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Contents

Sequential Adaptive Multi-Modality Target Detection and Classification Using Physics-Based Models

MURI Proposal, The University of Michigan, Ann Arbor

1 Abstract

The goal is to develop adaptive algorithms for detection and classification of the following: (1) vehicles under forest canopies; (2) land mines; and (3) underground structures. The data will be obtained from a variety of sensing modalities, including radar, optical and thermal emissions.

The approach will be to start with detailed physics-based radar propagation and scattering models for canopies, vehicles, and land mines already developed here in the Radiation Laboratory of the University of Michigan. These coherent models are capable of preserving detailed structure of tree canopies (species, density, vegetation moisture content, etc.) and also account for near- and far-field interactions among vegetation particles, as well as their interactions with embedded targets.

We will derive simpler models for these physics-based models which capture the relevant physics of each modality while preserving features essential to adaptive target detection algorithms. Hierarchical representations of the forward model will be the first avenue taken to accomplish model reduction. For this we will start by applying a recently developed theory of multi-dimensional anisotropic wavelets whose footprints can be matched to spatio-temporal resolution ellipsoids specified by the modality. Other low-dimensional models, obtained using functional approximation theory, will also be investigated.

The resulting lower-dimensional model will be used in a sequential adaptive detection procedure in which information from one sensor modality is used as a first stage to adaptively alter source waveforms and arrays for another modality. How to select and sequence modalities is a research question to be addressed. Modalities and sensors to be considered include: imaging radar at various frequencies, polarizations, and resolutions; thermal imagers at various frequency bands; and lidar.

The expected result of this research is a new approach to solving the above inverse problems by combining different sensor modalities. Specific algorithms for each of the above problems will be developed, along with a set of performance measurements obtained from both Monte Carlo simulations on existing detailed forward problem models, and from real data.

2 Problems Addressed and Objectives of Proposed Research

2.1 Problems Addressed by Proposed Research

The **goal** of the proposed research is to develop a set of algorithms to solve these problems:

- Detection of vehicles, possibly camouflaged, under a canopy of tree foliage ("tanks under trees," although other types of vehicles are also of interest). General features, such as rough size and shape, of the vehicles to be detected are assumed to be known for various classes of vehicles;
- Detection of buried objects (e.g., land mines) up to 6 inches deep in soil. General features of the objects and general propagation characteristics (e.g., dielectric constant) of the soil are assumed to be known;
- Detection of underground structures (e.g, buried fuel tanks) up to several feet deep. General propagation characteristics of the soil are again assumed to be known.

These specific problems are in response to MURI FY2002 topic #19, "Detection and Classification Algorithms for Multi-Modal Inverse Problems." DoD applications should be evident.

It is clear that each of these problems presents its own set of difficulties. In particular:

- Vehicle detection under forest canopies using radar is difficult due to multiple scattering off of tree foliage, tree trunks, and the terrain. A Rayleigh fading stochastic scattering model has been used for homogeneous terrain at low frequencies. Tree trunks have been approximated by smooth dielectric cylinders, again at low frequencies at which the bark roughness is negligible. Scattering from foliage is difficult to model at any frequency;
- Near-surface buried object detection using ground-penetrating radar is only possible if the transmitter and receiver are both on the ground (not unlike seismic prospecting). Seismic sources have proven to be more successful; a combined acoustic/radar approach by one of the PIs looks promising (see below);
- Detection of buried cities in the Sahara desert by remote sensing has shown striking results. Yet this is only possible for dry and sandy soil, which permits radar penetration. A recent passive acoustic/seismic method for subsurface imaging that uses ambient seismic noise as the source shows some promise (see below), but precise imaging using seismic techniques is still difficult, due to multiple scattering and diffraction.

2.2 Objectives of Proposed Research

This suggests that a combination of sensing modalities should be brought to bear on each of these problems. This requires the development of a unified approach to these problems which allows the specific physics of each of them to be incorporated into a unified framework of sensor selection and management. This leads to the following **objectives** of the proposed research:

- Develop an overall procedure for sensor management and sequential detection. Specific issues here include:
  1. Selection of sensing modalities that are most useful for a specific problem;
  2. Determining the value added by adding another modality–is it worth the cost?

3. Data-adaptive configuration of the source and receivers to a specific problem. Problem features include propagation and scattering characteristics of both the object(s) to be detected and the medium in which the problem is set;
4. Computation of thresholds for the likelihood-ratio-based detection algorithms;
5. Selection of figures of merit in order to govern the selection of optimal parameters and strategies for each of the above problems.

- Develop physics-based models for each problem of interest. Specific issues here include:

  1. Gain an understanding of the physics behind each of the problems of interest. This requires expertise in both radar and acoustic wave propagation;
  2. Develop approaches for using electromagnetic and seismic sources and receivers in various **and novel** configurations for each of the problems of interest.

- Simplify the physics-based models for each problem. Specific issues here include:

  1. Selection of basis functions to represent both the objects and wave propagation through the medium;
  2. Application of functional-analysis-based approximation theory to develop low-dimensional physics-based models that can be plugged into the sensor selection and management framework;
  3. Selection of figures of merit in order to accomplish the dimensionality reduction while gauging the impact of this on detection algorithm performance.

- Evaluate the results obtained. Specific issues here include:

  1. Availability of **realistic** models for developing and testing the algorithms;
  2. Behavior of the algorithms on real data;
  3. Evaluation of the performance of the algorithms.

3 Approach Used in Proposed Research

To achieve the objectives listed above, we propose the following approach. Since the overall framework for sequential detection and sensor management is the the most crucial aspect of this work, it is discussed most thoroughly. Since good models for radar propagation through foliage and scattering off of vehicles have already been developed by the Radiation Laboratory, we deemphasize this part of the problem, since physics-based models have already been developed for it. We also discuss in more detail novel approaches to the problems of land mine detection, using a combination of acoustic excitation and electromagnetic sensing, and underground structure mapping using ambient seismic noise.

3.1 Sequential Detection and Sensor Management Algorithms

3.1.1 Overview

We take an innovative approach to sequential target detection and classification and to sensor management by adopting task-driven optimal processing tightly coupled to mathematical wave

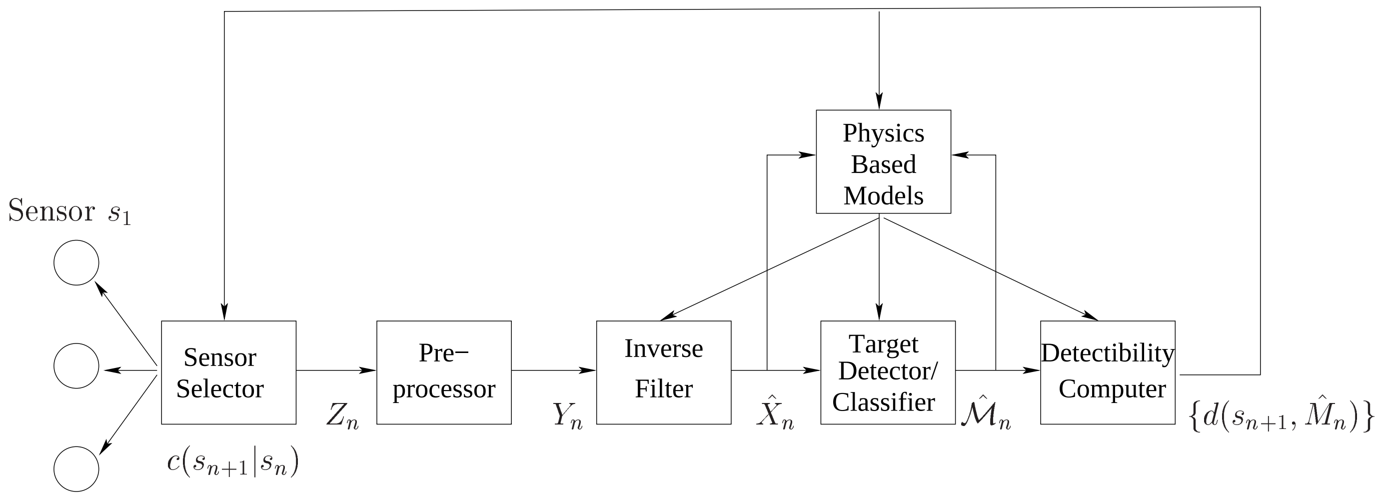

Figure 1: *System block diagram of the algorithm for target detection/classification and sensor selection.* $\{s_1 \ldots s_M\}$ *are possible sensors which can be deployed over successive time intervals* $n = 1, 2 \ldots$ *yielding raw measurements* $Z_1, Z_2, \ldots$. *At time* n, *a sensor* s_{n+1} *is selected on the basis of sensor switching costs* $c(s_{n+1}|s_n)$ *and the detectibility improvements* $d(s_{n+1}, \hat{\mathcal{M}}_n)$ *expected from sensor* s_{n+1} *over the next time interval.* $\hat{\mathcal{M}}_n \in \{\mathcal{M}_1, \ldots, \mathcal{M}_P\}$ *is the current most likely target model, computed at the output of a likelihood ratio detector/classifier which operates on the sequence of past reconstructions of the target* $\{\hat{X}_i\}_{i=1}^n$. *These are computed by an inverse filter applied to pre-processed measurements* $\{Y_n\}$, *where the pre-processing reduces effects of clutter and noise. Physics-based models of propagation, sensor sensitivity, and target signature are incorporated in real time into the inverse filter and other decision-making modules. The physics models are driven by target model decisions fed back from the detector/classifier.*

propagation and sensor sensitivity models described below. These models will be generated in real time from simulation software which specifically accounts for the medium, the sensor, and the statistical distribution of the model approximation error. The models will be used both to guide the computation of the inverse filter and the likelihood ratios used to perform detection, and also to predict the value-added by deployment of a different sensor over the next acquistion time period (see Figure 1). We will use a very powerful global optimization method for selecting the right sequence of sensors which combines target detection and sensor scheduling into a single overall objective function.

The driving task is to use a sequence of sensors to optimally detect and classify the target, whether it be a tank, a mine or an underground facility. As contrasted to the task of image reconstruction, we will construct a denumerable decision space consisting of a large database of P different fundamental target types. The perspective projection, orientation, reflectivity, and other attributes of the target will be incorporated into the channel and will be used in the inverse filter which generates a cleaner image of potential targets. To deal with the high combinatorial complexity of searching through the target model database we will organize the target types into a hierarchical binary tree structure and perform classification via a divide-and-conquer partitioning strategy. This reduces the search complexity from order P to order $\log P$, where P is the number of possible target models. To traverse down the decision tree we will implement recently developed binary hypothesis testing methods with provably optimal detection/classification performance.

The dynamical scheduling of sensors will be performed in a manner which maximizes the improvement in detectibility subject to a penalty on the cost of deployment for each of the sensors. This cost can be specified by factors such as: cost to switch sensors, e.g., if a UAV is already deployed its continued use incurs less cost than launching another UAV; probability of interception and destruction of a deployed sensor-type; and sensor size, weight and power. A pertinent and easily computed objective function for quantifying improvement in detectibility is the large deviations error exponent. A different exponent is associated with a particular sensor and involves computing information distances between density functions for each target-class. Our justification for using these information distances is that large deviations theory directly relates the error exponent to the expected decrease in probability of decision error due to deploying the sensor. More details on our proposed methods for estimation of these exponents are provided below.

Our mathematical framework accomodates both frequentist and Bayesian methods for attaining overall minimum probability of error, and we will investigate and compare both of these on the basis of implementation complexity and performance. The framework incorporates the specific capabilities of each sensor into the likelihood functions via the simulated physics of the propagation and sensor. Thus our framework is sufficiently general to cover a wide array of target and clutter scenarios (hidden mines, caverns, and vehicles) and sensor/propagation models (acoustic, electromagnetic, thermal, and chemical sensors).

In summary, the innovative features of our approach are the following:

1. Accurate physics for sensor and propagation are explicitly accounted for in inverse filtering and in all stages of decisionmaking.
2. We couple the process of target reconstruction directly to target detection by tailoring model approximations to detection performance, i.e. probability of decision error and error exponents, rather than to reconstruction mean-square-error.
3. Decisions on target presence and target class are performed using optimal sequential testing on a divide-and-conquer decision tree structure.
4. We develop high performance hybrid GLRT/Invariant/Bayes classifiers which combine the strengths of each strategy into one compound classification rule.
5. Dynamic sensor scheduling is performed using predictive models of performance improvement due to a particular sensor given past measurements.
6. The sensor selection criterion is composed of the predicted information gain due to each sensor and the cost of that sensor's deployment.

3.1.2 Sequential Detection and Classification

For known propagation channel, known targets, and known sensor sensitivity, optimal decisionmaking for target detection and identification has a simple formulation: implement the likelihood ratio (LR) test and a weighted maximum likelihood classifier to minimize the overall average probability of decision error. Under the simultaneous detection and classification framework introduced by Baygun and Hero, these tests are respectively [1]

$$\sum_k w_k f_{Y|\theta_k}(Y|\theta_k)/f_{Y|\theta_0}(Y|\theta_0) \underset{H_0}{\overset{H_1}{\gtrless}} \eta_d, \qquad \max_k f(Y|\theta_k)/f(Y|\theta_0) \underset{H_0}{\overset{H_1}{\gtrless}} \eta_c \tag{1}$$

where η_d is a detection threshold, η_c is a classification threshold, w_k are non-negative weights, Y are the sensor measurements, $f_{Y|\theta_k}(Y|\theta_k)$ is the likelihood function of the k-th target+noise model $\mathcal{M}_k$, having known parameters θ_k, $k \in \{1, \ldots, P\}$, and $f_{Y|\theta_0}(Y|\theta_0)$ is likelihood function of the noise alone, having known parameters θ_0. The parameters $\{\theta_i\}$ contain all of the information about the propagation model, the clutter and noise statistics, the sensor modality, and the target signature under that modality. The thresholds η_d and η_c can be selected to ensure a particular false alarm probability or to correspond to prior probabilities on the target hypotheses to ensure a minimum average probability of error [1].

When aspects of the propagation, target signature, and sensor sensitivity are unknown decisionmaking is considerably complicated by the presence of the unknown "nuisance" parameters among the parameters θ_i's. In this case there are no universally optimal decision rules such as (1). To deal with nuisance parameters we will consider three alternative classes of decision rules:

1. The generalized likelihood ratio (GLR) test: substitutes estimates of nuisance parameters into the LR and compares to a threshold.

$$\sum_k w_k \max_{\theta_k} f_{Y|\theta_k}(Y|\theta_k) / f_{Y|\theta_0}(Y|\theta_0) \underset{H_0}{\overset{H_1}{\gtrless}} \eta_d$$

   where the maximization is over the unknowns in the model θ_k. The implementation of the GLR requires finding maximum likelihood estimates of the θ_k's. The GLR has been derived by us and by others for many different scenarios pertinent to detection of tanks, mines and underground facilties, see [5, 6, 8] for a sampling of these results.

2. The maximal invariant (MI) test: obtains dimension reduction by projecting observations Y onto a subspace over which the densities are functionally independent of nuisance parameters. To this dimension reduced data (1) can be applied to the projected data. We have used invariance theory to specify invariant orbits of targets relative to certain groups of transformations, e.g., translation, perspective and orientation, relative to which we wish detection performance to be insensitive. Forms of the MI test have been derived by us and by others for pertinent scenarios [4, 7, 8].

3. The Bayes optimal test: selects priors p_{θ_k} for the nuisance parameters and projects the densities onto these priors. Decisions are then made according to the test

$$\sum_k p_k \int f_{Y|\theta_k}(Y|u) f_{\theta_k}(u) du \Big/ \int f_{Y|\theta_0}(Y|u) f_{\theta_0}(u) du \underset{H_0}{\overset{H_1}{\gtrless}} \eta_d$$

   where $p_k = P(\mathcal{M}_k)$ are priors on the target+noise models. Until recently, the only way to implement Bayes optimal tests required very slow and unstable Monte Carlo evaluation of the above integrals, called Monte Carlo marginalization [14]. However, more recently fast simulation methods for performing marginalization have become available based on sequential importance sampling [9] and have been applied to the blind deconvolution problem with denumerable target classes like in this proposal [10, 11]. These fast Monte Carlo simulation methods have even shown promise for real time applications in digital multiuser communications [13, 15]. We will adapt these importance sampling methods to the computation of Bayes optimal tests when the models $\{\mathcal{M}_k\}_{k=1}^P$ are constrained by the underlying physics of wave propagation and measurement.

Each of the aforementioned GLR, MI and Bayes optimal tests have analogous forms for target classification which are not shown here. We have shown [7, 8] that, at least for SAR imaging, none of these decision rules are universally better over all ranges of false alarm, SNR, and other parameter variations. This conclusion is expected to be equally valid for other sensing modalities. Hence we propose using a hybrid structure which simultaneously computes at least two of these three tests and chooses the majority decision. An example of the performance gains acheived by using such a hybrid testing strategy is shown for the "deep hide" target detection problem illustrated in Figure 2, taken from our recent paper [8]. In this experiment, a target having one of the SAR signatures in Fig. 2, hides along a boundary in an unknown clutter background. Target (e) was inserted into the SAR clutter image at column 305 of the forest/grassy-plain boundary at various amplitudes. After segmentation, each detector was implemented with a number $n-1$ of clutter-only chips acquired along the boundary used to estimate the clutter statistics. In Table 1 we show the minimum detectable target amplitude for each of three detectors for different numbers of clutter reference chips. The Structured Kelly test is the standard GLR approximation used for target detection in structured clutter. Note that the MI test outperforms (operates at lower minimal detectible threshold) the other tests when $n-1=200$, while the GLR outperforms the other tests for $n-1=250$. These are representative results which have been established by extensive simulations and experiments [7, 8] and establishes that our proposal of a hybrid test is justified.

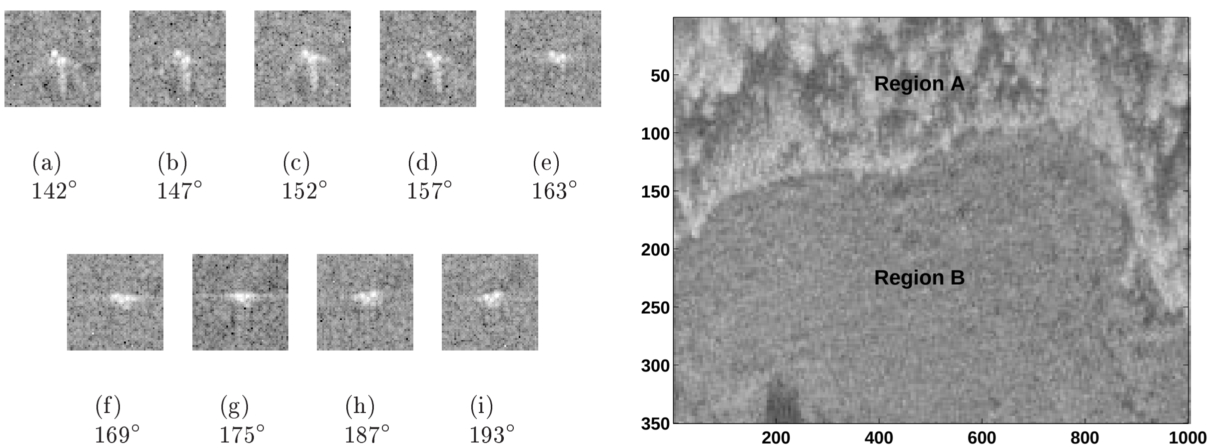

Figure 2: Canonical target images (54×54) at elevation 39° and different azimuth angles. Image in (e) is inserted in SAR clutter image at right.

Test	$\lvert a \rvert$	
	$(n-1=250)$	$(n-1=200)$
MI test 1	1.454×10^{-2}	0.609×10^{-1}
GLR 1	1.462×10^{-2}	1.042×10^{-1}
Structured Kelly	1.407×10^{-2}	1.049×10^{-1}

Table 1: Minimum detectable amplitudes for detection of the target at the correct location.

3.1.3 Sensor Management and Scheduling

Sensor management involves both sequencing of sensors and/or sequencing of probing waveform (spectral band, time-frequency structure, etc. of the transmitted pulse) from each sensor. For simplicity we will simply index both of these sequences by a single index ranging from 1 to M. As deployment of different sensors incur different costs, e.g., selecting a new sensor waveform is cheaper than launching a new sensor, we will incorporate a sensor switching cost into our selection criterion. The sequencing of sensors will be be performed by selecting one of the M sensors s_{n+1} at each time n which maximizes the expected detectibility of the target deemed most likely based on the previously acquired measurements (see Figure 1), penalized by the sensor switching cost. Such a scheme lies in the framework of stochastic scheduling and control, and sequential design of experiments, which provides tools for analysis and implementation. There is considerable flexibility in selection of the detectibility index and the switching costs.

Let the total surveillance time be T and assume that over each of L segments we can deploy one of M possible sensors $\{s_m\}_{m=1}^{M}$. If the detection probability were known for a given target and a given sensor the natural selection strategy would be to only deploy the one sensor that maximizes this probability, subject to the sensor deployment cost constraint. Of course in the present application this strategy is impractical since the target and clutter are unknown and, even if they were known, the detection probability is seldom simple to approximate accurately. We will adopt an implementable alternative sequential strategy which is based on two key ideas: 1) we use a simply computed detectibility index as a surrogate for the probablity of detection; and 2) we will sequentially select the sensor which minimizes the expected improvement in detectability of the most likely target.

To accomplish this we define the sensor scheduling objective function computed recursively after observing the (pre-processed) outputs $\mathcal{Y}_n = \{Y_1, \dots, Y_n\}$ of the previous sensors deployed at times $0, 1, \dots, n$

$$J_n(s_{n+1}, \mathcal{Y}_n) = d(s_{n+1}, \mathcal{Y}_n) - \rho C(s_{n+1}|s_n)$$

where $d(s_{n+1}, Y_n)$ is the expected detectibility improvement when one deploys sensor s_{n+1}, $C(s_n|s_{n-1})$ is a cost function that accounts for the cost of switching from sensor s_n to sensor s_{n+1}, and ρ is a positive scale factor. Many detectibility functions can be investigated. However, our philosphy is that it is best to work with a detectibility index which is tightly coupled to the actual expected increase in probability of target detection, yet reasonably simple to compute. Therefore we will work with the Rényi information divergence which is directly related to the probability of detection via the detection error exponent (see our recent work [3] which is motivated by the work of Dembo and Zeitouni [2]):

$$d(s_{n+1}, \mathcal{Y}_n) = (1-\alpha)^{-1} \ln \int f^{\alpha}_{Y_{n+1}|\hat{\mathcal{M}}_n} f^{1-\alpha}_{Y_{n+1}|\mathcal{M}_0} dY_{n+1}, \quad \alpha \in (0,1), \tag{2}$$

where $f^{\alpha}_{Y_{n+1}|\hat{\mathcal{M}}_n}$ denotes the probability density function under model $\mathcal{M}_n$. For $\alpha \approx 1$ this is approximately equal to the Kullback-Liebler distance between the null model $\mathcal{M}_0$ and the currently most likely target+noise model $\hat{\mathcal{M}}_n$, as computed by the target detector/classifier (see Figure 1). This distance can either be computed by assuming a tractible approximation to the measurement statistics given $\hat{\mathcal{M}}_n$, e.g. a Gaussian distribution, a full Monte Carlo simulation of the posterior $P(\mathcal{M}_n|Y_{n+1})$ (via sequential importance sampling), or a direct minimal spanning tree (MST) estimator. We have developed such estimation techniques for general classification and image registration problems [3, 12].

3.2 Physics-Based Model For Targets Under Foliage

The main goal of foliage-concealed target detection is to develop means to electromagnetically interrogate a composite scene of target plus vegetation in such a manner as to either: (a) penetrate the canopy without corruption of the phase and amplitude of the return from the target of interest; or b) use the return from the canopy itself to establish the distortion matrix for the effects of the clutter and subsequently account for them in order to electromagnetically "defoliate" the scene.

Due to exorbitant attenuation of electromagnetic waves at optical and infrared frequencies, the application of conventional and stand-alone optical and IR sensors for detecting a target hidden under foliage has been proved to be unsatisfactory. However, due to ability of electromagnetic waves to penetrate through foliage, particularly at low microwave frequencies, the application of ultra-wideband imaging radars for detection and identification targets under foliage has been investigated [16]. To date, the thrust of investigation on foliage-penetrating radars have been focused on the frequency range covering HF through lower UHF band, whose success has hampered by exorbitant false alarm rate generated by ground-trunk interaction and limited image resolution.

Having recognized the aforementioned challenges and difficulties associated with the existing foliage penetrating side-looking radars, The Radiation Laboratory of University of Michigan, in collaboration with the Army Research Laboratory, are considering the application of 3-D imaging millimeter-wave (MMW) radars and IR laser-radar (Lidar) for foliage covered target detection. The premise for this research stems from the fact that electromagnetic signals at millimeter-wave (MMW) frequencies can penetrate a few layers of foliage with some finite attenuation, and the fact that there are considerable number of openings through most foliage covers. Furthermore, very high resolution and far more compact radar systems can be designed at millimeter-wave frequencies that can easily be mounted on a tactical UAV. Indoor phenomenological studies and field experiments using Ka-band and W-band radars and military vehicles have been carried out. A preliminary detection algorithm for foliage-covered vehicles using 3D MMW imaging radar is developed and results are very encouraging. Fig.3 shows a HMMWV parked under a dense deciduous forest (during UoM/ARL a field experiment campaign in July 2000) and a high-resolution Ka-band image of the same target on a platform. Fig.4 also show a missile launcher detected using our MMW detection algorithm and a computer visualization of the test site. The red dots denote the backscatter returns that were identified as returns from a hard target, the see-through reddish surface are facets connecting the red dots, and the gray surface is a model of the Chinese missile launcher.

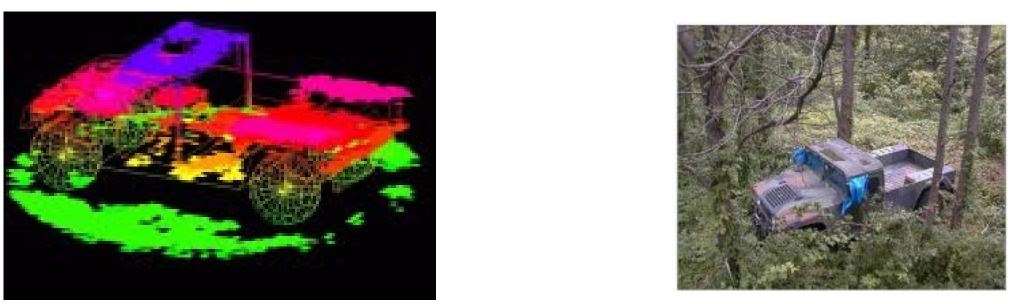

Figure 3: High resolution Ka-band 3D image of a HMMWV (left) and the same target during a field experiment for demonstrating foliage-covered target detection using mm-wave radars.

All of the techniques noted above have certain advantages and disadvantages that must be well understood, if a reliable multi-modal sensor detection method is to be developed. Considering the number system parameters, target attributes, and foliage conditions, generation of a comprehensive data set as a basis for target detection algorithm seems to be beyond the realm of possibilities. Even for a modest number of simultaneous sensors and targets, carrying out a controlled experiment can be very time consuming and expensive.


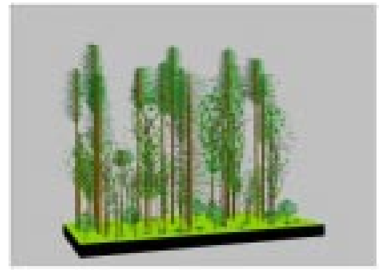

Figure 4: A Chinese missile launcher detected under a dense mix stand (left). The red dots were identified as return from the target among myriads of radar return from leaves and branches. Computer visualization of the forest stand (right). The foliage has been thinned out to allow visualization of the stand structure.

We propose the development of a comprehensive physics-based model for a composite foliage-plus-target. The emphasis will be on radar response including a real aperture as well as 2-D and 3-D SAR images. Modeling at optical and infrared, based on geometric optics, is somewhat intuitive, but they will be included.

3.2.1 Forest Model

From an electromagnetic scattering point of view, a tree can be considered as a complex structure composed of a group of randomly oriented scatterers structured in a semi-deterministic fashion, with electrical characteristics very much dependent on their moisture content. At VHF and higher frequencies, the dimensions of tree trunk, primary and secondary branches, and even leaves and twigs can be much larger than or comparable to the wavelength. Noting that a relatively large cluster of trees around an observation point (a point on a target) significantly contribute to the total field at that point, field calculation based on a brute-force numerical techniques is not possible at microwave frequencies or higher.

However, ignoring the multiple scattering among branches and leaves, a single scattering model can be constructed that, to a high degree of accuracy, can predict the total field within a forest. In modeling the forest one approach is to distribute the vegetation particles (leaves and branches) uniformly. But for frequencies up to about 3 GHz, it is important to preserve the structural information of tree canopies for accurate prediction of radar backscatter [17]. This effect is expected to be even more important when the observation point is within the forest.

Considering the number of branches and leaves on a tree and the variability in their sizes and orientations, generation of a tree structure can be a very difficult task. But this can be done efficiently by approximating tree structures by fractal geometries. Here we plan to use a statistical Lindenmayer system [17], in conjunction with botanical properties pertinent to specified tree species. In this model, the geometries of vegetation particles are approximated by canonical geometries such as dielectric disks, needles, and layered dielectric cylinders. Each particle in the medium is assumed to be illuminated by the incident wave attenuated by the foliage along the ray between the particle and the canopy top. The attenuation through the foliage is calculated using Foldy's approximation, and single scattering is invoked to compute the field scattered from all vegetation particles and their images in the ground plane in the vicinity of the observation point. The total field is then obtained by adding all scattered field components coherently. Details of this coherent forest model are described in [17, 18]. This model has been verified extensively using the data acquired by SIR-C (Shuttle Imaging Radar), JPL AIRSAR and TOPSAR [17, 18, 19] and was used in an inverse scattering problem to retrieve forest bio-physical parameters from a multi-frequency and polarimetric SAR data [20].

3.2.2 Proposed Tasks

The fractal-based coherent scattering model described before is the only accurate and physical foliage model to our knowledge. However, in order to make this model useful for the problem at hand, a number of improvements are required.

In order to accurately model the signature of a target under tree canopies, interaction of nearby trees and the target must be accounted for. This would require near-field calculation of scattered field from the adjacent tree trunks, branches and leaves at any point on the surface of the target. This field fluctuations can be very significant (as high as 20 dB at L-band) as demonstrated in [21]. Hence near-field scattering models for vegetation particles must be developed and incorporated into the coherent scattering model.

Modeling of scattering from targets is usually done using full-wave numerical simulations, such as method of moments (MoM), finite element method (FEM), and finite difference time domain (FDTD), or approximate analytical solutions such as ray tracing (geometric optics), physical optics (PO), and geometrical theory of diffraction (GTD). These code need be modified when the target is in a forest. For FEM and FDTD an enclosing box around the target will be considered and the tangential electric field on this surface will be calculated using the forest model. This incident field distribution is then used to solve the interior problem in a standard fashion. For ray tracing and and GTD, the rays emanated from the nearby targets will be used as the excitation. For MoM and PO, surface currents will be computed and used as excitation.

The combined target and foliage model must be used to generate simulated SAR images. The attributes of the SAR image produced using the physics-based model can easily be controlled and used for testing ATR algorithms. The standard approach for SAR image generation can be very time consuming. We propose a novel approach to generate the necessary information in a transformed domain, and achieve efficiency using a subsampling approach.

As a preliminary example of this approach, consider the simulation of a SAR image of three trees and a trihedral pictured in Fig. 5. The brute-force approach for directly computing the signal would require $6862 \times 3942 = 27050004$ grid point calculations, while the subsampled method requires only $140 \times 66 = 9240$. The computational load is reduced by a factor of more than 2900!

The simulation described above was run, and the resulting VV and HH polarization images are displayed in Fig. 5. The isolated bright dot at (x, y) is a point target for image calibration purposes. In this simulation, the effect of foliage interaction with trihedral was ignored.

As mentioned earlier, optical and infrared simulated images of the scene are also needed to examine the success of a multi-modal ATR algorithm. Fortunately, many optical visualization tools are commercially available where many of the environmental parameters such as source location, diffuse lighting (cloudy day), or haze can be adjusted. The scene shown in Fig.5 (left) is obtained using such a tool. Similar software can be modified to generate IR images by controlling the emissivity of the objects in the scene. Fig.6 shows optical and IR images of a synthetic scene of an M-1 tank behind a tree line. The tree structures are generated using the fractal model.

3.3 Mine Detection Using Acoustic and Electromagnetic Wave Interaction

Reliable detection and identification of landmines is not yet possible due to the complex nature of the problem. The properties of a mine (such as the dielectric constant, characteristic acoustic impedance, emissivity, etc.) are generally on the same order as the natural variations of the

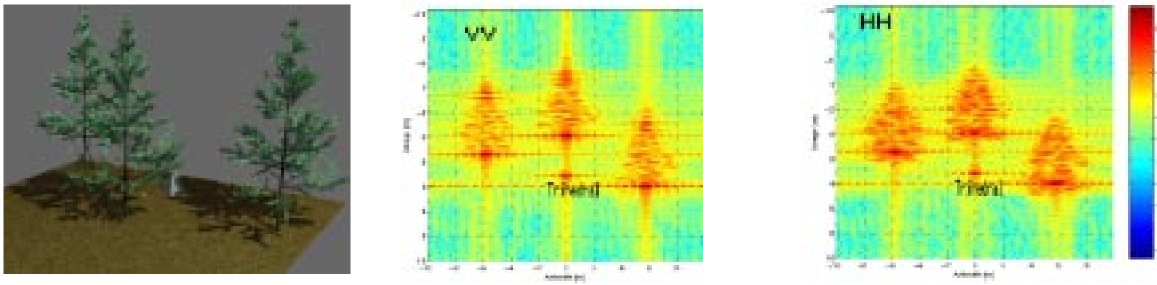

Figure 5: A scene composed of three red pines (10m height generated by the Fractal model) and a trihedral (left) in addition to simulated VV (middle) and HH (right) SAR images. The following parameters are used: center frequency 1.25 GHz, bandwidth 1 GHz, synthetic aperture length 1.2 Km, incidence angle 45°.

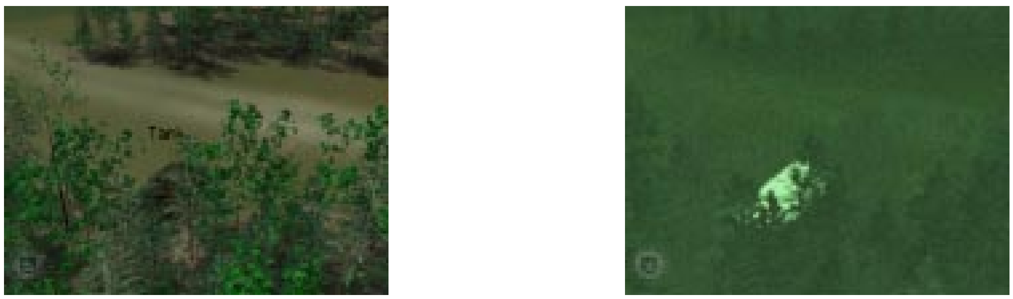

Figure 6: A tank hidden behind a tree line, generated at optical (left) and infrared (right).

medium in which the mine is embedded. Furthermore, the attenuation caused by the ground layer above the mine, clutter signals generated from the air-ground rough interface, and vegetation can all obscure the signal scattered from the mine itself. In such complex problems, a thorough understanding of the fundamentals is necessary to establish the limitations of existing methodologies and examine the feasibility of new ideas. **In this study, we propose to investigate the theoretical and experimental aspects of the buried target detection problem based on a combined acoustic and electromagnetic approach.** The electromagnetic and acoustic wave interactions that take place within the object will be investigated thoroughly. The interactions affect the response of both active (radar-based) and passive (radiometer-based) systems which will be considered separately. The proposed scenario is shown in Fig. 7 where an acoustic source launches an acoustic wave in the soil, mechanically exciting the buried objects, and an electromagnetic radar and/or radiometer measures the received electromagnetic signal from the vibrating objects. Significant displacement of an object only occurs when the object is excited at one of its acoustic resonances. Hence, the scattered electromagnetic Doppler spectrum will be composed of frequencies corresponding to the object's acoustic resonances. The frequency location of an object's resonances depends upon the object's shape and material properties and are generally different for different objects. Thus, the object's acoustic resonances observed in the electromagnetic Doppler response can be used as a basis for object detection and identification. Research into buried object detection has included the use of electromagnetic, acoustic, biological, and a host of other methods [22]. The literature on the many sensors and associated signal processing algorithms is enormous, and it is beyond the scope of this proposal to discuss them all. However, it is commonly believed that no single sensor technology provides a complete solution to the mine detection problem. Although research efforts in different areas must be continued to

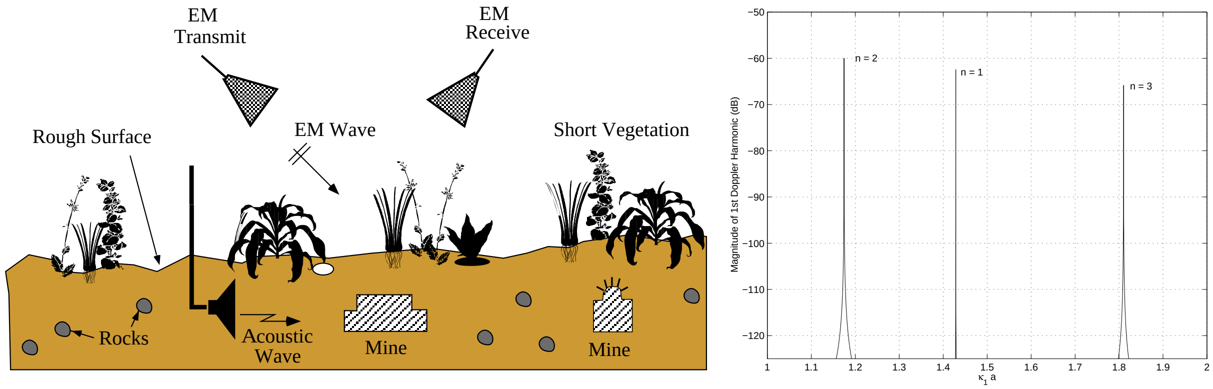

Figure 7: Example scenario for acousto-electromagnetic object detection (left). Variation of the 1st Doppler harmonic magnitude with acoustic frequency for a solid copper cylinder in air (right). For a 5 cm radius cylinder, the acoustic frequency sweep is from $f_a = 14.7kHz$ to $9.4kHz$.

optimize the capabilities of the individual sensors, it is believed that multiple sensor technologies should be used together to meet the stringent detection requirements of a very high probability of detection and very low false alarm rate. Consequently, a theoretical/numerical study of the phenomena associated with a hybrid acoustic and electromagnetic approach to buried object detection is proposed.

3.3.1 Proposed Hybrid Electromagnetic/Acoustic Approach

Only limited research has been done concerning the combined use of acoustics and electromagnetics in buried object detection [23, 24]. Experimental results are reported in [25, 26] where an electromagnetic radar is used to measure the surface displacement caused by a traveling surface acoustic wave. In each of these methods, object detection is based on the small changes in surface displacement when a buried object is introduced. The performance of these techniques is questionable when the surrounding soil medium is acoustically or electromagnetically inhomogeneous, or there is interference from vegetation. Other experimental results are reported in [27] where mechanical excitation is achieved through high-pressure water jets. In this technique, both acoustic and electromagnetic receivers are used to detect ground vibrations. Note that none of these approaches directly utilize the electromagnetic scattering from the vibrating object itself which can be a significant aid in object identification.

The interaction between acoustic and electromagnetic waves occurs as a result of two basic mechanisms. First, an incident acoustic wave upon an object will vibrate it such that its boundary changes with time. This creates a time-varying boundary condition for the electromagnetic scattering problem. Secondly, vibration of the object causes density fluctuations due to the compressions and dilations taking place within the object. The object's constitutive parameters (ϵ, μ, σ) used in the electromagnetic problem change with these density variations and thus also become time-varying. Both the boundary and density variations must be accounted for to obtain an accurate solution to the electromagnetic scattering problem. Since the boundary and constitutive parameters of the object become time-varying, the electromagnetic scattering problem becomes nonlinear, and the scattered field will contain a spectrum of frequencies (Doppler spectrum) different from the incident frequency.

Scattering from objects whose shape and density are fluctuating requires that Maxwell's equations be solved with time-varying boundary conditions and constitutive parameters. However, for practical cases when the object is not moving at relativistic speeds and the vibration frequency is much lower than the electromagnetic frequency, a simplified approach is possible. In this approach, the scattered fields from a vibrating object are computed at different points in time, as if the object is stationary at each instant. An incident monochromatic wave will then have a scattered wave whose magnitude and phase vary with time. A Fourier transform of the scattered field expression provides the scattered Doppler spectrum.

A study of the phenomena associated with acousto-electromagnetic object detection should begin with a model. A good model will provide insight into relevant measurable quantities associated with the phenomena and can reveal the theoretical advantages/limitations of a particular detection scheme. In addition, a physics-based model will allow experimentation with various signal waveforms under different environmental conditions.

3.3.2 Analytical Modeling

The purpose of the analytical study is to present a complete analysis of the electromagnetic scattering from acoustically excited objects in the context of buried object detection. The analytical solution is pursued for canonical geometries to establish the physical understanding and to be used as a reference for numerical simulations. We will exploit analytical techniques to study the acousto-electromagnetic scattering behavior of several canonical geometries including: 1) metallic and dielectric cylinders; 2) cylindrical shells; and 3) cylinders buried in acoustic and elastic half spaces with rough interface.

To begin the study, the acousto-electromagnetic scattering behavior of a solid metallic cylinder in a homogeneous background is developed. Using a metallic cylinder in a scattering model significantly reduces the complexity and is an ideal candidate to begin the investigation. The acoustic scattering from solid cylinders has been known for some time [28] and contains the exact solution for the cylinder's deformation. What is needed, however, is the electromagnetic scattering solution for a slightly deformed cylinder. Perturbation methods can provide an analytical solution to the problem, provided the irregularities are small and an exact solution exists for the unperturbed problem.

As a preliminary study, a λ_e (wavelength of electromagnetic wave) radius, solid copper cylinder illuminated by an incident acoustic plane wave in air with a power density of $1kW/m^2$ is considered. When the frequency of the incident acoustic wave is not close to a resonant frequency of the cylinder, it behaves as an impenetrable rigid cylinder. Consequently, there is negligible displacement at the surface of the cylinder, and the magnitude of the Doppler spectrum is also negligible. However, when the frequency of the incident acoustic wave is close to a resonance of the object, the mode corresponding to this resonance is excited and a measurable Doppler spectrum results.

To illustrate the effect of resonance on the scattered fields, the magnitude of the first harmonic of the Doppler spectrum in the backscatter is calculated as a function of the incident acoustic frequency [29]. Fig. 7 (right) shows that the first Doppler harmonic is highly sensitive to the acoustic resonances of the cylinder. This technique can be used in general to measure the acoustic resonances of any object.

A natural extension to the metallic cylinder case is to consider a solid dielectric cylinder. As pointed out earlier, the dielectric case presents an additional mechanism for the acousto-electromagnetic interaction. The displacement interior to the cylinder creates density fluctuations which, in turn, correspond to dielectric constant fluctuations within the cylinder. Thus, the electromagnetic scattering from a slightly inhomogeneous dielectric cylinder should also be derived.

Since the dielectric constant fluctuation is small, a perturbation method based on distorted Born approximation is appropriate for this purpose. Results from the two perturbation solutions, both shape and dielectric fluctuation cases, should be added coherently for the total result, and comparisons can be made to determine the relative contribution of each to the Doppler spectrum. To accurately characterize the dielectric fluctuation within the cylinder, the relationship between the density variation and dielectric constant fluctuation is [30] ($\mathbf{u}$ is displacement vector)

$$\delta\tilde{\epsilon}(\mathbf{r}) = -(\epsilon_d - \epsilon_0)\nabla \cdot \mathbf{u}(\mathbf{r}) \tag{3}$$

In addition to the acousto-electromagnetic scattering solution for solid cylinders, the solution for cylindrical shells will be derived. Cylindrical shells are more representative of actual man-made buried objects, such as buried pipes, and provide some diversity in the objects considered.

Next, the half space problem is treated. A novel, iterative approach to obtain the analytical solution for the electromagnetic scattering from a **cylinder buried beneath a plane interface** will be developed. The solution is easily extended to apply to the scattering from a buried cylinder (solid or shell) in an elastic half space. The exact solution for these cases yields the displacement on and within both the cylinder and plane interface. The existing solution for the electromagnetic scattering from a perturbed planar boundary is used together with the perturbed cylinder scattering solution from previous derivations to obtain the complete scattering solution for a cylinder buried in a homogeneous half space.

It is natural to question what effect a rough surface will have on the acousto-electromagnetic scattering from buried objects. Accordingly, scattering solutions for an acoustically vibrated **cylinder beneath a slightly rough interface** will be developed. Analytical solutions for electromagnetic scattering from slightly rough surfaces are well known. These existing solutions will be used in conjunction with acoustic rough surface scattering solutions to study the acousto-electromagnetic scattering behavior of a cylinder buried beneath a slightly rough surface.

3.3.3 Numerical Modeling

In general, numerical techniques such as MoM, FEM and FDTD could be used to calculate the scattering from a vibrating object. In this approach, which will be referred to as brute force method, the scattered field is computed at several closely spaced discrete time instants by discretizing the deformed object for each time instant. The drawbacks of the brute force approach are two-fold. One pertains to the lack of computational efficiency, which is encountered twice in implementing the brute force algorithm considering that the object must be re-discretized for each time instant, and requiring very fine discretization coresponding to very small distortions.

Furthermore, the solution may be inaccurate if the variation in the scattered field is smaller than the discretization error inherent in the numerical technique. This is especially true for acoustic excitation, since object vibration caused by an incident acoustic wave is generally very small. Instead, we propose a more efficient approach where the object is only discretized once, and time-varying impedance boundary conditions are applied at the unperturbed boundary to account for object vibration. The time-varying nature of the boundary is contained within surface impedance expressions; it can be isolated from the unperturbed component of the scattered field, resulting in accurate calculation of the Doppler spectrum no matter how small the vibration.

3.4 Underground Structures

Seismic methods have been used to locate underground structures (e.g., tunnels, cavities). Common seismic methods for doing this include reflection seismic imaging from the Earth's surface and cross-borehole seismic imaging. These methods are *active* methods requiring the target to be illuminated by a source of seismic energy and the target's presence is inferred from (i) the reflection it produces or (ii) the change in seismic-wave characteristics (e.g., velocity, amplitude) as the wave travels through the target. These methods also require that people be on the ground carrying out the seismic surveys. Consequently, these methods are not appropriate for military purposes when the idea is to gather information without detection (i.e., no seismic source) and compromising the safety of people.

Other seismic methods are *passive*, where seismic instruments are used to record (listen for) seismic energy emitted from the target. Passive seismic monitoring is commonly used in the petroleum industry and by earthquake seismologists to characterize petroleum reservoirs and the Earth, respectively, and the source of the seismic energy (e.g., earthquakes, microearthquakes or microtremors, explosions). However, for military purposes, such passive methods are not very useful because the foe is trying hard not to be detected, and so is quiet or silent.

3.4.1 Passive Seismic Imaging

Consequently, we need another seismic method for detecting, locating, and imaging underground structures. For this, we turn to recent developments in underwater acoustics. Recently, Buckingham and co-workers [32, 40] have shown that ambient noise can be used to image stationary or moving targets in the ocean. In the ocean, noise surrounds a target. The noise is from breaking waves, shipping traffic, rainfall, and sea life. At the same time, the target modifies this ambient noise field, depending on its size, shape, position, and composition, causing the noise energy to reflect and scatter. Buckingham and co-workers refer to illumination of underwater targets by ambient noise as "*acoustic daylight*," analogous to the illumination of objects by ambient light (daylight, sunlight). Their imaging process is called "*acoustic daylight imaging*."

Ambient seismic noise are ground motions in the absence of earthquakes or intentional (artificial) seismic-energy sources. These ground motions are sometimes called *microseisms*. They include very-long-period (hours; $<10^{-3}$ Hz) signals from solid Earth tides, long-period (2–20 seconds; 0.05–0.5 Hz) signals from ocean waves and atmospheric effects, and short-period (<2 seconds; >5 Hz) signals from wind and cultural noise. Typical noise levels will vary greatly between different sites and different frequencies [39].

Here, we propose to extend the noise-illumination concept to seismic imaging of underground structures. Recently, Doll and co-workers [33] did a literature review on passive seismic methods. They concluded that ambient seismic noise (≤ 100–200 Hz) could be used for imaging underground objects. They also determined that peaks resulting from cross-correlation of noise across an areal surface array of seismometers were caused by seismic energy moving across the array. In their study, this noise could be traced to ground roll (surface-wave energy) from traffic on a nearby road (see also Louie [35] and Moran [36]). Thus, the success of seismic imaging based on noise illumination may depend on separating surface-wave energy from body-wave energy scattered from underground targets.

Norton and Won [37] carried out numerical experiments to investigate the feasibility of seismic imaging using ambient seismic noise to illuminate underground targets. The targets were embedded in a homogeneous, isotropic, constant velocity medium. The authors assumed spatially-incoherent ambient noise and considered two receiver-array geometries (apertures): (i) a line of equally spaced receivers on the Earth's surface, and (ii) a line of equally spaced receivers on the Earth's surface plus two boreholes, one on each side of the target, containing strings of equally spaced receivers. The authors showed that under these conditions, they were able to resolve the horizontal and vertical position of underground objects. The second receiver geometry worked better than the first, because the objects were surrounded on three sides by receivers. Hence, there was better resolution of the objects' vertical position and sharper definition of their overall positions.

We propose to investigate this idea further. Our concept is that an *unattended ground sensor* (UGS) network (web) could be deployed on the Earth's surface over suspected underground facilities. These sensors would listen passively, taking independent snapshots of the ambient seismic noise field. Every so often, each sensor would get interrogated and the noise snapshots would be transmitted to higher-level processing center for analysis and interpretation. We propose that the deployment, scheduling, and management of the UGS network be as outlined in Figure 1. Eventually, after combining enough snapshots, the uncorrelated ambient noise will diminish and an image of the subsurface will appear [37].

3.4.2 Research Issues

1. Correction of effects of random sensor spacing, since this is the case in practice;

2. Separation of surface-wave and body-wave information. Both wave types can provide independent, complementary information about the subsurface. For example, the scattered upward-propagating body waves might provide the *seismic daylight* images of the subsurface. The dispersion characteristics of surface waves travelling in different directions across the UGS array might add information about location of the underground structure [34].

3. Obtaining independent velocity information. One source might be surface waves, using *spectral analysis of surface waves* (SASW) [41] or *multichannel analysis of surface waves* (MASW) [38, 42] techniques.

4. Networking of the unattended ground sensors with each other and with higher levels of command and control. We imagine that each UGS would be equipped with a power supply, global positioning system (GPS) device, a seismometer, enough memory to hold several traces of seismic data, plus other sensors for other purposes. However, each UGS must be unsophisticated so that if captured it does not compromise the operation.

5. Dealing with different illumination directions. Relative to a seismic array on the Earth's surface, noise sources on the Earth's surface is *front illumination* ("sun behind camera"), while noise sources from deep within the Earth is *back illumination* ("sun behind target"). Front illumination produces a bright target against a dark background, while back illumination produces a dark target (shadow) again a bright background.

3.5 Dimensionality Reduction of Physics-Based Models

The above problems all require extensive computation of the propagation of electromagnetic and/or acoustic waves through complex media such as soil or foliage. They also require computation of the scattering off of underground objects or structures. These computations involve solution of huge linear integral equations whose kernels are Green's functions [45]. The solution of these linear integral equations requires processing and analysis of systems of linear equations of very large dimensions. For practical application, reduction of the dimensionality of the problem becomes a necessity.

One possible way of achieving this is reformulation of a particular problem to a different domain such as space-phase Fourier domain or space-scale wavelet domain. This idea has been successfully applied to many problems in many areas of pure and applied mathematics such as harmonic analysis, approximation theory, or signal processing. A typical studied example involves solving equations with singular integral operators, e.g., Hilbert transform or more generally Calderón-Zygmund operators. It has been shown that these classes of singular integral operators studied in harmonic analysis have almost diagonal, sparse matrix representations in wavelet domains [56]. Since these operators can also be used to model some scattering problems, a wavelet domain with multiresolution structure adapted to a particular problem can reduce dimensionality of that problem [47, 55, 57].

Another possible approach is to use multipole methods. These permit fast computation of the matrix-vector product required in iterative methods for huge linear systems of equations, such as the preconditioned conjugate gradient method. If this were the only consideration, multipole methods would be preferred. However, the **overall** approach taken in this proposal, which requires low-dimensional representation of wave fields in not only propagation computations, but also in sensor management and sequential detection and classification, necessitates the use of a more general, signal-adaptive type of basis function. This motivates the use of wavelets as a starting point in our analysis.

3.5.1 Adaptive Anisotropic Multiresolution Analyses and Wavelet Bases

The majority of research in the theory of wavelets was concentrated on one dimensional constructions, higher dimensional isotropic wavelets and the classical function spaces associated with isotropic dilation structure. By an isotropic wavelet we mean a collection of functions $\Psi = \{\psi^1, \ldots, \psi^L\} \subset L^2(R^n)$, (most of the time $L = 2^n - 1$), such that the $\{2^{jn/2}\psi(2^j x - k) : j \in Z,\ k \in Z^n,\ \psi \in \Psi\}$ is an orthonormal basis of $L^2(R^n)$. The isotropic wavelets with desired properties can be obtained from the one dimensional wavelets with the corresponding properties by a standard tensoring technique. The resulting wavelets are easy to construct and study and they inherit properties of the corresponding univariate wavelet, e.g., smoothness, support size, vanishing moments, etc. Tensor wavelets are also separable, meaning that multivariable basis functions are products of univariate basis functions. They are also easy to implement in practical applications.

Nevertheless, separable isotropic wavelets have several drawbacks, such as limited possibilities of design and their special product structure. These unwanted features can be avoided by using non-separable wavelet bases. Several constructions of non-separable wavelet bases are already known. For example, there are two dimensional constructions by Cohen and Daubechies [52], Ayache [44], Belogay and Wang [46], Bownik and Speegle [49].

However, the main drawback of isotropic wavelet bases lies in the fact that they are not efficient for representing functions that have non-isotropic resolution properties. In order to overcome this problem it is necessary to go beyond the realm of isotropic wavelets by considering more general non-isotropic multiresolution structures and wavelet bases.

A general dilation structure on Euclidean space R^n is given by the action of an expansive matrix, i.e., a matrix all of whose eigenvalues λ satisfy $|\lambda| > 1$. In this setting an orthonormal wavelet is defined as a collection of functions $\Psi = \{\psi^1, \ldots, \psi^L\} \subset L^2(R)$ such that $\{|\det A|^{j/2}\psi^l(A^j x - k) : j \in Z, k \in Z^n, \psi \in \Psi\}$ forms an orthonormal basis for $L^2(R^n)$. Unless the dilation A is very special, e.g., $A = 2Id$, there is no general procedure of constructing such wavelets from one dimensional ones. Therefore completely new methods have to be designed and employed. Significant progress in this direction has been made for the class of expansive dilations with integer entries, where wavelets with good time-frequency localization (more precisely, r-regular wavelets) have been constructed [48]. Some progress has been also made for the larger class of dilations with rational entries, e.g., Auscher's construction of Meyer-type wavelets in one dimension [43], and it appears that wavelets with good time-frequency localization can be constructed also for this class.

The advantage of employing non-isotropic multiresolution analyses and wavelet bases with appropriate dilation structures stems from the fact they are more efficient for representing functions that have different resolution properties in different directions than usual isotropic wavelets. This has been shown in the case of anisotropic Hardy spaces [50] and it can been shown for many other non-isotropic variants of many classical function spaces such as Besov, Hölder, or Sobolev spaces. To achieve efficient representation of a certain class of functions with non-isotropic resolution it is necessary to employ multiresolution analysis and corresponding wavelets that are adapted to a particular resolution properties of a given class of functions by choosing compatible dilation structure. This requires not only fast implementations of wavelet transform algorithms for general dilations, but also methodology of finding dilation structures and wavelets yielding the most efficient representations. The possible approaches to these problems are described next.

3.5.2 Discrete Wavelet Transforms and Best Basis Algorithms

The strength of wavelet analysis in practical applications stems from the fact that there are fast algorithms for implementing discrete wavelet transforms. The majority of algorithms described in the wavelet literature are designed for isotropic wavelet bases [53, 54, 58, 59]. The key element of discrete wavelet transform is a recursive convolution and decimation of a signal with high-pass and low-pass filters that are determined by a multiresolution analysis and a wavelet. This procedure is particularly simple in the case of dyadic dilations, since in this situation there is only one high-pass and one low-pass filter. For a general dilation with integer entries it becomes necessary to use a collection of high-pass filters that is determined by the complexity of the action of a dilation. Nevertheless, the discrete wavelet transform can be also implemented in this situation [46, 52]. Likewise, it appears that the discrete wavelet transform can be implemented also for rational dilations [43, 53] in one and higher dimensions.

The next step is to find an appropriate dilation matrix and a wavelet from a prescribed dictionary of waveforms that gives the most efficient representation of a signal coming from a particular class of signals, e.g., synthetic aperture radar image of forested areas with common characteristic features. This problem falls under a general methodology of adaptive representation that seeks the sparsest possible representation of a signal with the linear $O(n)$ or nearly linear $O(n\log(n))$ time.

A special method that is tailored to wavelet basis expansions is the best basis algorithm of Coifman and Wickerhauser [59] that adaptively finds the optimal representation of a signal in a certain wavelet basis for a given cost function. This method is quite versatile, since the cost function could take different forms, e.g., it could measure the number of coefficients of a given unit vector $(\alpha_i)_i$ in a Hilbert space $\mathcal{H}$ that are above certain threshold, or it could represent the entropy of $(\alpha_i)_i$ that is given by $\exp(-\sum_i |\alpha_i|^2 \log|\alpha_i|^2)$. Even though the best basis algorithm was developed in dyadic case, it appears that it can be extended to a more general situation of non-dyadic non-isotropic dilations by considering multidimensional library trees [59]. The usual separable dyadic best basis algorithm can be then used as a benchmark of comparison with non-isotropic best basis algorithms.

Another method that appears to be well suited to the problem is basis pursuit [51] from an overcomplete dictionary of allowable waveforms. We propose to use dictionaries consisting of families of wavelet bases corresponding to several different dilation structures. The goal is to find the most efficient representation of a signal in these dictionaries by minimizing the ℓ^1 norm of coefficients of that representation. This method, which is based on convex optimization, often gives sparser representations than the usual method of frames optimization which is based on minimizing the ℓ^2 norms. Furthermore, since for a variety of dictionaries the basis pursuit is closely related with interior-point methods in linear programming, it also has fast implementations with nearly linear time [51]. Fast implementations seem also achievable for the proposed dictionaries.

3.6 Evaluation and Verification of Algorithms

A major feature of the proposed research is the combination of multiple types and configurations of sensors in novel ways. This makes the evaluation of the algorithms much more difficult than is usually the case, since there are so many more degrees of freedom in the problem formulation. Hence it is important that methods for testing and evaluating the algorithms be available, in order to verify that they are in fact yielding an improved level of performance. It is also necessary that this improvement can in fact be defined and verified.

A major advantage of the University of Michigan is the extensive set of full-wave simulation models that have already been developed in the Radiation Laboratory (see “Facilities” below). This includes models for scattering off of tree foliage and tree trunks, scattering off of various types of vehicles, and scattering off of various types of terrain.

This will permit fairly realistic testing of the algorithms for situations in which the ground truth is known, under many different conditions. This will in turn permit the development of figures of merit for evaluating the performance of the algorithms.

In particular, we will be able to compute Receiver Operating Characteristic (ROC) curves and Fisher Information for various choices of the following:

1. Number of sensors used; configuration of sensors; source waveforms;
2. Dimensionality of the propagation and scattering models;
3. Choice of sensor types (acoustic, electromagnetic, active, passive, etc.)
4. Level and type of interference, whether natural or artificial (jamming).

This will permit the use of figures of merit such as Fisher information, power (probability of detection) for a given false alarm rate) and area under the ROC curve. The relative value of increasing the number or type of sensors, vs. the cost in time and/or money in doing so, can then be evaluated explicitly. Monte Carlo testing is also possible only if good models are available.

Of course, it is also necessary that the algorithms be tested on real data. This necessitates sources of real data for a variety of sensor types and real-world situations. Our extensive existing collaborations with many DoD agencies (DARPA, ARL, ARO, CECOM) has already led to extensive access to existing data sets.

3.7 Expected Results of Proposed Research

The expected results of the proposed research are as follows:

1. A new approach to combining sensor modalities for object detection;

2. A new set of algorithms for specific problems in mine detection, vehicle detection under canopies, and underground structure detection;

3. A new set of performance measurements for these algorithms, under various amounts of noise, interference, sensor number and type, and dimensionality reduction;

4. Some novel ways of combining different sources and sensors that synergistically yield improved performance. An example of this is the combined acoustic/electromagnetic mine detection procedure described above. Other such combinations are expected to be revealed during the course of this research.

The utility of these results to DoD should be quite evident.

4 Facilities and Equipment

4.1 Facilities

The **facilities** in the Radiation Laboratory are well-suited for testing and verification of the algorithms to be developed in this project. The Laboratory is a major academic and research unit in the department of Electrical Engineering and Computer Science. Its faculty, research scientists and graduate students perform research in all aspects of electromagnetics including scattering, active and passive remote sensing, plasma, antennas, computational electromagnetics, and microwave/millimeter-wave circuits. The Radiation Laboratory of the University of Michigan is one of the best equipped higher educational institution in RF and microwave test equipment (from HF to W-band), radar instrumentation, far-field and near-field antenna pattern measurement facilities, and backscattering and bistatic scattering measurement facilities.

We are equipped with the state-of-the-art computation facilities and radar and optical image processing software and tools. Excellent full-wave simulation codes for point and distributed targets have been developed and will be utilized in this project. This will permit extensive validations. We also have extensive experimental facilities in the area of microwave, millimeter-wave, and optical remote sensing.

With regard to the image processing tasks, The Radiation Laboratory is fully equipped with the necessary computational environment. A dedicated research laboratory for microwave image analysis is equipped with a network of six Sun workstations, five LINUX workstations, and a PowerMac. These are supported by two 8mm tape drives, CDROM readers and writers and approximately 400GB of hard disk storage. The hardware is supported by PCI, ArcInfo and various other specialized software packages for processing and analysis of radar data.

Over the past ten years a complete suite of software has been developed for processing of SAR data from many different spaceborne, shuttle-borne, and airborne sensors. This software allows us complete control over all aspects of the processing including: format-conversion, error-correction, orthorectification, calibration, incidence-angle modeling, speckle-filtering, segmentation, classification, and biomass estimation.

This is all coupled with a detailed database of SAR backscattering characteristics of many types of terrain and vegetation, over a wide range of incidence angles. The lab's expertise in radar modeling, coupled with our image processing abilities makes for a complete end-to-end analysis and simulation infrastructure that is geared to problems concerning forested areas.

With regard to experimental facilities, The Radiation Laboratory maintains a number of outdoor and indoor systems and test equipment. Outdoor radar facilities include 9 fully-polarimetric stepped frequency scatterometers operating at L, C, X, Ku, Ka, and W bands. These fully polarimetric scatterometers are based on an HP8753 vector network analyzer (VNA). For these scatterometers, the integrated source for the HP8753 provides a synthesized source swept in the RF range from 300 kHz to 3 GHz. Appropriate up and down conversion is used in order to cover the frequency bands of interest. Use of a VNA as the signal processing unit of the scatterometers gives them phase measurement capability, good dynamic range, as well as highly-automated data acquisition. The time-domain capabilities of the analyzer also give the scatterometers efficient time gating. Two newly developed chirped Ka- and W- band polarimetric radars are also available for fast data collection (full polarimetric measurements in less than 6 μs). In addition to these radar systems a number of radiometer systems operating at L-band through 95 GHz are developed and being used in many ongoing projects. The radars and radiometers can be mounted atop of the boom truck (at a height of about 20m) as portable laboratories for outdoor experiments.

The Radiation Laboratory anechoic chamber is a fully equipped 60-foot-long tapered chamber allowing for antenna pattern and RCS measurement of targets of interest over a wide range of frequencies (200MHz - 140 GHz). The chamber is equipped with an azimuth over elevation over azimuth positioner and is set up for fully automatic measurements. We also maintain an indoor bistatic RCS measurement facilities for distributed targets which can be utilized for controlled experiments. The indoor bistatic facility can measure polarimetric bistatic scattering from a point target, random surface, buried targets or a random volume over a wide range of frequencies. Apart from the RF components, this facility is composed of a 2m$\times$2m sand-box atop of a precision turntable and two moving arches capable of scanning in azimuth and elevation directions. The motions of arches and the turntable are controlled by a computer. A relatively large near field scanner (3m$\times$3m) has recently been completed which allows for near-field antenna pattern measurements as well as an efficient near-field bistatic measurement.

4.2 Equipment

Due to the computationally intensive nature of the proposed work (evaluation of lower-dimensional models vs. higher-dimensional models, Monte Carlo simulations, etc.), a dedicated set of workstations will be required. The Radiation Laboratory has had success recently in using dedicated PCs for computation. We propose to purchase 6 workstations, along with appropriate software such as Matlab, during the first year. These will be used by the graduate students and postdocs who will carry out the bulk of the numerical simulation work for developing and evaluating the new algorithms.

5 Collaborations

Training of graduate students to perform world-class research as part of their Ph.D. thesis work is a vital part of the mission of the University of Michigan. The Dept. of Electrical Engineering and Computer Science has a strong track record in this regard. Research training of graduate students will be accomplished by normal 50% support of six graduate Ph.D. students.

The last page of the proposal is a reproduction of a letter of support from the Electro-Optics Infrared Group of the Ann Arbor Research and Development Center of Veridian Systems Division (formerly ERIM). Since they are only one mile away from the Dept. of EECS, this is an obvious and ideal collaboration. This group has been funded by DARPA in Multi-Sensor Exploitation Testbed and Adaptive Spectral Reconnaissance.

The letter makes it clear that they are interested in applying our results to their DoD work, and also employing some of our graduate students over the summer. This would be of obvious benefit to the research training of the graduate students, and it would also likely accelerate them up the learning curve to the point where they will be generating useful results. The benefit to DARPA should be evident.

The investigators have had several extensive previous collaborations with Veridian. Yagle supervised the Ph.D. thesis work of Chris Wackerman, and Hero supervised the Ph.D. thesis work of John Gorman. Both were on the organizing committee for ICASSP 1995 with John Ackenhusen (Hero as General Chair and Yagle as Technical Program Co-Chair). Hence the proposed collaboration would build on already-existing relationships.

It is important to emphasize that through our current collaborations with many DoD agencies (DARPA and ARL through a new MMW FOPEN program, ARO, CECOM, DARPA through FCS program, ARL through CTA program, etc.) we have collected, or have access to a vast set of existing measured data and conventional detection algorithms.

6 References

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7 Personnel and Curriculum Vitae

The Principal Investigator has no other ongoing research projects at this time.

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Education
Ph.D., Electrical Engineering, Massachusetts Institute of Technology, 1985
E.E., Electrical Engineering, M.I.T., Cambridge, MA, 1982
S.M., Electrical Engineering, M.I.T., Cambridge, MA, 1981
B.S.E.E., Electrical Engineering, University of Michigan, 1978
B.S.E., Engineering Science, University of Michigan, 1977

Professional Recognition
Office of Naval Research Young Investigator Award, 1990
NSF Presidential Young Investigator Award, 1988
Teaching Excellence Award, College of Engineering, UM, 1991-2
Class of 1938e Award, College of Engineering, UM, 1989

Recent Professional Service
Associate Editor, IEEE Signal Processing Letters, 1994-1998
Associate Editor, Multidimensional Systems and Signal Processing, 1994-1998
Associate Editor, IEEE Transactions on Image Processing, 1994-1997
Associate Editor, IEEE Transactions on Signal Processing, 1991-1993
Technical Program Co-Chair, ICASSP95, Detroit, MI, May 8-12, 1995
Member, IEEE Digital Signal Processing Technical Committee, 1992-present
Member, IEEE Image and Multidimensional Signal Processing TC, 1996-2002
Member-at-Large, Board of Governors, IEEE Signal Processing Society, 1998-2000
ABET Accreditation Leader, Electrical Engineering Program, 1999
Chief Program Advisor, Electrical Engineering Program, 2001-present

Five Relevant Publications:

1. R.R. Joshi and A.E. Yagle, "Levinson-Like and Schur-Like Fast Algorithms for Solving Block-Slanted-Toeplitz Systems of Equations Arising in Wavelet-Based Solution of Integral Equations," IEEE Trans. Sig. Proc. 46(7), July 1998.

2. A.E. Yagle, "Discrete Gel'fand-Levitan and Marchenko Matrix Equations and Layer Stripping Algorithms for the Discrete 2-D Schrodinger Equation Inverse Scattering Problem with a Nonlocal Potential," Inverse Problems.

3. A.E. Yagle and J. Frolik, "On the Feasibility of Impulse Reflection Response Data for the Two-Dimensional Inverse Scattering Problem," IEEE Trans. Antennas and Propagation 44(12), 1551-1564, December 1996.

4. J. Frolik and A.E. Yagle, "A Discrete-Time Formulation for the Variable Wave Speed Inverse Scattering Problem in Two Dimensions," Inverse Problems 12(6), 909-924, December 1996.

5. J. Frolik and A.E. Yagle, "Reconstruction of Multi-Layered Lossy Dielectrics from Plane Wave Impulse Responses at Two Angles of Incidence," IEEE Trans. Geosci. and Rem. Sensing 33(2), 268-279, March 1995.

ALFRED O. HERO, III, PROFESSOR, IEEE FELLOW
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Education
Ph.D., Princeton University, 1984
M.S., M.A., Princeton University, 1982
B.S., Boston University, 1980

Positions Held:
Professor, Statistics, The University of Michigan, 2000-present
Professor, Bio-Medical Engineering, The University of Michigan, 1998-present
Professor, Electrical Engineering and Computer Science, The University of Michigan, 1996-present

Five Relevant Publications:

1. "Comparison of GLR and invariance detectors under structured clutter covariance," H.S. Kim and A. O. Hero, IEEE Trans. on Image Processing, to appear Oct. 2001.
2. "Kullback proximal algorithms for maximum likelihood estimation," S. Chretien and A. O. Hero, IEEE Trans. on Inform. Theory, Vol IT-46, No. 5, pp. 1800-1810, Aug. 2000.
3. "Minimax emission computed tomography using high-resolution anatomical side information and B-spline models," A. O. Hero, R. Piramuthu, J. A. Fessler and S. R. Titus, IEEE Trans. On Information Theory (Special issue on Multiscale Statistical Signal Analysis and its Applications), Vol 45, No. 3, pp. 920-938, April 1999.
4. "Optimal simultaneous detection and estimation under a false alarm constraint," B. Baygun and A.O. Hero, IEEE Trans. on Inform. Theory, Vol. 41, No. 3, pp. 688-703, May 1995.
5. "Penalized maximum likelihood image reconstruction using space alternating generalized EM algorithms," J.A. Fessler and A.O. Hero, IEEE Trans. on Image Processing, Vol 4, No. 10, pp. 1417-1429, Oct 1995.

Synergistic Activities:

- Collaboration (1995-2000) with Dr. David Castenon, Dept. Electrical andComputer Engineering, Boston University, on automated target detection in SAR/EO imagery.
- Collaboration (1987-2000) with Dr. Leslie Rogers, Dept. Radiology, Division of Nuclear Medicine, University of Michigan, on image reconstruction and estimation strategies for PET and SPECT imaging.
- Collaboration (1999-) with Dr. Charles Meyer, Dept. Radiology, University of Michigan, on image registration of MRI/PET brain images.
- Collaboration (1992-) with Dr. Olivier Michel, Dept. Astrophysics, University of Nice, France, on tree structured non-linear prediction, graph theory, and time-frequency estimation.
- Collaboration (1999-) with Dr. Anand Swaroop, Dept. Human Genetics and Opthalmology, University of Michigan, on statistical analysis of geneticmicroarray data for retina.
- Collaboration (1996-2001) with Dr. Wayne Stark, Dept. EECS, University of Michigan, on low power signal processing for wireless communications.

KAMAL SARABANDI, PROFESSOR, IEEE FELLOW
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Education:
Ph.D., Electrical Engineering, University of Michigan, 1989
M.Sc., Mathematics, University of Michigan, 1989
M.Sc., Electrical Engineering, University of Michigan, 1986
B.Sc., Electrical Engineering, Sharif University of Technology, 1980

Synergistic Activities/Career Summary:
Professor Sarabandi has 20 years of experience with analytical and numerical simulation of wave scattering, wave propagation in random media, acoustic and electromagnetic wave interaction, communication channel modeling, microwave sensors, and radar systems and is leading a large research group including two research scientists, 10 Ph.D. and 4 M.S. students. Over the past ten years he has graduated 13 Ph.D. students. Dr. Sarabandi has published many book chapters and more than 90 papers in refereed journals on electromagnetic scattering, acoustic and electromagnetic wave interaction, random media modeling, wave propagation, antennas, microwave measurement techniques, radar calibration, inverse scattering problems, and microwave sensors. He has also had more than 160 papers and invited presentations in national and international conferences and symposia on similar subjects. He has served as the Principal Investigator on many projects sponsored by NASA, JPL, ARO, ONR, ARL, NSF, DARPA and numerous industries. Dr. Sarabandi is a Fellow of IEEE, a member of the IEEE Geoscience and Remote Sensing Society (GRSS) ADCOM, chairman of the Awards Committee of the IEEE GRSS, and a member of IEEE Technical Activities Board Awards Committee. He is serving as the Associate Editor of the IEEE Transactions on Antennas and Propagation (AP) and the IEEE Sensors Journal. He is also a member of Commission F of URSI and of The Electromagnetic Academy. Professor Sarabandi is listed in American Men & Women of Science and Who's Who in Electromagnetics.

Professional Appointments/Career History:

9/2000 -	Director of Radiation Laboratory, EECS Department, University of Michigan.
9/2001 -	Professor, EECS Department, The University of Michigan.
9/1996 - 8/2001	Associate Professor, EECS Department, The University of Michigan.
9/1992 - 8/1996	Assistant Professor, EECS Department, The University of Michigan.
9/1989 - 8/1992	Assistant Research Scientist, EECS Department, The University of Michigan.

Professional Recognition:
- Third Prize, IEEE AP/URSI 2001 paper contest with R. Azadegan.
- Third prize, IEEE MTTS'2001 paper contest with D. Perouli and L. Katehi.
- First prize, IEEE APS'2000 paper contest. D.E. Lawrence and K. Sarabandi.
- The 1999 German-American Council Foundation (GAAC) Distinguished Lecturer Award from the German Federal Ministry for Education, Science, and Technology.
- Third prize, IEEE IGARSS'99 paper contest. Wilsen, C.B., and K. Sarabandi.
- 1998 ARL Advanced Sensors Consortium Research Excellence Award, with Moonsoo Park.
- Second prize, IEEE AP-S'98 paper contest. M.D. Casciato, and K. Sarabandi.
- Henry Russel Award, The Regent of The University of Michigan, January 1997. The highest honor the University of Michigan bestows on junior faculty members.
- Teaching Excellence Award, EECS Department,The University of Michigan, March 1996.
- Second prize, IEEE AP-S'95 paper contest. A. Nashashibi, and K. Sarabandi.

MARCIN BOWNIK, ASSISTANT PROFESSOR
Dept. of Mathematics, The University of Michigan, Ann Arbor

Education:
Ph.D., Mathematics, Washington University, St. Louis, 2000.
M.A., Mathematics, Washington University, St. Louis, 1997
Magister, Mathematics, University of Warsaw, 1995.

Research Interests:

- Theory of anisotropic Hardy spaces using real variable methods in harmonic analysis
- Construction of wavelets associated with arbitrary dilations with nice properties
- Wavelets as a tool in investigating function spaces, e.g. anisotropic Hardy spaces
- Theory of wavelets and (quasi) affine frames; characterization theorems, dimension function
- Theory of shift invariant spaces in L^2 range function, range operator, refinable spaces
- Theory of matrix valued weights generalizing scalar Muckenhoupt weights
- Construction and study of non-separable multidimensional multiresolution analyses and wavelet bases with good time-frequency localization
- Wavelet dimension function and limitations on the existence of well-localized in time and frequency wavelets for general dilations
- Wavelet bases in non-isotropic function spaces, e.g., unconditional bases, Calderon-Zygmund singular integral operators in anisotropic Hardy spaces
- Characterization theorems for wavelet systems and its shift-invariant counterparts, quasi-affine systems

Selected Publications:

- M. Bownik, *The construction of r-regular wavelets for arbitrary dilations*, J. Fourier Anal. Appl. **7** (2001), 489–506.
- M. Bownik, *Anisotropic Hardy spaces and wavelets*, submitted to Mem. Amer. Math. Soc. (2000), available at `http://www.math.lsa.umich.edu/~marbow`
- M. Bownik and D. Speegle, *Meyer type wavelet bases in* R^2, submitted to J. Approx. Theory (2000), available at `http://www.math.lsa.umich.edu/~marbow`
- M. Bownik, *Combined MSF multiwavelets*, to appear in J. Fourier Anal. Appl. (2002).
- M. Bownik, Z. Rzeszotnik, and D. Speegle, *A characterization of dimension functions of wavelets*, Appl. Comput. Harmon. Anal. **10** (2001), 71–92.
- M. Bownik, *On characterizations of multiwavelets in* R^n, Proc. Amer. Math. Soc. **129** (2001), 3265–3274.
- M. Bownik, *The structure of shift invariant subspaces of* R^n, J. Funct. Anal. **177** (2000), 282–309.
- M. Bownik, *Inverse volume inequalities for matrix weights*, Indiana Univ. Math. J. **50** (2001), 383–410.
- M. Bownik, *A characterization of affine dual frames in* R^n, Appl. Comput. Harmon. Anal. **8** (2000), 203–221.
- M. Bownik, *Tight frames of multidimensional wavelets*, J. Fourier Anal. Appl. **3** (1997), 525–542.

RICHARD C. NOLEN-HOEKSEMA, ASSOCIATE RESEARCH SCIENTIST
Department of Civil and Environmental Engineering, The University of Michigan, Ann Arbor

Education:
Ph.D., Geophysics, Yale University, 1983.
M.Phil., Geophysics, Yale University, 1980.
M.S., Geophysics, Yale University, 1979.
B.A., Physics and Geology, Hope College, 1977.

Positions Held:
Associate Research Scientist, Dept of Civil & Environmental Engineering, University of Michigan, 1998–Present.
Associate Research Scientist, Dept of Geological Sciences, University of Michigan, 1995–1998.
Consulting Research Geophysicist and Rock Physicist, Independent Contractor, 1992–1995.
Research Associate, Department of Geophysics, Stanford University, 1988–1993.
Research Geophysicist, Chevron Oil Field Research Company, La Habra, California, 1985–1988.
Research Geologist, Cities Service Oil & Gas Corporation, Tulsa, Oklahoma, 1984–1985.
Post-doctoral Associate, Department of Geology & Geophysics, Yale University, 1983–1984.

Selected Publications:

- Nolen-Hoeksema, R. C. and R. B. Gordon (1987). "Optical detection of crack patterns in the opening-mode fracture of marble." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, **24**(2): 135–144.
- Knight, R. and R. C. Nolen-Hoeksema (1990). "A laboratory study of the dependence of elastic wave velocities on pore scale fluid distribution." *Geophysical Research Letters*, **17**(10): 1529–1532.
- Nolen-Hoeksema, R. C. (1993). "Porosity and consolidation limits of sediments and Gassmann's elastic-wave equation." *Geophysical Research Letters*, **20**(9): 847–850.
- Mavko, G. and R. C. Nolen-Hoeksema (1994). "Estimating seismic velocities at ultrasonic frequencies in partially saturated rocks." *Geophysics*, **59**(2): 252–258.
- Dvorkin, J., R. C. Nolen-Hoeksema, and A. Nur (1994). "The squirt-flow mechanism: Macroscopic description." *Geophysics*, **59**(3): 428–438.
- Yilmaz, Ö., R. C. Nolen-Hoeksema, and A. Nur (1994). "Pore pressure profiles in fractured and compliant rocks." *Geophysical Prospecting*, **42**(6): 693–714.
- Harris, J. M., R. C. Nolen-Hoeksema, R. T. Langan, J. W. Rector, III, M. Van Schaack, and S. K. Lazaratos (1995). "High resolution crosswell imaging of a west Texas carbonate reservoir: Part 1. Project summary and interpretation." *Geophysics*, **60**(3): 667–681.
- Nolen-Hoeksema, R. C., Z. Wang, J. M. Harris, and R. T. Langan (1995). "High resolution crosswell imaging of a west Texas carbonate reservoir: Part 5. Core analysis." *Geophysics*, **60**(3): 712–726.
- Tucker, K. E., P. M. Harris, and R. C. Nolen-Hoeksema (1998). "Geologic investigation of cross-well seismic response in a carbonate reservoir, McElroy field, west Texas." *American Association of Petroleum Geologists Bulletin*, **82**(8): 1463–1503.
- Nolen-Hoeksema, R. C. (2000). "Modulus-porosity relations, Gassmann's equations, and the low-frequency elastic-wave response to fluids." *Geophysics,* **65**(5): 1355–1363.
- Nolen-Hoeksema, R. C. and L. J. Ruff (2001). "Moment tensor inversion of microseisms from the B-sand propped hydrofracture, M-Site, Colorado." *Tectonophysics*, **336**(1–4): 163–181.

LELAND E. PIERCE, ASSISTANT RESEARCH SCIENTIST

Dept. of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor

Education:

PhD, Electrical Engineering, The Univ. of Michigan, 1991.
MSE, Electrical Engineering, The Univ. of Michigan, 1986.
BSE, Electrical Engineering, The Univ. of Michigan, 1983.
BSE, Aerospace Engineering, The Univ. of Michigan, 1983.

Related Experience and Qualifications:

Leland has been a researcher in his current position for over 10 years. His research interests include development of image processing techniques for radar remote sensing, scattering models for natural targets, integration of Geographical Information Systems (GIS), inverse scattering problems and image classification. In particular, the applications he has concentrated on have emphasized forestry applications.

Leland has been head of the Microwave Image Processing Lab since 1991, and has been involved with SAR data processing the whole time. He has authored a SAR processing packages that is sold as part of a commercial satellite image processing package, and has also authored SAR format conversion software that has been used by industry. He has authored numerous journal articles covering all aspects of SAR image filtering, classification, and biomass inversion.

Selected Publications/Presentations:

- Pierce, Leland E., Kamal Sarabandi, and Fawwaz T. Ulaby, "Application of an artificial neural network in a canopy scattering model inversion," *International Jrnl. of Remote Sensing.*, Vol. 15, No. 16, 1994, 3263–3270.
- Dobson, M. Craig, Fawwaz T. Ulaby, and Leland E. Pierce, "Land-Cover Classification and Estimation of Terrain Attributes Using Synthetic Aperture Radar," *Remote Sensing of Environment,* Vol. 51, No. 1, Jan. 1995, 199–214.
- Dobson, M. Craig, Fawwaz T. Ulaby, Leland E. Pierce, Terry L. Sharik, Kathleen M. Bergen, Josef M. Kellndorfer, John R. Kendra, Eric Li, Yi Cheng Lin, Adib Nashashibi, Kamal Sarabandi, and Paul Siqueira, "Estimation of Forest Biophysical Characteristics in Northern Michigan with SIR-C/X-SAR," *IEEE Trans. Geosci. Remote Sensing,* Vol. 33, No. 4, July 1995, 877–895.
- Dobson, M. Craig, Leland E. Pierce, and Fawwaz T. Ulaby, "Knowledge-based Land-cover Classification using ERS-1/JERS-1 SAR Composites," *IEEE Trans. Geosci. Remote Sensing.*, Vol. 33, No. 1, Jan. 1996, 83–99.
- Dobson, M.C., L.E. Pierce, and F.T. Ulaby, "Evaluation of SAR Sensor Configurations for Terrain Classification and Forest Biophysical Retrievals", Accepted to Int. J. Remote Sensing, March 2000.
- Bergen, Kathleen, Craig Dobson, Leland Pierce, Fawwaz Ulaby, "Characterizing Carbon in a Northern Forest using SIR-C/X-SAR Imagery," *Remote Sensing of Environment*, Jan 2000.
- Kobayashi, Yutaka, Sarabandi, Kamal, Pierce, Leland, Dobson, M. Craig, "Evaluation of the JPL TOPSAR for extracting tree heights," *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 38, No. 6, pp. 2446-2454, Nov. 2000.
- De Roo, Roger, Munn, J, Pierce, L.E., Nashashibi, A.Y., Ulaby, F.T., Samples, G.S., "SPRI: Simulator of Polarimetric Radar Images," Accepted for publication in IEEE Trans. Aerospace and Electronics Systems, 5-2001.
- Sarabandi, Kamal, Charles Brown, Leland Pierce. "Tree Height Estimation from the Polarimetric and Interferometric Radar Response," Presented at IGARSS'99.

8 Costs

8.1 Budget

The budget is at right.
Costs are given over
the following periods:

- May 1, 2002-Nov. 30, 2002
- Dec. 1, 2002-Nov. 30, 2003
- Dec. 1, 2003-Nov. 30, 2004
- Dec. 1, 2004-Apr. 30, 2005

for the 3-year base period.

They are also given
for the 2 option years:

- May 1, 2005-Nov. 30, 2005
- Dec. 1, 2005-Nov. 30, 2006
- Dec. 1, 2006-Apr. 30, 2007

8.2 Budget Justification

Salary for 15% academic year is requested for the PI with 10% requested for the three Co-P.I.s. It is proposed that two research scientists be assigned to this project with 50% effort each. Support for six graduate student research associates (GSRAs) is also requested. The GSRA will work 50% on the project during the calendar year. The GSRA compensation package includes tuition remission. Tuition is typically incurred for two semesters per year per GSRA. In addition, two full time post-doctoral researchers are to be assigned to this project.

A modest 10% salary support is requested for an experienced Administrator. The individual identified in the budget will have no departmental duties under this effort and will be responsible for assisting the P.I. and GSRA in the administration of the proposed project. Their role will be to ensure that all ancillary support functions are handled efficiently and in a timely manner, and that all records and accounts required for the proper conduct of the project are appropriately maintained. These duties include but are not limited to: (1) maintaining records of research expenditures so that the PD can respond to university and sponsor inquiries; (2) providing an up-to-date monthly overview of the financial status of the grant funds; (3) preparing both short-term and long-term budget projections, as required; (4) recommending, preparing, and filing any supplemental paperwork, such as requests for rebudgeting, time extensions, and the like; (5) acting as liaison between the P.I. and the appropriate officials in the University's contracts and grants office, e.g., to procure and disseminate to the project participants information pertaining to changes in policies and, and to ensure compliance with funding agency guidelines; and (6) assisting in the preparation of progress reports and correspondence, travel, personnel and procurement relating to the grant. It is anticipated that collaborative framework of this research project will add an extra burden of communication and administration that is more efficiently delegated to the administrative staff, thereby freeing the senior staff for the scientific effort.

For the purposes of hourly wage calculation, a 12 month staff work year is defined as 2080 hours (40 x 52). The PI on this proposal works an academic year of 9 months for their base salary, with additional pay available for effort during summer months.

All direct labor rates are established from current actual rates, adjusted for merit increases at a rate of 5% per year, each September.

Fringe benefits are estimated at 28%. This is an average rate. Actual rates will be based on the selection of benefits by personnel assigned to the project.

We request **travel funds** to cover costs of transportation and lodging for all senior research staff to attend one domestic and one international scientific conference per year, for presentation of findings. Typical conferences would include ICASSP, ICIP and APS. The principal investigators are also budgeted for biannual sponsor meetings.

Typical meetings might be as follows (these are taken from a recent proposal):

Pittsburgh , 3 trips per year for a period of 3 days each Lodging @ 100/night x 2 = 200 Meals at $60/day x 3 = 180 RT airfare = 765

Three trips to Los Angeles or vicinity, 3 days each Lodging @ 150/night x 2 = 300 Meals at $75/day x 3 = 225 RT airfare = 1500

One location to be determined by DARPA Lodging @ 120/night x 2 = 240 Meals at $75/day x 3 = 225 RT airfare = 1500

6 trips to international locations such as: Saint Petersburg, Russia International Conference on Integrated Navigation Systems, May 2002 Lodging @ 120/night x 2 = 240 Meals at $75/day x 3 = 225 RT airfare = 2200

International Symposium on Communication Systems & Digital Signal Processing Staffordshire University, Stafford, United Kingdom, July 2002 Lodging @ 120/night x 2 = 240 Meals at $75/day x 3 = 225 RT airfare = 800

Joint-Control Applications/Computer Aided Control Systems Design, Glasgow, Scotland September 2002 Lodging @ 120/night x 2 = 240 Meals at $75/day x 3 = 225 RT airfare = 600

All airfares are based upon booking less than two weeks in advance with no restrictions, coach class, roundtrip as quoted by travel.Yahoo.com.

The **materials and supplies** category includes funds for copying, toll charges, mailing, books, computer software and consumable supplies such as transparencies. These expenses would relate directly to the research subject and would be used solely to benefit the project. Postage and expedited mail services for mailing of materials would be directly related to the research project such as manuscript submissions, etc. This budget category ($6,000 per year) will be used by all personnel assigned to this project.

Publication, reports and reprint costs are anticipated at an initial rate of $2,000 per year.

These estimates are based upon previous experience with similar research projects and are considered to be reasonable for the effort expended.

An **annual increase** of 5% is built into the budget for all salary and tuition related expenses.

Indirect costs are calculated as 51% of the total direct costs less tuition (MTDC).