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Arye Nehorai

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Illinois at Chicago
Dept. of Electrical & Computer Engineering
1020 Sciences and Engineering Offices (SEO)
851 South Morgan St.(M/C 154)
Chicago, IL 60607

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. Arje Nachman
Air Force Office of Scientific Research
875 North Randolph St., Rm 3112
Arlington, VA 22203

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14. ABSTRACT
We developed statistical time-reversal imaging and Cramer-Rao bounds (CRB's) for point targets and scatterers; realistic clutter modeling, random scattering reflections, compound Gaussian distributions, and signal dependence; maximum likelihood estimators, CRB's, and sequential target detectors in compound-Gaussian clutter; polarimetric radar algorithms for detecting/tracking targets in clutter; microstrip antennas design with suppressed radiation in horizontal directions and reduced coupling, and 6D vector antenna; optimal synthesis of a directional beam with full polarization control; estimated building layouts and objects behind walls using exterior radar measurements and EM modeling; robust least-squares beamformers (spatial filters) for estimating unknown source signals under steering vector uncertainties; tight lower bounds on the mean-square error (MSE) of estimating multiple change points of measurement models; unification of minimal Bayesian bounds on the MSE of estimators; performance bounds on image registration useful for optimum design of registration algorithms; image reconstruction method for diffuse optical tomography; electromagnetic inverse solutions based on Poisson point spatial model for estimating unknown source (e.g., brain) signals.

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			Arye Nehorai

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Radar Array Signal Processing in the Presence of Scattering Effects

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Arye Nehorai
Department of Electrical and Systems Engineering
Washington University in St. Louis
One Brookings Drive
St. Louis, MO 63130
Ph. 314-935-7520
Email: nehorai@ese.wustl.edu
Web: http://ese.wustl.edu/~nehorai/

1 Rationale

One of the most challenging and common problems in detecting and estimating a target with radar systems is the presence of scatterers in the environment. The echoes reflected by the scatterers are often viewed as a source of interference (clutter) that reduces the system performance. However, by appropriate modeling and exploitation of these echoes, the performance of the radar sensing could be enhanced dramatically.

In order to achieve the goal of significantly improve the radar capabilities, we considered realistic models for the target and environment reflections. We included both physical (electromagnetic) and statistical aspects. The backscattered electromagnetic field depends on the properties of the transmitted signal, such frequency and polarization. Hence, we considered models depicting how the features of this signal are affected by the medium materials through which the signal propagates. We designed signal processing methods that exploit the information provided by these modeling aspects. Our detection algorithms were developed to have high sensitivity to the presence of a target in highly cluttered environment by optimally detecting changes in the measured features. Our estimation methods determine efficiently the parameters of both the target and its environment, achieving the optimal performance bounds. As an important aspect of our research, we computed universal bounds analytically for each of the problems.

We developed first solutions for complex targets in which the usual point-target assumption is no longer valid. We designed time-reversal imaging methods to resolve and estimate targets composed by distributed point scatterers. We derived statistical measurement models based on the physical models of the multistatic response matrix, the distorted wave Born approximation and Foldy-Lax multiple scattering models. We developed an algorithm for estimating the location and scattering coefficient of each point target, as well as we analyzed the algorithm performance.

We also considered the problem of targets in cluttered scenarios for high-resolution and low-grazing-angle radars. Under these conditions, conventional Gaussian models can not properly represent the clutter statistics. Then, we proposed the use a compound-Gaussian model with inverse-gamma texture. We derived an algorithm to estimate the clutter distribution parameters.

Then, we considered the presence of a scattering surface near the target. Due to the multipath propagation generated by the surface, conventional systems suffer of low performance. We proposed exploiting polarimetric information to improve the system capabilities in order to resolve the target from its multipath image. We derived signal models taking into account the polarimetric effect of the target and the surface, as well as we compared the performance of polarimetric systems with respect to the conventional scalar system.

Moreover, we addressed other topics related to sensing applications and advance modeling beyond the original goals of the proposal. We considered the problem of estimating building layouts and moving objects behind walls using exterior radar systems. These are challenging tasks involving complex electromagnetic modeling and many unknown parameters. We also developed polarimetric algorithms for target detection and tracking using realistic clutter models. We derived advanced sensing methods using beamforming techniques and performance measures of change detection in distribution parameters, useful to detect the appearance and disappearance of a target in a minimal delay time. We proposed a unification of minimal Bayesian bounds on the MSE of estimators and derived performance bounds on image registration useful for optimum design of registration algorithms.

We analyzed the capability of systems for resolving closely spaced sources by defining the angular resolution limit. We formulated the synthesis of polarimetric beampatterns as a convex optimization problem. We considered the design vector sensor antennas and antennas with reduced coupling. We also developed new optical sensors systems, inspired by the biological compound-eye, and analyzed its performance.

In the following section, we discuss further our contributions under this project.

2 Developed Research

2.1 Modeling of Channel and Environment

Compound-Gaussian Clutter Modeling: Compound-Gaussian models are used in radar signal processing to describe heavy-tailed clutter distributions, such as foliage clutter data. The important problems in compound-Gaussian clutter modeling are choosing the texture distribution and estimating its parameters. Many texture distributions have been studied, and their parameters are typically estimated using statistically suboptimal approaches. In [1] and [2] we consider the widely used gamma texture model, and propose an inverse-gamma texture model. The inverse gamma distributed texture is important for modeling compound-Gaussian clutter, due to the simplicity of estimating its parameters. We develop maximum-likelihood (ML) and method of fractional moments (MoFM) estimates to find the parameters of this distribution. We compute the Cramér-Rao bounds (CRBs) on the estimate variances and present numerical examples. We also show examples demonstrating the applicability of our methods to real clutter data. Our results illustrate that, as expected, the ML estimates are asymptotically efficient, and also that the real data can be very well modeled by the inverse gamma distributed texture compound-Gaussian model.

Low-Grazing-Angle Propagation: Tracking targets and radio sources flying near the surface is a problem of considerable relevance, mainly because the presence of multipath fading degrades the system performance. In [3] we consider the problem of passive estimation of source direction-of-arrival (DOA) and range using polarization-sensitive sensor arrays, when the receiver array and signal source are near the surface. The scenario of interest is the case of low-grazing-angle propagation. We present a general polarimetric signal model that takes into account the interference of the direct field with the field reflected from smooth and rough surfaces. Using the Cramér-Rao bound (CRB) and mean-square angular error (MSAE) bound, we analyze the performance of different array configurations, which include an electromagnetic vector sensor (EMVS), a distributed electromagnetic component array (DEMCA), and a distributed electric dipole array (DEDA). By computing these bounds, we show significant advantages in using the proposed diversely polarized arrays compared with the conventional scalar-sensor arrays.

2.2 Target Detection

Polarimetric Detection: Polarization diversity has proved to be a useful tool for radar detection, especially when discrimination by Doppler effect is not possible. In [4] we address the problem of improving the performance of polarimetric detectors for targets in heavy inhomogeneous clutter. First, we introduce a new polarimetric radar model that includes the realistic dependence of the clutter reflections on the transmitted signal. Then, we develop a polarimetric detection test that is robust to inhomogeneous clutter. We run this polarimetric test against synthetic and real data to assess its performance in comparison with existing polarimetric detectors. We also propose a polarimetric design algorithm to further improve the target-detection performance. A numerical analysis is presented to demonstrate the potential performance improvement that can be achieved with this algorithm.

Sequential Detection: Sequential detection allows the analysis of an incoming data flow and the detection of changes in the distribution of these measurements. In [5] we develop the sequential detection algorithm for a target under compound-Gaussian clutter. Both the target and clutter parameters are assumed unknown. We first derive estimates for these parameters, then discuss the sequential detection algorithm for two cases: target parameter is known and unknown. We consider detections for both the target appearance and disappearance. We examine the relationship between several performance measurements for the sequential detector, including the false-alarm rate and the average detection delay. In the numerical example part, we first illustrate the performance of our algorithms. Then we present an example of the optimal polarimetry design in the sequential detection.

2.3 Modeling, Parameter Estimation, and Target Tracking

Time-Reversal Imaging: The key idea behind the so-called physical time-reversal methods is to record a signal emitted by sources or reflected by targets using an array of transducers; then transmit the time-reversed and complex conjugated version of the measurements back into the medium. One application of this time-reversal refocusing property is to detect and locate a target by computational or virtual time reversal through imaging. In this case, after receiving the signal reflected from the target, a back-propagated process is computed rather than implemented in the real medium. In [6] and [7] we present a statistical framework for the fixed-frequency computational time-reversal imaging problem assuming point scatterers in a known background medium. Our statistical measurement models are based on the physical models of the multistatic response matrix, the distorted wave Born approximation and Foldy-Lax multiple scattering models. We develop maximum likelihood (ML) estimators of the locations and reflection parameters of the scatterers. Using a simplified single-scatterer model, we also propose a likelihood time-reversal imaging technique which is suboptimal but computationally efficient and can be used to initialize the ML estimation. We generalize the fixed-frequency likelihood imaging to multiple frequencies, and demonstrate its effectiveness in resolving the grating lobes of a sparse array. This enables to achieve high resolution by deploying a large-aperture array consisting of a small number of antennas while avoiding spatial ambiguity. Numerical and experimental examples are used to illustrate the applicability of our results.

Through-the-Wall Imaging: Estimating building layouts and moving objects behind walls using exterior radar measurements is a challenging task involving complex electromagnetic modeling, many unknown parameters, and limited number of sensors. In [9] we propose using the jump-diffusion algorithm as a powerful stochastic tool that can be used to estimate the number of walls, estimate their unknown positions and other parameters. We develop an efficient iterative procedure that first finds low frequency estimates, which are then used to initiate our more accurate estimation at higher frequencies. We show that with proper frequency selection, building layout can be estimated using radar measurements at only a few frequencies. Our proficient usage of the available frequency bandwidth improves the computational speed that otherwise would be hampered by the forward electromagnetic modeling and slow convergence rate. Then, in [10] we consider the estimation of moving targets behind concrete wall reinforced with metallic bars. We add coherently electric field measured by the sensor array to estimate the wall thickness and concrete permittivity. We show that these parameters have major influence on the estimation accuracy. We apply beamforming to the signals reflected from targets to estimate their number and positions. The proposed solution is based on accurate physical models calculated using the method of moments. We also developed algorithm in the case when the parameters of metallic bars are known. We refine the estimation by modeling the influence of the bars on the signal waveform. The resulting images become more focused and the target spreads are reduced.

Bayesian Polarimetric Target Tracking: In [11] we develop a sequential Bayesian tracking algorithm for targets in clutter. We employ polarization diversity to improve the tracking accuracy. We use an array of electromagnetic (EM) vector sensors to fully exploit the polarization information of the reflected signal. We apply a sequential Monte Carlo method to track the target parameters, including target position, velocity, and scattering coefficients. This method has the advantage of being able to handle nonlinear and non-Gaussian state and measurement models. The measurements are the output of the sensor array; hence, the information about both the target and its environment is incorporated in the tracking process. We design a method for selecting the transmit signal polarization one-step ahead based on a recursion of the posterior Cramér-Rao bound. We also derive an algorithm using Monte Carlo integration to compute this criterion and a suboptimal method that reduces the computation cost. Numerical examples demonstrate both the performance of the proposed tracking method.

Target in Compound-Gaussian Clutter: In [1] we develop maximum likelihood (ML) methods for jointly estimating the target and clutter parameters in compound-Gaussian clutter using radar array measurements. In particular, we estimate i) the complex target amplitudes, ii) a spatial and temporal covariance matrix of the speckle component, and iii) texture distribution parameters. Parameter-expanded expectation-maximization (PX-EM) algorithms are developed to compute the ML estimates of the unknown parameters. We also derived the Cramér-Rao bounds (CRBs) and related bounds for these parameters. We first derive general CRB expressions under an arbitrary texture model then simplify them for specific texture distributions. We consider the widely used gamma texture model, and propose an inverse-gamma texture model, leading to a complex multivariate clutter distribution and closed-form expressions of the CRB. We study the performance of the proposed methods via numerical simulations. In addition, in [12] we develop an algorithm for selecting the transmit signal polarization that minimizes a CRB function. We propose also suboptimal versions of this algorithm and illustrate the performance as well as compare our algorithm with numerical examples.

Robust Beamforming: In [13] we treat the problem of beamforming for signal estimation in the presence of steering vector uncertainties, where the goal is to estimate a signal amplitude from a set of array observations. Conventional beamforming methods typically aim at maximizing the signal-to-interference-plus-noise ratio (SINR). Recently, a maximum likelihood (ML) approach was introduced that leads to an iterative beamformer. Here we suggest an expected least-squares (LS) strategy that results in a simple linear beamformer. We then demonstrate through simulations that the LS beamformer often performs similarly to the ML method in terms of mean-squared error and outperforms conventional SINR-based approaches. Then, in [14] we consider strategies that attempt to minimize the MSE between the estimated and unknown signal waveforms. The methods we suggest all maximize the SINR but at the same time are designed to have good MSE performance. Since the MSE depends on the signal power, which is unknown, we develop competitive beamforming approaches that minimize a robust MSE measure. Two design strategies are proposed: minimax MSE and minimax regret. We demonstrate through numerical examples that the suggested minimax beamformers can outperform several existing standard and robust methods, over a wide range of signal-to-noise ratio (SNR) values. Finally, we apply our techniques to subband beamforming and illustrate their advantage in estimating a wideband signal.

2.4 General Performance Bounds

Time-Reversal Imaging: The resolution improvements of time reversal methods through exploiting nonhomogeneous media have attracted much interest recently with broad applications, including underwater acoustics, radar, detection of defects in metals, communications, and destruction of kidney stones. In [8] we analyze the effect of inhomogeneity generated by multiple scattering among point scatterers under a multistatic sensing setup. We derive the Cramér-Rao bounds (CRBs) on parameters of the scatterers and compare the CRBs for multiple scattering using the FoldyLax model with the reference case without multiple scattering using the Born approximation. We find that multiple scattering could significantly improve the estimation performance of the system and higher order scattering components actually contain much richer information about the scatterers. For the case where multiple scattering is not possible, e.g., where only a single target scatterer exists in the illuminated scenario, we propose the use of artificial scatterers, which could effectively improve the estimation performance of the target despite a decrease in the degrees of freedom of the estimation problem due to the introduced unknown parameters of the artificial scatterers. Numerical examples demonstrate the advantages of the artificial scatterers.

Image Registration: Registration is a fundamental step in image processing systems where there is a need to match two or more images. Applications include motion detection, target recognition, video processing, and medical imaging. Although a vast number of publications have appeared on image registration, performance analysis is usually performed visually, and little attention has been given to statistical performance bounds. Such bounds can be useful in evaluating image registration techniques, determining parameter regions where accurate registration is possible, and choosing features to be used for the registration. In [15] we derive the Cramér-Rao bounds on a wide variety of geometric deformation models, including translation, rotation, shearing, rigid, more general affine and nonlinear transformations. For some of the cases, we give closed-form expressions for the maximum-likelihood estimates, as well as their variances, as space permits. We also extend the bounds to unknown original objects. We present numerical examples illustrating the analytical performance bounds.

Performance Analysis on Change Detection: In [16] and [17] we compute lower bounds on the mean-square error of multiple change-point estimation. In this context, the parameters are discrete hence the well known Cramér-Rao bound is not applicable. Consequently, we focus on the computation of the Barankin bound, the greatest lower bound on the covariance of any unbiased estimator, which is still valid for discrete parameters. We first give the structure of the so-called Barankin information matrix and derive a simplified form of the Barankin bound. We show that the particular case of two change points is fundamental to finding the inverse of this matrix. Several closed-form expressions of the bound are given for changes in the parameters of Gaussian and Poisson distributions. We finally present some numerical examples to compare the proposed bound with the performance achieved by the maximum likelihood estimator.

Bayesian Bounds: Minimal bounds on the mean square error are generally used in order to predict the best achievable performance of an estimator for a given observation model. In [18] we are interested in the Bayesian bound of the Weiss-Weinstein family. Among this family, we have Bayesian Cramer-Rao bound, the Bobrovsky- MayerWolf-Zaka bound, the Bayesian Bhattacharyya bound, the Bobrovsky-Zaka bound, the Reuven- Messer bound, and the Weiss-Weinstein bound. We present a unification of all these minimal bounds based on a rewriting of the minimum mean square error estimator and on a constrained ptimization problem. With this approach, we obtain a useful theoretical framework to derive new Bayesian bounds. For that purpose, we propose two bounds. First, we propose a generalization of the Bayesian Bhattacharyya bound extending the works of Bobrovsky, Mayer-Wolf, and Zaka. Second, we propose a bound based on the Bayesian Bhattacharyya bound and on the Reuven-Messer bound, representing a generalization of these bounds. The proposed bound is the Bayesian extension of the deterministic Abel bound and is found to be tighter than the Bayesian Bhattacharyya bound, the Reuven-Messer bound, the Bobrovsky-Zaka bound, and the Bayesian Cramer-Rao bound. We propose some closed-form expressions of these bounds for a general Gaussian observation model with parameterized mean. In order to illustrate our results, we present simulation results in the context of a spectral analysis problem.

Angular Resolution Bounds: We define in [19] a statistical angular resolution limit (ARL) on resolving two closely spaced point sources in a three-dimensional reference frame, using constraints on the probabilities of false alarm and detection for a hypothesis test. The ARL can be used as a performance measure for sensor arrays in localizing remote sources and is applicable to different measurement models and applications (e.g., radar, sonar, or astronomy). By considering the asymptotic performance of the generalized likelihood ratio test (GLRT), we compute the analytical expression of the ARL and show that it is proportional to the square root of the Cramér-Rao bound (CRB) on the angular source separation, or asymptotically the lower bound on the mean-square angular error ($\mathrm{MSAE}_{\mathrm{CRB}}$). Numerical examples illustrate that the proposed ARL is practically computable and achievable with large data samples. Our analytical result can replace the commonly used experiential resolution limits in existing literature.

2.5 Antenna Design

The effects of the sensors and antennas is usually disregarded when designing signal processing techniques. The usual assumptions consider that there is no coupling between the antennas in a array of sensors. Frequent simplifications of the radar problem model the radar signal as a scalar wave, under the assumption of identically polarized sensor arrays for transmission and reception. We addressed the problem of reducing the coupling of antennas in a sensor arrays, as the design of vector sensor antennas capable of sensing polarization differences among the received signal.

Reduced Coupling Antennas: The near-field coupling occurs when one antenna is in the near-field zone of another antenna. This coupling is not clearly recognized in the literature, although it can dominate when antennas are closely spaced. In [20] we design a microstrip antenna with reduced coupling. To that purpose, we designed an array of pins that interconnect the patch and the ground. We adjust the currents of the pins by dimensioning their radii and locations to suppress radiation in horizontal directions and coupling among array elements.

Vector Sensors: Polarization is one type of waveform diversity that may be exploited to improve both radar and communication systems performance. Analytical results show that in order to obtain the best performance improvements, based upon the use of polarization diversity, knowledge of the full electric and magnetic field components is required. Vector sensor antennas are able to measure these components and thus they enable the exploitation of polarization diversity. In [21] we describe a distributed approach to design a 6D vector antenna in a distributed fashion using both electric dipole and magnetic loops as constitutive elements.

2.6 Other Research Topics

Polarized Beampattern Synthesis: Utilizing polarized waveforms enables increasing the capacity of communication systems and improving the performance of active sensing systems. In [22] we consider the optimal synthesis of a directional beam with full polarization control using an array of electromagnetic vector antennas (EMVA). In such an array, each antenna consists of $p \geq 2$ orthogonal electric or magnetic dipole elements. The control of polarization and spatial power pattern are achieved through carefully designing the amplitudes and phases of the weights of these dipole antennas. We formulate the problem in a convex form, which is thus efficiently solvable by existing solvers such as the interior point method. Our results indicate that vector antenna array not only enables full polarization control of the beampattern, but also improves the power gain of the main beam (over the sidelobes), where the gain is shown to be linearly proportional to vector antenna dimensionality p. This implies that EMVA not only offers the freedom to control the beampattern polarization, but also virtually increases the array size by exploiting the full electromagnetic (EM) field components. We also study the effect of polarization on the spatial power pattern. Our analysis shows that for arrays consisting of pairs of electrical and magnetic dipoles, the spatial power pattern is independent of the mainbeam polarization constraint.

Biological Compound-Eye: In [23] and [23] we propose a detector array for detecting and localizing sources that emit particles including photons, neutrons, or charged particles. The array consists of multiple eyelets. Each eyelet has a conical module with a lens on its top and an inner sub-array containing multiple particle detectors. The array configuration is inspired by and generalizes the biological compound eye: it is spherically shaped and has a larger number of detectors in each individual eyelet. Potential applications of this biomimetic array include artificial vision in medicine (e.g., artificial eyes for the blind) or robotics (e.g., for industry or space missions), astronomy (e.g., for remote stars), security (e.g., for nuclear materials), and particle communications. We assume Poisson distribution for each detectors measurement within the observation time window. Then we construct a parametric model for the detection rate of the Poisson-distributed measurements by assuming a circular Gaussian lens-shaping function (LSF), which is commonly used in optical and biological disciplines. To illustrate how the model fits practical cases, we apply it to an example of localizing a candle from 20 miles away and estimating the parameters under this circumstance. In addition, we discuss the hardware setup and performance measure of the proposed array, as well as its fundamental constraints. Then, we analytically and numerically analyze the statistical performance of the array. We compute the statistical Cramer-Rao bounds (CRBs) on the errors in estimating the direction of arrival of the incident particles; we derive a lower bound on the mean-square angular error (MSAE) of source localization for any specific array configuration; we consider two source-direction estimators, the maximum likelihood estimator (MLE) and the weighted direction estimator

(WDE), and analyze their MSAE performance. In the numerical examples, we quantitatively compare the performance of the proposed array with the biological compound eye; show the array performance as a function of the array configuration variables; optimally design the array configuration; illustrate that the MLE asymptotically attains the performance bound, while the WDE is nearly optimal for sufficiently large SNR; and analyze the hardware efficiency by comparing the two MSAE bounds

3 Interactions

Throughout the project term, we had communications with many researchers and engineers in government labs and industry, who have shown interest in our results, in particular:

- Dr. Muralidhar Rangaswamy, AFRL.
- Dr. Richard Chen, NRL.
- Dr. Harry Schmitt, Raytheon.

Part of our research work was performed in collaboration with the following researchers:

- Dr. D. Erricolo, Department of Electrical and Computer Engineering, University of Illinois at Chicago. Topic: design of vector sensor antenna.
- Dr. A. J. Devaney, Department of Electrical and Computer Engineering, Northeastern University, Boston. Topic: time-reversal imaging techniques.

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