular patch antenna: ***: calculated by VSIE in this paper, o o o: calculated by the integral equation approach with spectral domain Green's function, ---- (Solid line): measured results. **(b)** Input impedance of a curved rectangular patch antenna with different radius of curvature: . . . (flat, i.e.,R=∞), +++(R=160 mm) , o o o (R=80 mm), * * * (R= 53.5 mm).

Transition Plans

The research results from this project can be extended into a number of other DoD as well as commercial applications. The following efforts have been made for the transition of technology.

(a) The hybrid surface-volume algorithm can be applied to simulate wave propagation in complex environment. For example, it can be used to search for an optimum transmitter location in a building for maximum transmission coverage. For this purpose, we have added two features in the program. One is to calculate the near-field of radiation, and one is to add the dipole antenna as radiation source instead of a remote radar in RCS application. These two features allow users to calculate field distribution inside and outside a complex room (including fixed furniture) as well as in a building. We have some simulation results published on technical journals.

(b) The program can be applied to evaluate the microwave radiation distribution in human body and hence to evaluate the radiation effect of wireless cell phone and other microwave source on human health.

(c) With the ever increasing of the clock speed on computers and other electronic devices, the wave feature in high-speed circuits will dominant, and hence the traditional circuit theory needs to be modified for the high frequency applications. The modification of the theory relies on the extraction of circuit parameters at microwave frequencies. Since in general a high-speed printed circuit consists of dielectric material (substrate) as well as conductors (ground plane, wires, leads, and interconnects), our hybrid volume-surface integral equation can be modified for circuit analysis. For this purpose, we have added a feature in the program to calculate input impedance of microwave circuits. We are planning to added S-parameter extraction function to the program as well so that multi-port microwave circuits can be analyzed.

Monthly planned and actual budget (in $, Month 1 is May 2000)

MONTH	PLANNED BUDGET	EXPENDITURES*	SPONSOR FUND
05/00	8095.60	0	40,478
06/00	8095.60	7290	
07/00	8095.60	5914	
08/00	8095.60	5909	
09/00	8095.60	4847	
10/00	8193.83	4948	
11/00	8193.83	2110	
12/00	8193.83	2323	
01/01	8193.83	3589	
02/01	8193.83	4867	
03/01	8193.83	6099	
04/01	8193.83	7253	
05/01	8193.83	8350	
06/01	8193.83	8825	
07/01	8193.83	19060	
08/01	8193.83	12705	88,326
09/01	8193.83	8668	
10/01	8431.92	4431	
11/01	8431.92	3808	
12/01	8431.92	3965	
01/02	8431.92	6254	
02/02	8431.92	8268	
03/02	8431.92		
04/02	8431.92		
05/02	8431.92		
06/02	8431.92		
07/02	8431.92		
08/02	8431.92		
09/02	8431.92		
10/02	8573.29		
11/02	8573.29		
12/02	8573.29		
01/03	8573.29		
02/03	8573.29		
03/03	8573.29		
04/03	8573.29		
TOTAL	300,000.00	139,483	128,804

* The numbers shown in this column are the amount after the indirect rate is corrected.

Budget remaining (for FY02 and FY03): $171,196.

The positive balance in the first few month in 2000 is due to delay in graduate student and pos doc hiring. This has been reported in writing to ONR in 2001.

Summary

This report presented the overall progress and achievements for the last two years of the project period, with emphasis on the FY02. The hybrid surface-volume integral equation algorithm has been implemented for first order and second order quadrilateral meshes. The multilevel fast multipole algorithm has been integrated into the program so that it can handle electrically large-sized complex targets. The program has been applied to (a) calculate radar cross section of dielectric coated targets, (b) analyze of the interaction of antenna array with radomes, (c) extraction of the circuit parameters of high-speed circuits. The test and verification of the program demonstrated that it has a number of advantages over the surface integral equation based algorithm. The research results from this project have important impact on low observable vehicle design, signature prediction for target recognition, antenna placement, and microwave radiation evaluation and assessment.