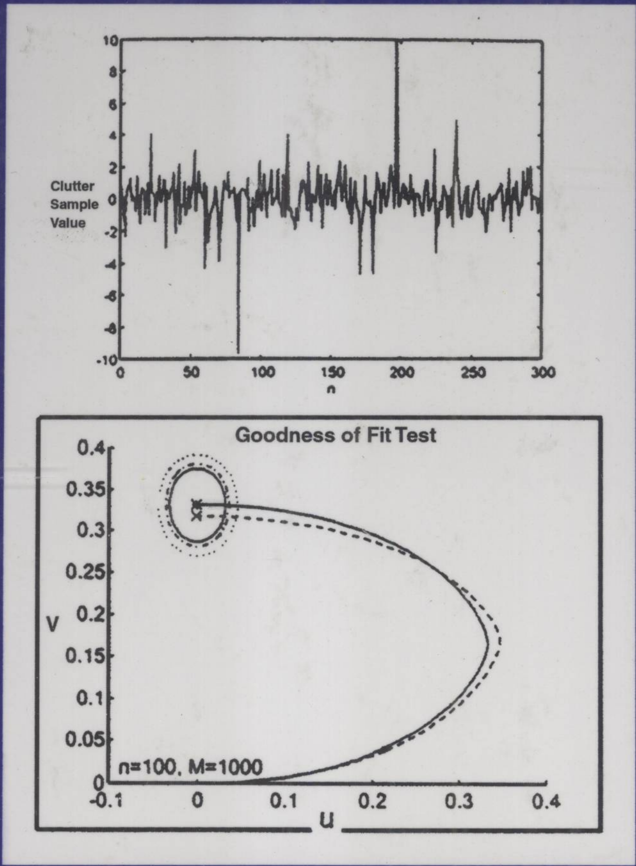

Adaptive Antennas and Receivers

Edited by

Melvin M. Weiner

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ADAPTIVE ANTENNAS AND RECEIVERS

EDITED BY

MELVIN M. WEINER

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In memory of our parents, Kate and William

Melvin and Donald Weiner

In memory of my wife, Clara

Ronald Fante

Preface

The primary intent of this book is to provide an introduction to state-of-the art research on the modeling, testing, and application of adaptive antennas and receivers. As such, it provides a baseline for engineers, scientists, practitioners, and students in surveillance, communication, navigation, government service, artificial intelligence, computer tomography, neuroscience, and security intrusion industries. This book is based on work performed at Syracuse University and The MITRE Corporation with sponsorship primarily by the U. S. Air Force.

At issue is the detection of target signals in a competing electromagnetic environment which is much larger than the signal *after* conventional signal processing and receiver filtering. The competing electromagnetic environment is *external* system noise (herein designated as "noise") such as clutter residue, interference, atmospheric noise, man-made noise, jammers, external thermal noise (optical systems), *in vivo* surrounding tissue (biological systems), and surrounding material (intrusion detection systems). The environment is statistically characterized by a probability density function (PDF) which may be Gaussian, or more significantly, nonGaussian. For applications with an objective of target detection, the signal is assumed to be from a moving target within the surveillance volume and with a velocity greater than the minimum discernable velocity.

In radars, which look down at the ground to detect targets, the clutter echo power can be 60 to 80 dB larger than the target echo power before signal processing. The target is detected by measuring the difference in returns from one pulse to the next. This method is based on the underlying assumption that the clutter echo power and the radar system are stable between pulses whereas the target signal is not. The degree of stability influences the subclutter visibility (SCV), i.e., the ratio by which the target echo power may be weaker than the coincident clutter echo power and still be detected with specified detection and false-alarm probabilities. The receiving systems of interest comprise an antenna array, digital receiver, signal processor, and threshold detector.[1]

The electromagnetic environment is assumed to be characterized by a "noise" voltage with a PDF that is *temporally* Gaussian but not necessarily *spatially* Gaussian. Conventional signal detection, for a specified false alarm rate or bit error rate, is achieved by measuring the magnitude-squared output of a linear Gaussian receiver compared to a single threshold determined by the variance of the noise voltage averaged over all the cells of the total surveillance volume.

A linear Gaussian receiver is defined as a receiver matched to the frequency spectrum of the signal and assumes a temporally Gaussian PDF "noise" voltage. In conventional signal detection, the probability of signal detection within any cell of the surveillance volume is small if the signal power is small compared to the average noise variance of the total surveillance volume.

This book considers the more general case where the "noise" environment may be spatially nonGaussian. The book is divided into three parts where each part presents a different but sequentially complementary approach for increasing the probability of signal detection within at least some of the cells of the surveillance volume for a nonGaussian or Gaussian "noise" environment. These approaches are: Approach A. *Homogeneous Partitioning of the Surveillance Volume*; Approach B. *Adaptive Antennas*; and Approach C. *Adaptive Receivers*.

Approach A. *Homogeneous Partitioning of the Surveillance Volume*. This approach partitions the surveillance volume into homogeneous, contiguous subdivisions. A homogeneous subdivision is one that can be subdivided into arbitrary subgroups, each of at least 100 contiguous cells, such that all the subgroups contain stochastic spatio-temporal "noise" sharing the same PDF. At least 100 cells/subgroup are necessary for sufficient confidence levels (see Section 4.3). The constant false-alarm rate (CFAR) method reduces to Approach A if the CFAR "reference" cells are within the same homogeneous subdivision as the target cell. When the noise environment is not known *a priori*, then it is necessary to sample the environment, classify and index the homogeneous subdivisions, and exclude those samples that are not homogeneous within a subdivision. If this sampling is not done in a statistically correct manner, then Approach A can yield disappointing results because the estimated PDF is not the actual PDF. Part I *Homogeneous Partitioning of the Surveillance Volume* addresses this issue.

Approach B. *Adaptive Antennas*. This approach, also known as *space-time adaptive processing*, seeks to minimize the competing electromagnetic environment by placing nulls in its principal angle-of-arrival and Doppler frequency (space-time) domains of the surveillance volume. This approach utilizes $k = \mathrm{NM}$ samples of the signals from N subarrays of the antenna over a coherent processing interval containing M pulses to (1) estimate, in the space-time domain, an $NM \times NM$ "noise" covariance matrix of the subarray signals, (2) solve the matrix for up to N unknown "noise" angles of arrival and M unknown "noise" Doppler frequencies, and (3) determine appropriate weighting functions for each subarray that will place nulls in the estimated angle-of-arrival and Doppler frequency domains of the "noise".

Approach B is a form of filtering in those domains. Consequently, the receiver detector threshold can be reduced because the average "noise" voltage variance of the surveillance volume is reduced. The locations and depths of the nulls are determined by the relative locations and strengths of the "noise" sources in the space-time domain and by differences in the actual and estimated "noise" covariance matrices. The results are influenced by the finite number k of stochastic data samples and the computational efficiency in space-time processing the samples. Part II *Adaptive Antennas* addresses these issues and presents physical models of several applications.

Approach C. *Adaptive Receivers*. For each homogeneous subdivision of the surveillance volume, this approach generally utilizes a nonlinear, nonGaussian receiver whose detection algorithm is matched to the sampled "noise" voltage spatial PDF of that subdivision. When the nonGaussian "noise" waveform is spikier than Gaussian noise, the nonlinear receiver is more effective than a linear receiver in reducing the detecton threshold for a given false alarm rate *provided that the estimated spatial PDF is an accurate representation of the actual PDF*. If the estimated spatial PDF is Gaussian, then the nonlinear receiver reduces to a linear Gaussian receiver. At issue are (1) how to model, simulate, and identify the random processes associated with the *correlated* "noise" data samples and (2) how to determine the nonlinear receiver and its threshold that are best matched to those data samples. Part III *Adaptive Receivers* addresses and illustrates these issues with some applications.

Approach C should not be implemented until Approaches A and B have been implemented. For a prespecified false alarm probability, Approach A or B alone have a better probability of target detection than in their absence. The combination of Approaches A and B has a better probability of target detection than Approach A or B alone. The combination of Approaches A, B, and C has a still better probability of target detection. For this reason, this book often refers to the combination of Approaches A, B, and C as the *weak* signal problem, (*i.e.*, small signal-to-noise ratio case); the combination of Approaches A and B or Approach A or B alone as the *intermediate* signal problem, (*i.e.*, intermediate signal-to-noise ratio case); and the absence of all three approaches as the *strong* signal problem, (*i.e.*, large signal-to-noise ratio case). Approaches A and C are usually more difficult to implement than Approach B alone because "noise" spatial PDF is more difficult to measure than "noise" variance. However, for the weak signal problem, Approaches A and C can be worth the effort as is shown in Part III. All of these approaches have benefited from orders-of-magnitude increases in the speeds of beam scanning and data processing made possible by recent technological advances in integrated circuits and digital computers. However, equally important, are the recent advances in methodology which are reported in this book.

Adaptive antennas originated in the 1950s with classified work by S. Applebaum followed later by P. W. Howells, both of whom published their work about 40 years ago.[2,3] Practical techniques for space-time processing of the sampled data originated with B. Widrow and colleagues approximately a year later.[4]

A nonlinear nonGaussian receiver for weak signal detection, in the presence of "noise" whose PDF is not necessarily Gaussian, originated with D. Middleton approximately 45 years ago.[5] The receiver is designated a "locally optimum detector" (LOD) because, in a Taylor series expansion of the numerator of the likelihood ratio (LR) about a unity operating point, only the second term (a linear test statistic) is retained and the first term (a constant) is combined as part of the threshold. Thus, for small signal-to-disturbance ratio, a sensitive yet computationally simpler test statistic is obtained, resulting in either a nonlinear receiver for non-Gaussian disturbances or a linear matched filter for Gaussian disturbances with deterministic signals. Unlike an adaptive receiver, Middleton's LOD utilized a fixed detection algorithm and threshold that were determined *a priori* to the detection process.

The feasibility of an adaptive receiver was made possible less than 15 years ago when Aydin Ozturk (Professor, Dept. of Mathematics, Syracuse University) developed an algorithm for identifying and estimating univariate and multivariate distributions based on sample-order statistics.[6,7] At that time, my brother, Donald D. Weiner (Professor, Dept. of Electrical and Computer Engineering, Syracuse University), in collaboration with his doctoral student Muralidhar Rangaswamy and A. Ozturk, conceived the idea of an adaptable receiver which (1) sampled in real time the "noise" environment, (2) utilized the Ozturk algorithm to estimate the "noise" PDF, and (3) utilized the Middleton LOD by matching its detection algorithm and threshold to the estimated "noise" PDF.[8,9]

By 1993, with additional collaboration from Prakash Chakravarthi, Mohamed-Adel Slamani (doctoral students of D. D. Weiner), Hong Wang (Professor, Dept. of Electrical and Computer Engineering, Syracuse University) and Lujing Cai (doctoral student of H. Wang), the core ideas for much of the material in this book had been developed.[10,11] With the exception of Chapters 9 and 10, all of the materials in this book are based on later refinements, elaborations, and applications by D. D. Weiner, his students (Thomas J. Barnard, P. Chakravarthi, Braham Himed, Andrew D. Keckler, James H. Michels, M. Rangaswamy, Rajiv R. Shah, M. A. Slamani, Dennis L. Stadelman), his colleagues at Syracuse University (A. Ozturk, H. Wang), students of H. Wang (L. Cai, Michael C. Wicks), his colleagues at Rome Laboratory (Christopher T. Capraro, Gerard T. Capraro, David Ferris, William J. Baldygo, Vincent Vannicola), his son (William W. Weiner), and Fyzodeen Khan (colleague of T. J. Barnard). Chapter 9 is contributed by George Ploussios (consultant, Cambridge, MA). Chapter 10 consists of reprints of all the refereed journal papers on adaptive antennas individually authored by Ronald L. Fante (Fellow, The MITRE Corporation) or co-authored with colleagues Edward C. Barile, Richard M. Davis, Thomas P. Guella, Jose A. Torres, and John J. Vaccaro.

My interest in the core ideas of this book originated in 1993 from two invited talks at the MITRE Sensor Center.[12,13] The two talks utilized novel mathematical tools (such as the *Ozturk algorithm* and *spherically invariant random vectors*) for more effective implementation of homogeneous partitioning, adaptive antennas, and adaptive receivers. Since that time, the utilization of these tools for those purposes has been reported in the journal literature but not in a book. In July 2003, Marcel Dekker Inc. asked me to recommend a prospective author for a book on *smart* antennas. Smart antennas are nothing more than adaptive antennas (with or without the signal processing associated with adaptive antennas) which are specifically tailored for the wireless mobile communication industry. Since there were already several books on smart antennas, the publisher agreed instead to accept a proposal from me for the present book.

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