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This report summarizes research accomplishments in the 3-year period Nov. 1, 1989 - Oct. 31, 1992. The primary accomplishments were in the areas of (i) nonlinear and robust filters - order statistics and related filters, multivariate medians, analysis, and applications; (ii) signal detection in non-Gaussian noise - ARE, quantization, distributed detection, nonparametric detection; and (iii) nonlinear radial basis function networks in signal processing. Reference is made to 28 publications.				
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FINAL TECHNICAL REPORT OF RESEARCH ON STATISTICAL TECHNIQUES FOR SIGNAL PROCESSING

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Saleem A. Kassam
Principal Investigator
University of Pennsylvania
Philadelphia, PA 19104

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Statistical Techniques for Signal Processing: Final Report AFOSR Grant 90-0050, 11/1/89-10/31/92

In this report we summarize our activity during the last three years under the above research grant. Some significant, original, and interesting results have been obtained and reported during this period: these have been listed as publications [1]-[28] on page 7.

During this period, under AFOSR support, *two* Ph.D. dissertations [1,2] and *two* Master's theses [3,4] were completed, and a book chapter [5] was written. *Eleven* journal papers were prepared (including one under review), and *twelve* conference papers were presented. AFOSR support during this period provided salary for two summer months for the Principal Investigator, and twelve months of support for one graduate research assistant, each year.

The investigations that we have conducted during this research grant period may be categorized as falling into two broad areas: these are the areas of *Nonlinear and Robust Filters*, and of *Signal Detection in Non-Gaussian Noise*. We describe below the primary results we have obtained in these two areas, as well as other new results and activity.

A. Nonlinear and Robust Filters: Order Statistics and Related Filters, Multivariate Medians, Analysis, and Applications.

Nonlinear filtering based on order statistics and related techniques (e.g. median filtering) has been of much interest in statistical signal processing. Our work has been recognized as having contributed some very significant ideas, analyses, and results in the development of this key area of signal processing research and applications. During this grant period we have continued to make some significant advances on several aspects of nonlinear and robust filters, as described below.

Nonlinear filters such as the L-filter (based on linear combinations of order statistics) are useful for robust edge-preserving filtering and smoothing in non-Gaussian (impulsive) noise. Such filters do not, however, allow control over the frequency response which is a very desirable feature offered by non-robust linear filters. The *combination filter*, or C-filter, is a nonlinear filter for real-valued inputs (univariate case) which combines the desirable characteristics of linear finite-impulse response and nonlinear L-filters. Such filters are of interest as edge-preserving robust filters which are capable also of providing "frequency response" control. They allow frequency-sensitive functions such as deconvolution or interference rejection to be effectively performed in the presence of impulsive noise and without loss of signal details or edges. Combination filters are based on joint time-order and rank-order processing of input data. Our contributions and results on this useful filter structure have been published in the journal paper [10]. Given in [10] are several interesting illustrations of the various applications of C-filters, in *image processing, channel equalization, and deconvolution*. Another application of C-filters in detection in impulsive environments has been described in [23]. The dissertation [1] contains further details on C-filters.

We also began during this grant period a new effort focused on development of *multivariate nonlinear (order statistics) filters*. Our particular focus has been on multivariate extensions of the median and related filters, for use in applications such as multi-spectral image processing and narrowband (complex-valued data) signal processing. While the univariate median filter is easy to define, extensions to the multivariate case are not so obvious because there is no natural criterion for rank-ordering in p-dimensional Euclidean

space for $p > 1$. We have made some interesting observations and definitions in recent preliminary work [19, 24, 25], and are working to further these results. In particular, in [24] and [25] we have defined a new bivariate median (the *radial median*) that appears to enjoy some useful properties and justification as a natural extension of the univariate median. Its extension to higher dimensions produces a rather complex implementation, however and needs additional work. The thesis [4] contains some other observations and results on bivariate median filters.

In addition to this effort on multivariate nonlinear filters, we are continuing to obtain a better understanding of the univariate robust edge-preserving properties of median-type filters, by relating their properties directly to the *influence functions* and *extended influence functions* of the associated underlying estimators. An interesting application of the influence function and its extensions has been made by us in analyzing the edge-preserving and smoothing behavior of nonlinear filters such as the order-statistics based L-filters and related filter structures. While the influence function is best known for its role in characterizing the robustness of estimators, the mathematical framework underlying it also gives asymptotic expressions for the moments of estimators. We have made use of this, and obtained the influence functions and approximate performance characterization of filters such as the modified trimmed mean filter. For such filters exact analysis is often quite difficult. We have shown that the approximate asymptotic results are in good agreement with results obtained from exact analysis (in simple cases) and simulations. This approach and results have been given in [22,26] and in a recent journal paper [15]. We are extending this method to characterize other filters with more general structures in current work. In a recent paper [27] we have discussed how a general *adaptive* filter structure based on order statistics can be designed and analyzed for performance using the influence function as a tool. In particular, we have examined the mean-median hybrid filter (which adapts smoothly between averaging inputs and using their median, depending on the characteristics of the input) as an example of this type of application. Even such a simple filter is difficult to analyze exactly for performance with a non-homogeneous (edge-bearing) signal input. We have shown in a journal paper that has been accepted for publication [16] that the influence function approach is very useful in characterizing the actual performance of this type of filter, and have described its use in the edge-preserving smoothing of noisy images.

The use of order statistics has been widely considered for the purpose of *constant false alarm rate (CFAR)* detection of radar pulses in noise and clutter. For CFAR detection one has to be able to automatically set detector test parameters to achieve a fixed value for the false-alarm probability, because the clutter and noise power is not known. At the same time, the adaptive parameter setting algorithm has to be able to follow abrupt changes in clutter power levels, otherwise excessive false alarms are generated at such clutter edges. Some new ideas for CFAR radar detection in exponentially distributed clutter have been developed in this grant period. *Adaptive selection* of an order statistic based on different subsets of the data window has been described in [17]. We have improved upon this scheme further, and a full paper on this approach is being prepared for publication. Another approach uses trimmed means, with a fixed amount of lower order-statistics trimming but with a variable, *adaptive trimming* of the higher order-statistics. We have been able to demonstrate useful gains in performance for such a CFAR scheme, and a full paper on this approach has been accepted for publication [12].

B. Signal Detection in Non-Gaussian Noise: ARE, Quantization, Distributed Detection, Nonparametric Detection

One significant advance that we have made in the area of signal detection and non-Gaussian noise modelling followed from our use of new models for describing signals and noise which are not simply additive and independent, a simplifying restriction under which most previous studies have been made. Our *multiplicative and signal-dependent noise models* allow new results and insights to be developed which are of both theoretical and practical significance. Papers [6] and [7] describe our ideas and detailed results on new statistical models for use in the study of signal detection and estimation schemes in non-Gaussian noise. They allow observations to be described as desired signals in additive as well as multiplicative noise and signal dependent noise, and provide in particular the structures of *locally optimum* detection schemes. These results are interesting as additions to the body of previous theoretical results which had been obtained for simple models only, and they provide insights useful in practice regarding optimum processing schemes in the presence of noise which is not only additive.

The *asymptotic relative efficiency* (ARE) is a useful asymptotic measure for gauging the relative performance of two detectors. It is particularly useful in comparing nonlinear detectors operating under non-Gaussian conditions. The ARE provides an appealingly simple measure to characterize the asymptotic relative performance of two tests, but the relative performance for finite sample sizes is known to sometimes converge very slowly to the ARE value. One part of our effort was devoted to enhancing the utility of the asymptotic relative efficiency (ARE) as a measure of relative performance of signal detectors. In our work we have been able to give a characterization and development of the ARE which allows it to more accurately predict observed finite-sample-size detector relative performances (such as overshoots in the relative efficiency above the ARE value). The work reported in [18] and in the paper [8] focuses on the canonical problem of detection of known signals in additive noise, and provides analytical insights and simple enhancements of the ARE measure to allow finite sample size relative performance to be more accurately predicted. We expect that this work can be extended to other scenarios.

We have also obtained new results on *detectors using quantized observations*, where our initial focus has again been on the additive noise model. The use of quantized data is necessary in many situations, and optimum quantization schemes for signal detection have received much attention. We have considered the practical case where the partitioning of input observations is constrained to be time-invariant, even for non-stationary signals, and have obtained new results extending earlier solutions. This work also made use of the new noise models we described in [6] and [7]. One interesting observation was that even for the classical case of Gaussian signals in Gaussian noise, the locally optimum quantization of data is *not* necessarily symmetric. These new results have been published in [9, 20].

The detection of signals in noise using observations collected over a number of sensors *distributed* over a spatial field, and which do not communicate directly with one another, has formed one main focus of our work on signal detection theory. We have been working towards the goal of extending the well-known developments in single-sensor (or centralized) detection theory to the generally more difficult but important case of *distributed detection*. This type of scheme is of practical significance and also presents interesting problems of analysis. In distributed signal detection each sensor does a local processing of its data before passing on the result to a central processor. The central processor makes the final decision based on the results it gets from all the local sensor processors. The local processors effect a data reduction, often only to one-bit local decisions, out of considerations of communication capacities, security, or reliability. The design of the

system for optimum overall performance requires consideration jointly of local and central processor decision rules, and can get quite difficult. Previous analyses have generally assumed that the observations at the different sensors are statistically independent. This is clearly not always reasonable: for example, if the signal is emanating from a single source it will tend to be correlated at each of the sensors. We have obtained some very good general results on *locally optimum* distributed detection schemes, and are hoping to continue our work in this and related directions during the next grant period. The dissertation [2] was completed recently and contains some significant new results on distributed signal detection in non-Gaussian noise. It describes results giving explicitly the structures of the local and central processors for dependent observations due to correlated random signal arrivals. The analysis is carried out for weak signals, which allows asymptotic techniques to be used. The results are interesting generalizations of earlier work on weak-signal-optimum centralized detection structures. Some preliminary results on this topic were published in [21]. A full paper on this aspect of signal detection theory has been published very recently [11]. In [2] the distributed signal detection problem was also viewed as a problem of *optimum quantization*, and some new results were established on optimum quantization for weak signal detection.

The dissertation [2] also contains an application of distributed signal detection in *constant false alarm rate (CFAR)* detection for radar pulses in exponentially distributed noise and clutter. The cell-averaging CFAR scheme was analyzed for two-sensor distributed systems, with some interesting results on performance improvements. In other work on CFAR detection that has been accepted for journal publication [14], we have made some interesting observations on the *statistical optimality* (based on invariance, sufficiency and completeness) of the classical cell-averaging CFAR detector.

Finally, we have completed work on one aspect of *nonparametric detection of random signals* which adds to the existing body of results on nonparametric tests in the statistics literature. The locally most powerful rank test structure has been derived by us for random signals in additive random noise, a problem involving convolutional combinations of signal and noise pdf's. These results will appear shortly in the journal paper [13].

C. Nonlinear Radial Basis Function Networks in Signal Processing

Lately we began looking into the use of nonlinear networks related to neural networks but which have a simpler structure making them very interesting for adaptive signal processing applications. The *radial basis function (RBF)* network allows the output to be a nonlinear function of a multivariate input, with weights or parameters which appear in a linear manner in the output. The nonlinear elements are radially invariant functions of the differences between the input and a set of "centers". This structure turns out to have some appealing characteristics, and in preliminary work we have applied it to accomplish adaptive interference cancellation when the interference appears in an available reference input in a nonlinear manner. The work we have done strongly suggests that further work is warranted to exploit the unique capability that this type of processing structure seems to allow. In [28] we give our initial results on the interference cancelling application, and show that major improvements in performance can be realized compared to linear adaptive filter structures.

D. Other Activity

During this grant period the Principal Investigator has completed a book chapter on advances in *Nonparametric Detection* [5] which will appear in a compendium of recent advances in the field of signal detection. He also began working on a book on *Statistical Signal Processing*.

The Principal Investigator has given invited talks at several universities on these research areas, and has also made an invited presentation at a recent workshop held in conjunction with the Seventh International Conference on Multivariate Analysis.

He served as *Associate Editor for Detection Theory* for the IEEE Transactions on Information Theory.

The Principal Investigator is on the advisory board for the *International Conference on Nonlinear Signal Processing* held in Finland in January 1993.

He was also the research advisor of another full-time graduate student (Rich Kozick) at the University of Pennsylvania, who was supported on a separate Air Force Laboratory Graduate Fellowship.

List of Publications

Doctoral Dissertations

- [1] P. P. Gandhi, "Order Statistic and Rank Based Processors for Filtering and Detection" *Dept. of Elect. Eng., Univ. of Penn.* (1990)
- [2] R. S. Blum, "Distributed and Quantized Weak-Signal Detection" *Dept. of Elect. Eng., Univ. of Penn.* (1991)

Master's Theses

- [3] J. Moulton, "Image Processing for Speckle Reduction" *Dept. of Elect. Eng., Univ. of Penn.* (1990)
- [4] S. Osmani, "Performance Characteristics of Some Bivariate Median Filters" *Dept. of Elect. Eng., Univ. of Penn.* (1990)

Book Chapter

- [5] S. A. Kassam, "Nonparametric Detection" in *Advances in Statistical Signal Processing, Vol.2: Signal Detection*. (Poor and Thomas, Eds.) CSC Press, 1993 (in press)

Journal Papers

- [6] I. Song & S. A. Kassam, "Locally Optimum Detection of Signals in a Generalized Observation Model: The Known Signal Case," *IEEE Trans. Inform. Theory*, **36**, 502-515, May 1990
- [7] I. Song & S. A. Kassam, "Locally Optimum Detection of Signals in a Generalized Observation Model: The Random Signal Case," *IEEE Trans. Inform. Theory*, **36**, 516-530, May 1990
- [8] R. S. Blum & S. A. Kassam, "Approximate Analysis of the Convergence Behavior of Relative Efficiency to ARE for Known Signal Detection," *IEEE Trans. Inform. Theory*, **37**, 199-206, January 1991
- [9] R. S. Blum & S. A. Kassam, "Asymptotically Optimum Quantization with Time-invariant Breakpoints for Signal Detection," *IEEE Trans. Inform. Theory*, **37**, 402-407, March 1991
- [10] P.P. Gandhi & S. A. Kassam, "Design and Performance of Combination Filters for Signal Restoration," *IEEE Trans. Signal Processing*, **39**, 1524-1540, July 1991
- [11] R. S. Blum & S. A. Kassam, "Optimum Distributed Detection of Weak Signals with Dependent Sensors," *IEEE Trans. Inform. Theory*, **38**, 1066-1079, May 1992
- [12] I. Ozgunes, P. P. Gandhi, & S. A. Kassam, "A Variably Trimmed Mean CFAR Radar Detector," *IEEE Trans. Aero.space & Electronic Systems*, **28**, 1002-1014, October 1992
- [13] I. Song & S. A. Kassam, "Locally Optimum Rank Detection of Correlated Random Signals in Additive Noise," *IEEE Trans. Inform. Theory*, **38**, 1311-1322, July 1992

- [14] P. P. Gandhi & S. A. Kassam, "Optimality of the Cell-Averaging CFAR Detector," *IEEE Trans. Inform. Theory*, (accepted for publication)
- [15] N. Himayat & S. A. Kassam, "Approximate Performance Analysis of Edge Preserving Filters," *IEEE Trans. Signal Processing*, (accepted for publication)
- [16] N. Himayat & S. A. Kassam, "A General Structure for Adaptive Order Statistics Filtering," *IEEE Trans. Image Processing* (accepted for publication)

Conference Papers

- [17] P. P. Gandhi & S. A. Kassam, "Adaptive Order Statistic and Trimmed Mean CFAR Radar Detectors," *Proc. 1989 IEEE Region Ten Conf.(TENCON)*, November 1989
- [18] R. Blum & S. A. Kassam, "The Use of ARE in Finite Sample Size Detector Performance Prediction," *Abstracts IEEE Int. Symp. on Information Theory*, 134, January 1990
- [19] S. A. Osmani, P.P. Gandhi & S. A. Kassam, "Performance Characteristics of Some Bivariate Median Filters," *Proc. Conf Inform. Sciences & Systems (Princeton)*, 215-220, March 1990
- [20] R. Blum & S. A. Kassam, "A General Result for Locally Optimum Quantization with Time Invariant Breakpoints," *Proc. Conf. Inform. Sciences & Systems (Princeton)*, 695-700, March 1990
- [21] R. S. Blum & S. A. Kassam, "Optimum Distributed Detection of Weak Signal in Dependent Sensors," *Proc. 24th Annual Asilomar Conf. on Signals, Syst., & Comp.*, 134-138, November 1990
- [22] N. Himayat & S. A. Kassam, "A Characterization of Edge Preserving Filters Based on the Influence Function and its Extensions," *Proc. Conf: Inform. Sciences & Systems (Johns Hopkins Univ.)*, March 1991
- [23] P. P. Gandhi, "Detection of Known Signals in Correlated Impulsive Noise Using Combination Filters," *Proc. Conf. Inform. Sciences & Systems (Johns Hopkins Univ.)*, pp. 493-498, March 1991
- [24] S. A. Kassam & N. Himayat, "Bivariate Median Filters: New Definitions and Properties," *Proc. IEEE Pacific Rim Conf. Commun., Comp. & Signal Process.*, May 1991
- [25] S. A. Kassam & M. Aburdene, "Multivariate Median Filters and Their Extensions," *Proc. IEEE Int. Circ. & Systems Symp.*, 85-88, June 1991
- [26] N. Himayat & S. A. Kassam, "A Theoretical Study of Some Nonlinear EdgePreserving Smoothing Filters," *Proc. IEEE Inter. Conf. Systems Eng.*, 261-264, August 1991
- [27] N. Himayat & S. A. Kassam, "A General Structure for Adaptive Order Statistics Filtering," *Proc. Conf. Inform. Sciences & Systems (Princeton)*, 319-324, March 1992
- [28] I. Cha & S. A. Kassam, "Interference cancellation using radial basis function networks," *Sixth IEEE SP Workshop on Statistical Signal and Array Processing*, October 1992

Book

S. A. Kassam and H. V. Poor, *Statistical Signal Processing*
(In Preparation for 1993 Publication)

Invited Presentations

"Robust Filters and Applications" Villanova University, Nov. 1989

"Robust Filters for Image Processing" Drexel University, April 1991

"Nonlinear Filters for Signal and Image Processing" Lehigh University, Nov. 1991

Invited Speaker at Workshop on Multidimensional Signal Processing, Sixth
International Conf. on Multivariate Statistics, Penn State Univ., May 1992