# REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

| 1. AGENCY USE ONLY ( Leave Blank) | 2. REPORT DATE<br>09/22/99 | 3. REPORT TYPE AND DATES COVERED<br>Final Progress Report 08/15/96-08/14/99 |
|---|---|---|

**4. TITLE AND SUBTITLE**
Modeling and ATR for Foliage and Ground Penetating Radar

**5. FUNDING NUMBERS**
DAAH04-96-1-0388

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**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

*ARO 35550.1-EL*

19991101 120

**11. SUPPLEMENTARY NOTES**
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

**12 a. DISTRIBUTION / AVAILABILITY STATEMENT**

Approved for public release; distribution unlimited.

**12 b. DISTRIBUTION CODE**

**13. ABSTRACT (Maximum 200 words)**

This project has involved both numerical simulation of electromagnetic scattering and the associated signal processing for ultra-widenband synthetic aperture radar (SAR) for foliage and ground penetrating radar (FOPEN and GPEN, respectively). With regard to the modeling, we have developed a fast multipole method (FMM) model for electromagnetic scattering from electrically large conducting targets in the presence of a half space, with application to scattering from surface/subsurface unexploded ordnance (UXO), as well as for scattering from surface vehicles, such as tanks. The FMM simulator is significantly faster than conventional method-of-moments (MoM) solvers. allowing solution of problems that were heretofore intractable. The code has been delivered to the Army Research Laboratory (ARL), and successfully compared with data measured by ARL. In addition to this modeling, we have developed hidden Markov model (HMM) automatic target recognition algorithms, applicable to the SAR detection and discrimination of concealed targets. Within the context of the HMM, we have employed a physics based matching pursuits feature parser. This signal processing paradigm has been successfully applied to ARL-measured FOPEN and GPEN data.

**14. SUBJECT TERMS**
fast multipole method, hidden Markov model, SAR

**15. NUMBER OF PAGES**
4

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OR REPORT<br>UNCLASSIFIED | 18. SECURITY CLASSIFICATION ON THIS PAGE<br>UNCLASSIFIED | 19. SECURITY CLASSIFICATION OF ABSTRACT<br>UNCLASSIFIED | 20. LIMITATION OF ABSTRACT<br>UL |
|---|---|---|---|

NSN 7540-01-280-5500
Standard Form 298
(Rev.2-89)

DTIC QUALITY INSPECTED 4

## A. Statement of the Problem Studied

Over the three years of funding, significant progress has been made on both signal processing and electromagnetic modeling for FOPEN and GPEN SAR. Considering first the modeling, we have developed a fast multipole method (FMM) simulator for electrically large targets embedded in a half-space region (i.e., for targets in the vicinity of soil). The model is applicable to very general targets, including buried or surface unexploded ordnance (UXO), vehicles and weapons. The model is also applicable for simulating the scattered fields from fiducial targets (trihedrals) placed above soil, these models playing a critical role in the calibration of foliage penetrating (FOPEN) radar systems, such as the ARL BoomSAR. In the future we will apply the FMM model for calibration of the BoomSAR, with this playing a critical role in the development of automatic target recognition algorithms for FOPEN systems.

Concerning signal processing, we have developed a hidden Markov model (HMM) algorithm, which exploits the multi-aspect data available from a synthetic aperture radar (SAR) system. We have applied this algorithm to FOPEN imagery measured by ARL, at Aberdeen Proving Ground. We have demonstrated marked detection performance via HMMs, vis-à-vis the conventional processing applied for this sensor. In the preceding fiscal year we have utilized relatively simple features, to assess the performance of the HMM algorithm itself, without exploiting the most sophisticated features. More recently we have directed significant attention to the development of improved features, via the wave-based matching-pursuits algorithm.

## B. Summary of Most Important Results

During the course of this research, two significant developments have occurred. For the first time, the fast multipole method (FMM) has been extended to the case of targets in the presence of a half space. This is a notable escalation in complexity vis-à-vis previous work in this field, which has heretofore been restricted to the case of free-space scattering. Significant work has been undertaken to properly handle the dyadic half-space Green's function.

The other significant development involves the hidden Markov model (HMM) as applied to the SAR problem. Hidden Markov models are widely applied in speech processing, where they have been very effective. We are the first to expend HMMs to SAR processing, in the context of a physics-based matching-pursuits feature parser. The HMM is an entirely new processing paradigm for this problem class, opening up a new direction of basic research.

## C. Refereed Publications

[1] S. Vitebskiy and L. Carin, "Late-time resonant frequencies of buried bodies of revolution," *IEEE Trans. Antennas Prop.*, vol. 44, pp. 1575-1583, Dec. 1996.

[2] S. Vitebskiy, L. Carin, M. Ressler and F. Le, "Ultra-wideband, short-pulse ground-penetrating radar: theory and measurement," *IEEE Trans. Geoscience and Remote Sensing,* vol. 35, pp. 762-772, May 1997.

[3] T. Dogaru and L. Carin, "Time-Domain Sensing of Targets Buried Under a Rough Air-Ground Interface", *IEEE Trans. Antennas Prop.,* vol. 46, pp. 360-372, March 1998.

[4] N. Geng, C.E. Baum, and L. Carin, "On the low-frequency natural response of conducting and permeable targets," *IEEE Trans. Geoscience and Remote Sensing,* vol. 37, pp. 347-359, Jan. 1999.

[5] L. Carin, R. Kapoor, C.E. Baum, "Polarimetric SAR imaging of buried landmines," *IEEE Trans. Geoscience and Remote Sensing,* vol. 36, pp. 1985-1988, Nov. 1998.

[6] D. Wong and L. Carin, "Analysis and processing of ultra-wideband SAR imagery for buried landmine detection," *IEEE Trans. Antennas Propagat.,* vol. 46, pp. 1747-1748, Nov. 1998.

[7] T. Dogaru, L. Collins, and L. Carin, "Optimal detection of a deterministic target buried under a randomly rough interface," submitted to *IEEE Trans. Antennas Propagat.*

[8] L. Carin, N. Geng, M. McClure, J. Sichina, and L. Nguyen, "Ultra-wideband synthetic aperture radar for mine field detection," *IEEE Antennas and Propagation Magazine* (invited), vol. 41, pp. 18-33, Feb. 1999.

[9] N. Geng and L. Carin, "Ultrawideband, short-pulse scattering from a dielectric body of revolution buried in a lossy, dispersive layered medium," *IEEE Trans. Antennas Propagat.,* vol. 47, pp. 610-619, April 1999.

[10] N. Geng, D. Jackson, and L. Carin, "On the resonances of dielectric bodies of revolution buried in a lossy, dispersive layered medium," to appear in the *IEEE Trans. Antennas Propagat.*

[11] P. Runkle, P. Bharadwaj, and L. Carin, "Hidden Markov model multi-aspect target classification," to appear in *IEEE Trans. Signal Proc.,* vol. 47, pp. 2035-2040, July 1999 .

[12] P.K. Bharadwaj, P.R. Runkle, and L. Carin, "Target identification with wave-based matching pursuits and hidden Markov models", accepted for publication in the *IEEE Trans. Antennas Propagation*

[13] P. Runkle, L. Carin, L. Couchman, T. Yoder, and J. Bucaro, "Multi-aspect identification of submerged elastic targets via wave-based matching pursuits and hidden Markov models," *J. Acoutical Soc. Am.,* vol. 106, pp. 605-616, Aug. 1999

[14] N. Geng and L. Carin, "Short-pulse electromagnetic scattering from arbitrarily oriented subsurface ordnance," *IEEE Trans. Geoscience and Remote Sensing*, vol. 37, pp. 2111-2113, July 1999.

[15] N. Geng, M. Ressler, and L. Carin, "Wideband VHF scattering from a trihedral reflector situated above a lossy dispersive halfspace," *IEEE Trans. Geoscience and Remote Sensing,* vol. 37, pp. 2609-2617, Sept. 1999.

[16] N. Geng, A. Sullivan and L. Carin, "Fast multipole method for scattering from a arbitrary PEC target above or below a lossy half space," *Microwave and Optical Tech. Letts.*, June 20, 1999.

[17] N. Geng, A. Sullivan and L. Carin, "Fast multipole method analysis of scattering from a three-dimensional target in a half-space environment," submitted to the *IEEE Trans. Antennas Propagation*

[18] N. Dasgupta, N. Geng, T. Dogaru and L. Carin, "On the extended-Born technique for scattering from buried dielectric targets," accepted for publication in the *IEEE Trans. Antennas Propagation*

[19] T. Dogaru and L. Carin, "Application of multiresolution time-domain schemes to two-dimensional electromagnetic scattering problems," submitted to the *IEEE Trans. Antennas Propagat.*

[20] P. Runkle, L. Nguyen, J. McClellan and L. Carin, "Multi-aspect target detection for SAR imagery using hidden Markov models," submitted to the *IEEE Trans. Geoscience and Remote Sensing.*

[21] N. Geng, A. Sullivan and L. Carin, "Multi-level fast-multipole algorithm for scattering from conducting targets above or embedded in a lossy half space," submitted to *IEEE Trans. Geoscience Remote Sensing*

[22] A. Sullivan, R. Damarla, N. Geng, Y. Dong and L. Carin, "Ultra-Wideband Synthetic Aperture Radar for Detection of Unexploded Ordnance: Modeling and Measurements," submitted to *IEEE Trans. Antennas Propagation*

## D. Participating personnel

Dr. Norbert Geng (post doc)
Dr. Anders Sullivan (post doc)
Traian Dogaru (PhD earned June 1999)
Mark McClure (PhD earned June 1998)

## E. Report of Inventions

None