ARMY RESEARCH LABORATORY

Characterization of the Effects of Cavities and Canopies on Radar Target Signatures

Geoffrey H. Goldman

ARL-TN-154

February 2000

Army Research Laboratory
Adelphi, MD 20783-1197

ARL-TN-154 February 2000

Characterization of the Effects of Cavities and Canopies on Radar Target Signatures

Geoffrey H. Goldman
Sensors and Electron Devices Directorate

Abstract

I conducted a literature search on electromagnetic models for cavities and canopies and their effect on radar target signatures. This report is a simple analysis of cavities as well as a review of electromagnetic codes that simulate the radar backscatter of targets with cavities. I also review imaging and parametric techniques to describe targets with cavities and canopies. Finally, recommendations are offered for enhancing signature generation for hardware-in-the-loop (HWIL) and software-in-the-loop (SIL).

Contents

Figures

1. Introduction

The radar backscatter from military targets has been extensively investigated since the start of World War II. The principles of radar are based on Maxwell's equations, which were first published in 1873. Hertz showed in 1886 that electromagnetic waves could be reflected by metallic and dielectric bodies. Several investigators simultaneously made advancements in the field of radar prior to World War II. The tactical advantages obtained using radar systems during World War II spurred increased research and development.

The radar signature of an object is its amplitude, phase, and polarization response to radar illumination [1]. Several scattering mechanisms have been identified for complex targets such as planes, tanks, and missiles. To help identify these mechanisms, a target can be considered as a collection of independent simple shapes. The scattering mechanisms listed by Knott in descending order of significance are reentrant structures, specular scattering, traveling waves, edge and vertex diffraction, creeping waves, interactions between simple shapes, and surface discontinuities [2]. Scattering by reentrant structures is listed before specular scattering because most specular scattering will not be returned to a monostatic radar, while reentrant structures will often produce significant backscatter. This provides strong motivation for further study of reentrant structures such as cavities and canopies.

The definition of cavity resonator according to the IEEE Standard Dictionary of Electrical and Electronics Terms is a space normally bounded by an electrically conducting surface in which oscillating electromagnetic energy is stored, and whose resonance frequency is determined by the geometry of the enclosure. The Electronics Designers' Handbook further defines resonant cavities as devices whose physical dimensions are on the order of a wavelength of the energizing source. Resonant cavities can also be classified according to whether or not they have reentrant structures. Reentrant structures have metallic boundaries that extend into the interior of the cavity and "trap" the radiation.

The backscatter of radar signals from targets can be described as a wave or particle phenomenon. At radar high frequencies, the photons in the electromagnetic waves behave like billiard balls bouncing off a surface; the angle of incidence is equal to the angle of reflectance. At lower frequencies, the electromagnetic waves induce currents and charges on the surface of a target, which in turn create fields that reradiate. The scattering regime is dependent upon the ratio of the wavelength (λ) of the radar signal to the size of the target (L). For cavities, L refers to the largest dimension on the opening of the cavity, not the length. The scattering regimes are Rayleigh scattering for $\lambda >> L$, resonance region scattering for $\lambda \approx L$, and the high frequency region for $\lambda << L$.

The scattering regime for canopies and cavities of military targets depends on the radar system and the targets of interest. Analysis of target signatures is important for surveillance, tracking, and fire-control radar systems, which cover a wide range of radar frequencies. Typical cavities on military targets are jet engine and rocket inlets and exhausts, antennas and electrooptic sensors and their covering, and the region between a tank turret and the chassis. Analysis of cavities in target signatures can potentially be performed in all scattering regimes. A canopy is an overhanging cover. A canopy on a jet or a helicopter will generally be a reentrant structure in the high-frequency or resonance regime if the material used to construct the canopy is translucent to the radar signal. Stealth targets will have a canopy that is either highly absorptive or reflective of wideband radar signals. For the Rayleigh scattering regime, energy will not propagate into a cavity or canopy. Conceptually, this is analogous to energy not propagating in a waveguide below the cutoff frequency. Therefore, this region is usually not of interest.

2. Cavity Backscatter

For the high-frequency regime, ray-tracing techniques can often be used to approximate the radar cross section (RCS) backscatter. For an untreated cavity, energy conservation requires that energy in is equal to energy out. For a cavity with sufficient multiple bounces to randomize the direction of the exiting energy, the RCS is equal to twice the effective area of the opening of the cavity. The lip or rim also can have a significant RCS backscatter. The RCS for a rounded edge is $\sigma = \lambda a / 2\pi$ and the RCS of a knife edge is $\sigma = L_e^2 / \pi$ for specular incidence with the electric field perpendicular to the edge [3]. The RCS of the contribution from the untreated lip of a cavity is on the same order as that of the interior of the cavity. For a waveguide-like structure excited by high-frequency radiation, we can calculate the propagation velocity using ray-tracing techniques. The velocity of a wave in the direction of the axis of the waveguide is approximately the speed of light multiplied by the cosine of the incident angle, and the scattering is not dispersive.

For the resonance region, multiple modes can be excited, depending upon the shape and material of the cavity, similar to the modes of a waveguide with shorted endplates. A mode refers to an electromagnetic wave with a structure that remains the same as it propagates. The mode with the lowest cutoff frequency is called the dominant mode. The smaller the size of the cavity, the higher the cutoff frequency. A wave that contains neither electric nor magnetic field in the direction of propagation is referred to as transverse electromagnetic (TEM). A wave that contains electric field but no magnetic field in the direction of propagation is referred to as transverse magnetic (TM). A wave that contains magnetic field but no electric in the direction of propagation is referred to as transverse electric (TE). Hybrid waves require all field components and can be considered as a coupling of TE and TM modes by the cavity boundary. Resonance circuits are often described by

$$Q = \omega \frac{U}{W_L} , \qquad (1)$$

where Q = quality factor, ω = frequency, U = energy stored, and W_L = average power lost. High Q values characterize cavity resonators. Coupling structures, such as a coaxial cable acting as an electrical probe or a waveguide with slots or holes, are required to transfer energy into and out of the cavity. Targets with exterior-interior coupling often generate high Q resonances. For example, diffraction from the external rim of a cavity can be coupled with the modes in the interior of the cavity. We can illustrate the mechanisms for the RCS backscatter from a cavity in the resonance region by examining the theory associated with waveguides. The propagation velocity of the dominant mode in a waveguide for a frequency that is just above the cutoff frequency is well below the speed of light. As the frequency is increased, the velocity of the dominant mode in the direction of the axis of the waveguide approaches the speed of light.

The natural resonances embedded in some target signatures can be used by radar systems for noncooperative target recognition (NCTR) [4]. Much research is focused on reducing the radar signatures of our military assets. Three basic mechanisms are used to reduce the backscatter from cavities. First, the cavity can be placed in a low-energy region such as in the interior of the target or in a region shielded by other structures. Second, the rim or edge of the cavity can be shaped and treated with radar absorbing material (RAM). Third, the cavity can be shaped, shielded, and treated with RAM or lossy inserts. Radar reduction techniques have been extensively studied and have a large effect on the backscatter from cavities. Most of the research done in this field is classified.

3. Modeling Cavities

Numerous techniques are available to predict the EM (electromagnetic) backscatter from targets with cavities. Exact analytic solutions for the fields radiated by cavities have been found only for very simple geometries. For example, a two-dimensional slot in an infinite ground plane and a three-dimensional rectangular box have been solved using separation of variables and mode-matching techniques. For more complicated targets, exact numerical solutions are based upon either the integral or partial differential form of Maxwell's equations. Numerous codes and techniques have been developed with the goal of decreasing computation time without significantly degrading accuracy. In fact, Shlager and Schneider compiled a total of 2300 publications from 1966 to 1997, including 430 publications in 1997 on a subtopic of this field [5]. Solutions based upon partial differential equations (PDEs) are applied to targets with complex penetrable materials and complex geometries in a finite space, while solutions based upon integral equations (IEs) are usually applied to perfect electric conductor (PEC) targets in an unbounded space. The IEs can be solved using the method of moments (MoM), the fast multipole method (FMM), or recursive T-matrix algorithms (RTMAs), and the PDEs can be solved using the finite-difference time-domain (FD-TD) method or the finite element method (FEM). FMM and RTMA solutions decrease the computation time relative to MoM solutions, but have a small degradation in accuracy. The FMM technique is an iterative solution that requires $O(N^{1.5})$ operations per iteration as opposed to MoM, which is a direct technique that has $O(N^3)$ computational complexity [6]. Targets described by bodies of revolution (BORs) and bodies of translation (BOTs) can be solved more efficiently by taking advantage of symmetries [7]. Further improvements in computation time can be achieved by using approximate solutions.

For targets in the high-frequency regime, codes that use ray-tracing or physical optics-based calculations can provide good results, provided that limited coupling exists between subsections of the target. Mature RCS prediction codes such as Xpatch and Computer-Aided-Design Drafting Scattering (CADDSCAT) are capable of generating signatures of large complex targets from geometric models [8,9]. Xpatch became a product of Science Applications International Corporation (SAIC) when it recently acquired DEMACO, and CADDSCAT became a product of Boeing when it acquired McDonnell Douglas. In general, there are large errors associated with modeling targets with cavities using high-frequency codes. The accuracy of high-frequency codes can be improved by combining exact and approximate solutions with significantly less computation time compared to that of MoM and FD-TD codes.

Hybrid techniques attempt to model RCS backscatter by subdividing a target and accurately modeling each section, then combining the solutions so that the fields match at the boundaries. Various levels of hybridization exist, ranging from simple superposition to multiple interactions. Hybrid techniques can be formulated as either field-based or current-based analysis. For example, current-based techniques, such as physical optics (PO), can be used to approximate induced currents on large simple structures, and MoM techniques can be used to calculate induced currents on smaller cavities. Significant efforts are currently being made to develop hybrid techniques to model the radar signatures of large complex targets.

A major effort by the Department of Defense (DoD) is under way to improve the computational electromagnetic (CEM) capabilities through the Parallel Computational Electromagnetics for Simulation Enabling Technology Transition at Enhanced Rates (PACE SETTER) project [10]. This project is supported by the Electromagnetic Code Consortium (EMCC) and funded by the Office of the Secretary of Defense (OSD) and through the High Performance Computing Modernization Office (HPCMO). PACE SETTER is an HPC (high-performance computing) software support initiative and is part of the Common High Performance Computing Software Support Initiative (CHSSI) in the Computation Technological Area (CTA) of computational electromagnetics and acoustics. DEMACO, now a division of SAIC, is the lead contractor, and Analytic Designs, IBM, Northrop Grumman, Rockwell, the University of Illinois, HyPerComp, and the University of Michigan are subcontractors. The program started in February 1997 and is funded for 5 years. Xpatch was selected by the PACE SETTER project as the high-frequency code with which other low-frequency and hybrid codes will be integrated. The integration will include a user-friendly graphical user interface (GUI), a common set of analysis tools, and three-dimensional CAD models that can be used by each CEM method.

Numerous techniques have been developed to model the RCS backscatter from cavities that are being integrated into Xpatch. Brick is an FEM code that can be used to predict scattering from a cavity, slot, and protruding antennas [11]. It was developed by the Active Electronic Countermeasures (ECM) Branch of Wright Laboratory's Avionics Directorate and is based on a University of Michigan code. AIMJET is hybrid code used to model the backscatter from jet engines. It uses the Adaptive Integral Method (AIM) to analyze the scattering from engine blades and was written by Hristros Anastassiu at the University of Michigan Radiation Laboratory. Xcavity is an FEM-based code used to simulate small cavities, gaps, and apertures and was written by Jian-Ming Jin when he was at the University of Illinois; he is now with SAIC. The fast Illinois solver code (FISC) is an FMM code used to predict the backscatter from geometrically small PEC and impedance boundary condition (IBC) targets. It was developed by J. Song, C. Lu, W. Chew, and S. Lee, along with the DEMACO division of SAIC [12,13].

Numerous other techniques can be used to predict the RCS of cavities [14]. Researchers at the University of Illinois have published extensively in this area [15–18]. Neilson et al describe a method for computing the resonance frequencies in a cavity consisting of a series of waveguide sections [19]. DoD has conducted extensive classified research on predicting the RCS of engine inlets and the effect of canopies; this research is slowly being declassified or downgraded [20–23]. The best code for modeling military targets with cavities and canopies is application dependent, but the quality of the individual codes selected in the PACE SETTER project, together with the added value of the integrated environment, makes this approach the potentially preferred solution for solving many problems. A beta version of the Xpatch 4.0 was scheduled for release in July 1999.

The two major competing goals for a predictive EM code are accuracy and speed. Moore's Law predicts that every 18 to 24 months, the computation speed of computers will double. Steady increases in computational capacity, coupled with the improvements in hybrid EM codes, will enable increases in simulation accuracy simultaneous with decreases in computer simulation time. The weak link in the accuracy for many complex targets will shift from the EM code to the description of the target. Real targets have thousands of parts with various materials, configurations, weathering effects, and tolerances. These factors make it difficult to describe targets with known designs. Foreign targets with unknown designs are even more difficult to describe.

4. Target Signature

The effect of cavities and canopies on target signatures can depend upon frequency, orientation, and polarization. However, for targets with isolated waveguide-like structures, components of the signature can be independent of both the polarization of the radar signal and the orientation of the target. For hardware-in-the-loop (HWIL) and software-in-the-loop (SIL) simulations, target signatures can be computed efficiently and accurately from point-scatter models [24]. Point-scatter models of complex targets are typically generated from measured inverse synthetic aperture radar (ISAR) images [25]. Figures 1 and 2 show a geometric model and a 2-D ISAR image of a 1:30 scale model for a Lockheed VFY-218 airplane provided by the Electromagnetic Code Consortium and reproduced from Wang et al [26].

The brightness on the right side of the image in figure 2 is due to radiation resonating in the engine inlets, which gets delayed in time and dispersed in frequency. For targets with cavities that have high Q values, features of the image can be repeated in downrange and extend significantly beyond the end of the target. Many instrumentation radar systems are designed to measure target signatures within a narrow range window and will truncate this effect.

It is difficult to capture the effects of cavities and canopies on target signatures using traditional point-scatter modeling techniques [27]. In general, the RCS backscatter from cavities is large and dispersive as a function of time and frequency. This violates the assumption used by most imaging algorithms and can result in artifacts and "incorrect" image locations [28,29]. If the scattering is nondispersive, image location errors will occur due to multibounce effects. Even if a sufficient number of scatterers are used to capture these blurred areas in the image, rotating the scatterers will generate errors in the new signatures.

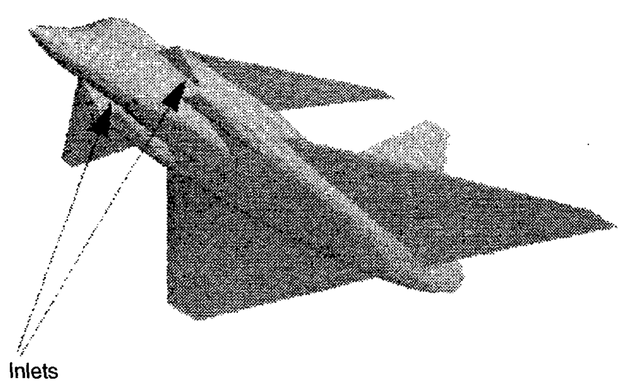

Figure 1. Geometric model of a VFY-218 airplane.

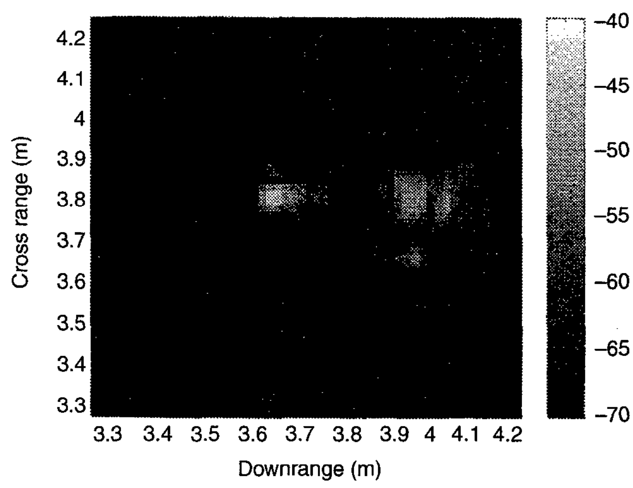

Figure 2. ISAR image of VFY-218 scale model for frequencies 8 to 16 GHz and angles 0 to 40°.

Research in the area of noncooperative target recognition (NCTR) for ultra-wideband systems can be extended to analyzing the effects of cavities on target signatures for low-bandwidth systems. Ultra-wideband radar signals can excite complex natural resonance frequencies that are embedded in the target signature. High-frequency target signatures of targets with cavities have similar resonance characteristics. Although ultra-wideband target signatures will generally vary as a function of aspect angle and polarization, their natural resonance frequencies are invariant and can be used for target identification. Ultrawideband signatures have been parameterized using Prony's method and the singular expansion method (SEM) [30–32], which decompose the signal into damped exponential functions. These techniques require modification before they can be applied to lower bandwidth systems seeking larger targets because specular returns cannot easily be separated from the returns of resonating cavities.

Several imaging algorithms are available to "correctly" image targets with dispersive features. Borden describes a technique to reduce the artifact in the image of a truncated waveguide [33]. The downrange image of the waveguide will appear as a zero-order Bessel function that is shifted, dilated, and blurred. Borden describes a technique to deconvolve the effects of each mode in the waveguide from the image. The algorithm requires that the dimensions of the waveguide are known. Joint time-frequency (JTF) techniques have been used to image targets with dispersive features [34–36]. Algorithms have been developed that combine JTF and ISAR imaging techniques [37–39]. These techniques decompose the image into time-dependent Gaussian-basis functions that can be recombined to reduce or highlight dispersive features. A technique called matching pursuits can be used to image targets with nonorthogonal basis functions [40]. A "dictionary" of nonorthogonal functions is chosen that corresponds with features in the signature of the targets [41]. This technique is similar to CLEAN, which attempts to extract point-scatter functions from the image [42].

Because of the complexity of military targets, nonanalytic solutions are an appealing approach for target signature parameter estimation. Nonanalytic techniques such as genetic algorithms, expert systems, and neural networks can be combined with analytic and/or nonanalytic models to characterize target signatures. Rihaczek and Hershkowitz [43] describe a generic model to characterize the effects of dispersive scattering from complex targets. They suggest that the blurring in ISAR images computed using range-Doppler techniques can be modeled with a cubic phase distortion. Goldman uses a hybrid genetic algorithm/expert system to identify parameters in the model suggested by Rihaczek and Hershkowitz. Li et al [44] use a genetic algorithm to identify model parameters for a model suggested by Altes [45]. More sophisticated algorithms can be developed by combining other analytic and nonanalytic methods. Initially, nonanalytic algorithms usually require more computation time, but for many applications the final results are computationally efficient.

5. Conclusion

The effect of cavities and canopies on target signatures can depend upon frequency, orientation, and polarization. However, for isolated waveguide-like structures and targets in the resonance region, invariant features can be embedded in the signature. For targets with cavities that have high *Q* values, features of the image can be repeated in downrange and extend significantly beyond the end of the target. Target signatures can be obtained using a variety of techniques with trade-offs among speed, accuracy, and robustness. Currently, target signatures of large, complex targets are usually obtained from radar measurements. The signature of smaller targets can be simulated using exact numerical solutions. The signature of larger targets can be computed using approximate solutions, but dispersive features such as cavities and canopies cannot be accurately reproduced. The PACE SETTER project is developing an integrated environment with the potential to increase both the speed and accuracy of simulating target signatures. However, EM predictive codes require detailed models describing target geometry and composition, which often do not exist.

HWIL and SIL simulations often use point-scatter models to simulate target signatures. Point-scatter models derived from ISAR images of measured or simulated data do not accurately represent the phenomenology associated with cavities or canopies. The size of the resulting errors in HWIL or SIL simulations depends upon the application, and for many cases it is negligible [46]. When increased accuracy is required, either the point-scatter models should be supplemented or new techniques should be used to characterize the signatures. Improvements in the simulation of target signatures are required to meet the constraints of the particular HWIL or SIL environment.

Numerous analytic and nonanalytic techniques are available to identify and quantitatively describe the effects of cavities and canopies on target signatures. Once the effects are determined, point-scatter models can be supplemented by adding time- and frequency-dependent amplitude and phase terms.

Acknowledgments

I would like to thank Herb Dropkin and Ron Chase for their assistance in gathering and interpreting information relating to this report.

References

1. Web address: http://www.nawcwpns.navy.mil/~rrl/pages/defs.html.
2. E. F. Knott, "Radar observables," ch. 4 in *Tactical Missile Aerodynamics: General Topics* **141**, M. Hemsch, ed., AIAA, Washington, DC (1992).
3. J. F. Shaeffer, "Hip-pocket estimation, data presentation, and reduction," ch. 14 in *Radar Cross Section*, 2nd ed., E. F. Knott, J. F. Shaeffer, and M. T. Tuley, eds., Artech House, Boston (1993), p 562.
4. M. A. Morgan and P. D. Larison, "Natural resonance extraction from ultra-wideband scattering signatures," *Ultra-Wideband Radar: Proc. 1st Los Alamos Symposium*, B. W. Noel, ed., CRC Press, Boca Raton (1992).
5. K. L. Shlager and J. B. Schneider, "A survey of the finite-difference time-domain literature," ch. 1 in *Advances in Computational Electrodynamics, The Finite-Difference Time-Domain Method*, A. Taflove, ed., Artech House (1998).
6. L. Gurel, "Fast radar cross section (RCS) computation via the fast multipole method," NATO/AGARD (SPP) (7 October 1996).
7. H. M. Al-Rizzo, J. M. Tranquilla, S. M. Al-Amri, and H. T. Alhafid, "Application of the generalized multipole technique (GMT) to high-frequency electromagnetic scattering from perfectly conducting and dielectric bodies of revolution," *J. Comput. Phys.* **136** (1997), pp 1–18.
8. S. W. Lee, *Xpatch: A High Frequency RCS Computation Code for Facet Targets and Curved Patches*, DEMACO, Technical Report (August 1992).
9. D. M. Elking, J. M. Roedder, D. D. Car, and S. D. Alspach, "A review of high-frequency radar cross section analysis capabilities at McDonnell Douglas Aerospace," *IEEE Trans. Antennas Propag.* **37**, No. 5 (October 1995).
10. B. Marsolf, S. Kosanovich, D. Andersh, and J. Hughes, *Large Scale Multidisciplinary Electromagnetic Computations*, American Institute of Aeronautics and Astronautics, AIAA-98-2475 (1998). See www.demaco.com/papers/sbr1/.
11. W. Kent, G. Wilson, J. Berrie, and N. Albright, *Advanced Warning Receiver Antenna Analysis and Design*, Air Force Weapons Laboratory, WL-TR-93-1113 (July 1993).
12. J. M. Jin, F. Ling, S. T. Carolan, J. M. Song, W. C. Gibson, and W. C. Chew, *A Hybrid SBR/MoM Technique for Analysis of Scattering From Small Protrusions on a Large Conducting Body*, Center for Computational

Electromagnetics, Research Report No. CCEM-24-97, University of Illinois at Urbana-Champaign (5 September 1997).

13. J. M. Song, C. C. Lu, W. C. Chew, and S. W. Lee, *Fast Illinois Solver Code (FISC) Solves Problems of Unprecedented Size at the Center for Computational Electro-magnetics, University of Illinois*, Research Report No. CCEM-23-97 (27 August 1997).

14. T. D. Hubing, *Survey of Numerical Electromagnetic Modeling Techniques*, TR91-1-001.3 (1991).

15. J. Jin, *Electromagnetic Scattering From Large, Deep, and Arbitrarily Shaped Open Cavities*, Center for Computational Electromagnetics Research Report No. CCEM-28-97, University of Illinois at Urbana-Champaign (23 September 1997).

16. X. Q. Sheng, J. M. Jin, J. M. Song, C. C. Lu, and W. C. Chew, *On the Formulation of Hybrid Finite-Element and Boundary-Integral Method for 3D Scattering*, Research Report No. CCEM 7-97 (30 April 1997).

17. C. C. Lu and W. C. Chew, *A Near-Resonance Decoupling Approach (NRDA) for Scattering Solution of Near Resonant Structures*, Research Report No. CCEM-15-96 (21 November 1996).

18. S. T. Carolan and J. M. Jin, *Hybridization of the Method of Moments and the Shooting-and-Bouncing-Ray Method for Scattering From Large Geometries With Small Protrusions*, Research Report No. CCEM-16-97 (2 July 1997).

19. J. M. Neilson, P. E. Latham, M. Caplan, and W. G. Lawson, "Determination of the resonant frequencies in a complex cavity using the scattering matrix formulation," *IEEE Trans. Microwave Theory Techniques* **37**, No. 8 (August 1989).

20. J. D. Kelly and G. A. Taylor, *RCS of Engine Cavities*, DTECH D 180-18898-1 (1975).

21. L. A. Nicholls, *A Study of a Ray-Tracing Method for the Theoretical Estimation of the Radar Cross Sections of Engine Intakes of Jet Aircraft at Microwave Frequencies*, Weapons Systems Research Laboratory, Australia, WSRL-0297-TM (1983).

22. J. H. Lawrence, *Windshield Technology Demonstration Program*, Air Force Flight Dynamics Laboratory, AFFDL-TR-77-1 (July 1975).

23. S. A. Owens, *Automation of an RCS Measurement System and Its Application to Investigate the Electromagnetic Scattering From Scale Model Aircraft Canopies*, Air Force Institute of Technology, AD-A215 741 (December 1989).

24. R. F. Olson, *Real-Time MMW Target Signature Model Implementation on an I860 Multiprocessor System*, Simulation Technologies, Inc., CR-RD-SS-97-25 (December 1996).

25. W. P. Yu, L. D. To, and K. Oh, "N-point scatterer model RCS/glint reconstruction from high-resolution ISAR target imaging," *Proc. End Game, Measurement, and Model Conference* (1991), pp 197–212.

26. H.T.G. Wang, M. L. Sanders, and A. Woo, "Radar cross section measurement data of the VFY 218 configuration," TR NAWCWPNS TM-7621, Naval Air Warfare Center, China Lake, CA (January 1994) as cited in S. Qian and D. Chen, *Joint Time Frequency Analysis, Methods and Applications,* Prentice Hall, NJ (1996), pp 238.

27. A. W. Rihaczek and S. J. Hershkowitz, "Man-made target backscatter behavior of conventional radar resolution theory," *IEEE Trans. Aerosp. Electron. Syst.* **32**, No. 2 (April 1996), pp 809–824.

28. G. Dural and D. L. Moffatt, "ISAR imaging to identify basic scattering mechanisms," *IEEE Trans. Antennas Propag.* **AP-42** (January 1994).

29. H. R. Witt and E. L. Price, "Scattering from hollow conducting cylinders," *Proc. Inst. Elec. Eng.* **115** (January 1999).

30. M. P. Hurst and R. Mittra, "Scattering center analysis via Prony's method," *IEEE Trans. Antennas Propag.* **AP-35** (August 1987), pp 986–988.

31. C. E. Baum, *The Singular Expansion Method, Transient Electromagnetic Fields,* L. B. Felsen, ed., Springer-Verlag, New York (1976).

32. R. Carriere and R. L. Moses, "High resolution radar target modeling using a modified Prony estimator," *IEEE Trans. Antennas Propag.* **AP-40** (January 1992) pp 13–18.

33. B. Borden, "Reduction of radar artifacts caused by target inlets," *IEEE Trans. Antennas Propag.* **AP-47**, No. 5 (May 1999).

34. A. Moghadder and E. K. Walton, "Time-frequency-distribution analysis of scattering from waveguide cavities," *IEEE Trans. Antennas Propag.* **AP-41** (May 1993), pp 677–680.

35. H. Ling and H. Kim, "Wavelet analysis of backscattering data from an open-ended waveguide cavity," *IEEE Microwave Guided Wave Lett.* **2** (April 1992), pp 140–142.

36. M. Carr, J. L. Volakis, and D. C. Ross, "New time-frequency techniques for identification and extraction of scattering mechanisms," *Antennas and Propagation Society International Symposium* **1** (June 1998), IEEE.

37. L. C. Trintinalia and H. Ling, "Extraction of waveguide scattering features using joint time-frequency ISAR," *IEEE Microwave Guided Wave Lett.* **6**, No. 1 (January 1996).

38. V. V. Chen and S. Qian, "Reconstruction of ISAR image by joint time-frequency transformation," *Signals, Systems, and Electronics, Proc. ISSSE '95,* URSI International Symposium (1995), pp 251–254.

39. L. C. Trintinalia and H. Ling, "Joint time-frequency ISAR algorithm for imaging targets with non-point scattering features," *Signals, Systems, and Electronics, Proc. ISSSE '95,* URSI International Symposium (1995).

40. S. G. Mallat and Z. Zhang, "Matching pursuits with time-frequency dictionaries," *IEEE Trans. Signal Process.* **41**, No. 12 (December 1993), pp 3397–3415.

41. P. Runkle and L. Carin, "Multi-aspect target identification with wave-based matching pursuits and continuous hidden Markov models," *Proc. 1999 IEEE International Conference on Acoustics, Speech, and Signal Process.* **4** (1999), pp 2115–2118.

42. J. Tsao and B. D. Steinberg, "Reduction of sidelobe and speckle artifact in microwave imaging: The CLEAN technique," *IEEE Trans. Antennas Propag.* **AP-36**, No. 4 (1988), pp 543–556.

43. G. H. Goldman, *Preliminary Study of a Hybrid Genetic Algorithm/Expert System for Modeling Complex Radar Signatures*, Army Research Laboratory, ARL-TR-2028 (October 1999).

44. Q. Li, J. Rothwell, K-M Chen, and D. P. Nyquist, "Scattering center analysis of radar targets using fitting scheme and genetic algorithm," *IEEE Trans. Antennas Propag.* **AP-44**, No. 2 (February 1996).

45. R. A. Altes, "Sonar for generalized target description and its similarity to animal echolocation systems," *J. Acoust. Soc. Am.* **59** (January 1976), pp 97–105.

46. K. R. Harrison, *Validation of Longbow Primary Test Vehicle Target Model*, Simulation Technologies, Inc., TN-131-068 (February 1990).

Distribution

Admnstr
Defns Techl Info Ctr
Attn DTIC-OCP
8725 John J Kingman Rd Ste 0944
FT Belvoir VA 22060-6218

US Army Aviation Missile Cmnd
Attn AMSAM-RD-SS-HW R Applegate
(3 copies)
Attn AMSAM-RD-SS-HW J Jordan
Redstone Arsenal AL 35898-5000

Simulation Techl
Attn J Cole
3307 Bob Wallace Ave SW 4
Huntsville AL 35805-4066

US Army Rsrch Lab
Attn AMSRL-SE-RM S Stratton
Aberdeen Proving Ground MD 21005

US Army Rsrch Lab
Attn AMSRL-DD J Miller
Attn AMSRL-CI-LL Techl Lib (3 copies)
Attn AMSRL-CS-AS Mail & Records Mgmt
Attn AMSRL-CS-EA-TP Techl Pub (3 copies)
Attn AMSRL-SE-R A Sindoris
Attn AMSRL-SE-R B Wallace
Attn AMSRL-SE-RM C Ly
Attn AMSRL-SE-RM E Burke
Attn AMSRL-SE-RM G Goldman
(15 copies)
Attn AMSRL-SE-RM H Dropkin
Attn AMSRL-SE-RM J Silvious
Attn AMSRL-SE-RM K Tom
Attn AMSRL-SE-RM R Wellman
Attn AMSRL-SE-RM T Pizzillo
Attn AMSRL-SE-RM D Vance
Attn AMSRL-SE-RU R Damarla
2800 Powder Mill Rd
Adelphi MD 20783-1197

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE February 2000	3. REPORT TYPE AND DATES COVERED Summary, 5/99-11/99

4. TITLE AND SUBTITLE Characterization of the Effects of Cavities and Canopies on Radar Target Signatures

5. FUNDING NUMBERS
DA PR: AH16
PE: 62120A

6. AUTHOR(S) Geoffrey H. Goldman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Attn: AMSRL-SE-RM email: ggoldman@arl.mil
2800 Powder Mill Road
Adelphi, MD 20783-1197

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TN-154

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783-1197

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
ARL PR: 0NE4H1
AMS code: P622120.H16

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
I conducted a literature search on electromagnetic models for cavities and canopies and their effect on radar target signatures. This report is a simple analysis of cavities as well as a review of electromagnetic codes that simulate the radar backscatter of targets with cavities. I also review imaging and parametric techniques to describe targets with cavities and canopies. Finally, recommendations are offered for enhancing signature generation for hardware-in-the-loop (HWIL) and software-in-the-loop (SIL).

14. SUBJECT TERMS
Cavity, canopy, radar, target signatures

15. NUMBER OF PAGES
23

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102