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Louis L. Scharf and Clifford T. Mullis

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University of Colorado
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Boulder, CO 80309-0425

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13. ABSTRACT *(Maximum 200 words)*
This report summarizes our work on four general problems during the three-year period of the contract: (1) estimation of frequency-wavenumber, (2) matched subspace filters, (3) maximum likelihood estimation of modes from space-time data, and (4) statistical inference within the wavelet representation. We have generalized the theory of multiwindow estimators of the power spectrum to multiwindow estimators of the frequency wavenumber spectrum and of the related correlation sequence. We are now applying these ideas to the derivation of adaptive filters. We have developed a theory of matched subspace detectors for detecting signals which lie in low-dimensional model subspaces. The theory bridges the gap between generalized likelihood ratio theories and invariance theories. We have generalized the theory of maximum likelihood for identifying time domain modes and space domain directions of arrival. We have characterized subband decompositions for perfect reconstruction, developed filter design algorithms for constructing near perfect reconstruction filterbanks from nonorthogonal analysis filters, and derived algorithms for predicting and filtering in periodically correlated time series.

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SIGNAL PROCESSING IN THE LINEAR STATISTICAL MODEL

PRINCIPAL INVESTIGATOR: Louis L. Scharf, 303/492-8283
DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING
UNIVERSITY OF COLORADO
BOULDER, CO 80309-0425

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Principal Investigators: Louis L. Scharf and C. T. Mullis

Mailing Address: Electrical & Computer Engineering, Box 425
University of Colorado
Boulder, CO 80309-0425

Phone Number: (303) 492-8283 E-Mail Address: scharf@prony.colorado.edu, mullis@prony.colorado.edu

a. Number of Papers Submitted to Refereed Journals but not yet published: 10 (list attached)

b. Number of Papers Published in Refereed Journals: 11 (list attached)

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h. Number of Invited Presentations at Workshops or Professional Society Meetings: 3 (list attached)

i. Number of Contributed Presentations at Workshops or Professional Society Meetings: 16 (list attached)

j. Honors/Awards/Prizes for Contract/Grant Employees: 2 (list attached)

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Overview of Research

In 1991 we submitted a proposal entitled "Matched Subspace Filtering for Detection, Estimation, and Time Series Analysis." In it we proposed to study four problems:

1. Estimation of the Frequency-Wavenumber Spectrum;
2. Matched Subspace Filters for Matched Field Processing;
3. Maximum Likelihood Identification of Modes from Space-Time Data; and
4. Statistical Inference Within the Wavelet Representation.

With ONR support under contract N00014-89-J-1070, we studied these problems. Let's review our findings.

1. In references [CSM91] and [ClS92], we generalized the results of [MuS91] to characterize the class of quadratic estimators of the frequency-wavenumber spectrum that are required to be non-negative and invariant to temporal and spatial modulation. These estimators take the form

$$\hat{S}(\kappa, \theta; \mathbf{y}) = \mathbf{y}^* \mathbf{D}^*(\kappa, -\theta) \mathbf{V}^* \mathbf{V} \mathbf{D}(\kappa, -\theta) \mathbf{y},$$

where κ is wavenumber, θ is frequency, the vector $\mathbf{y}$ is a lexicographically-ordered version of space-time data, $\mathbf{D}$ is a Kronecker product of modulator matrices for time and space, and $\mathbf{V}$ is a matrix of space-time windows [CSM91], [ClS92]. The mean-squared error for this quadratic estimator is bounded by

$$\text{mse}(\kappa, \theta) \geq \frac{1}{M+1} \left(S(\kappa, \theta) \right)^2,$$

where M is the number of windows used to construct the estimator. This bound for mean-squared error actually obscures the selectivity and the variance of the estimator. Generally, we wish to resolve a cell of frequency-wavenumber space in order to concentrate energy, but the more we concentrate it the higher is the variance of the concentration. So, the problem is to choose a number of windows equal to the time-bandwidth product for the data and the cell to be resolved. The selection of separable space-time windows is discussed at length in [ClS92] and [Cla92]. More generally, the designer of an estimator that resolves energy or power into frequency-wavenumber cells can design a multiplicity of orthogonal windows which have quite general spectral shapes in frequency and wavenumber.

2. In references [ScF94] and [BeS94], we have generalized what was previously known about detection and estimation of rank-one signals to the detection and estimation of rank-r signals obscured by rank-t interferences. This work produces linear and quadratic forms in oblique projections. These projections project data onto one subspace along the direction of another. The singular values of the oblique projections determine the performance of the linear and quadratic forms, and these singular values depend on the geometrical angles between the subspaces. With these results, we have been able to gain new insights into the resolution of closely spaced subspaces $\langle H \rangle$ and $\langle S \rangle$ and into the detection of signals that lie in a subspace $\langle H \rangle$ that is near to an interfering subspace $\langle S \rangle$. As an example of what our results have produced, we list here the signal-to-noise ratio (SNR) in an optimum subspace detector and the gain against noise (G) when resolving two closely spaced subspaces:

$$\text{SNR} = \frac{\mu^2}{\sigma^2} \underline{\theta}^* \mathbf{H}^* \mathbf{P}_{\mathbf{S}}^{\perp} \mathbf{H} \underline{\theta}$$

$$\begin{aligned} G &= \text{tr} \left[\mathbf{H}^* \mathbf{P}_{\mathbf{S}}^{\perp} \mathbf{H} \right]^{-1} \\ &= \sum_{i=1}^{M} \frac{1}{\sin^2 \theta_i} \end{aligned}$$

$$\mathbf{P}_{\mathbf{S}}^{\perp} : \text{projection onto } \langle S \rangle^{\perp}.$$

These formulas illustrate that the angles θ_i between the signal subspace $\langle H \rangle$ and interference subspace $\langle S \rangle$ determine performance. In our work on the geometry of the Cramer-Rao bound [ScM93], we have shown that the variance for resolving the subspace components of a signal is bounded as

$$\begin{aligned} V &\geq \mathrm{tr}\,[\mathbf{H}^{*}\mathbf{P}_{\mathbf{S}}^{\perp}\mathbf{H}]^{-1} \\ &= \sum_{i=1}^{M} \frac{1}{\sin^2 \theta_i}, \end{aligned}$$

where now **H** and **S** are sensitivity matrices that describe how parameter variations influence the measured data. In summary, performance bounds, noise gains, and signal-to-noise ratio gains all depend on

$$\mathrm{tr}\,[\mathbf{H}^{*}\mathbf{P}_{\mathbf{S}}^{\perp}\mathbf{H}]^{-1} = \sum_{i=1}^{M} \frac{1}{\sin^2 \theta_i},$$

where θ_i are principal angles between subspaces. When these angles are small, parameter estimation variance is high, noise gain is high, and signal-to-noise ratio is low. These findings clarify, for example, the difficulty of solving matched field processing problems when medium parameters produce normal mode subspaces which are nearly collinear. We consider our results on these problems to be essentially complete, except for their extensions to Hilbert spaces and to special subspaces such as subbands of wavelet decompositions.

3. In references [Cla92] and [ClS94], we have derived maximum likelihood estimators for the parameters of two-dimensional damped harmonic signals that are sensed by a two-dimensional array. The results apply to the processing of data in linear arrays that extend over space and take data over time. The likelihood maximization for this problem was actually achieved by minimizing residual error in the orthogonal subspace of the 2-D signals, using a new characterization of this subspace and a computing algorithm that uses a prediction polynomial in one dimension and a Lagrange interpolating polynomial for interpolating between the two dimensions. The algorithm minimizes the quadratic form

$$\mathrm{tr}\left[(\mathbf{Y} - \mathbf{FS})^{*}\mathbf{R}^{-1}(\mathbf{Y} - \mathbf{FS})\right],$$

where $\mathbf{Y}$ is the array data, $\langle F \rangle$ is a candidate 2-D subspace, $\mathbf{S}$ is a candidate set of mode parameters, and $\mathbf{R}^{-1}$ is the broadband covariance matrix. In [ClS94], the authors derive Cramer-Rao bounds for 2-D deterministic modal analysis. We consider this work to be complete.

4. In reference [Spu94], Spurbeck has established the connection between algebraic resolutions of identity and subband decompositions of l_2. He has constructed oblique projections onto arbitrary subsampled subspaces along nearby subsampled subspaces. These projections generalize the usual projections associated with QMF filters and suggest that one can build oblique projections for resolving nonorthogonal subsampled time series that might arise in multiuser communication. He has also shown what happens to the second-order properties of wide-sense stationary sequences that propagate through subband decompositions which do not have the perfect reconstruction property: they become periodically correlated. In references [SpS92] and [SpS94], the authors have imbedded scalar periodically correlated time series in vector WSS time series and constructed least-squares filters for equalizing and estimating periodically correlated time series. These results illustrate that filterbanks or subband decompositions are very natural structures for filtering periodically correlated time series. We are continuing to develop a toolkit for filtering periodically correlated time series by filtering the corresponding (internal) vector WSS time series.

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[AaM93] K. Aas and C. T. Mullis, "Minimum Mean-Squared Error Transform Coding and Subband Coding," *IEEE Trans Signal Proc* (submitted January 1993), accepted contingent upon revision.

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[Cla92] M. P. Clark, "Estimation Techniques for Sensor Array Processing," Ph.D. Dissertation, University of Colorado at Boulder (May 1992).

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[MuS91] C. T. Mullis and L. L. Scharf, "Quadratic Estimators of the Power Spectrum," Chapter One in *Advances in Spectrum Analysis* (Prentice-Hall, 1991).

[Sch94] L. L. Scharf, "A Data Version of the Gauss-Markov Theorem," unpublished notes (July 1994).

[Sch94] L. L. Scharf, "Matched Subspace Detector for Periodically Modulated Noise," unpublished notes.

[Sch93] L. L. Scharf, "A Multiadjustment Adaptive Filter," patent disclosure, University of Colorado (December 1993).

[Sch91] L. L. Scharf, "The SVD and Reduced-Rank Signal Processing," *Signal Processing* **24**, pp. 111–130 (November 1991).

[ScF94] L. L. Scharf and B. Friedlander, "Matched Subspace Detectors," *IEEE Trans Signal Proc* **SP-42**:8 (August 1994).

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[Spu94] M. Spurbeck, "Filter Bank Analysis and Design," Ph.D. Dissertation, University of Colorado at Boulder (December 1994).

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[SpS94] M. Spurbeck and L. L. Scharf, "Least Squares Filter Design for Periodically Correlated Time Series," *Proc 7th IEEE Workshop on SSAP*, Quebec (July 1994).

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[Uen94] N. Ueng-Teng, "Frame Building," unpublished notes (1994).

[VoS94] S. D. Voran and L. L. Scharf, "A Quantized Gauss-Markov Theorem," in preparation.

[Zie95] F. Ziel, "MIMO Filters with Redundacy: Connections with Channel Coding and Frames," Ph.D. Dissertation, University of Colorado at Boulder, (May 1995).

a. **Papers submitted to refereed journals** (and not yet published):

L. T. McWhorter and L. L. Scharf, "Exact Maximum Likelihood Estimation of AR Parameters," submitted to *IEEE Trans Signal Proc* (March 1994).

L. T. McWhorter and L. L. Scharf, "Quadratic Performance Bounds for Parametric Estimators," submitted to *IEEE Trans Inform Th* (1994).

K. Aas and C. T. Mullis, "Minimum Mean-Squared Error Transform Coding and Subband Coding." *IEEE Trans Signal Proc* (submitted January 1993), accepted contingent upon revision.

A. J. Thorpe and L. L. Scharf, "Data Adaptive Reduced-Rank Methods for Solving Least Squares Problems," accepted and to be published in *IEEE Trans Signal Proc* (1994).

M. Vis and L. L. Scharf, "A Note on Recursive Maximum Likelihood for Autoregressive Modeling," accepted and to be published in *IEEE Trans Signal Proc* (September 1993).

K. Aas, K. A. Duell, and C. T. Mullis, "Synthesis of Extremal Wavelet-Generating Filters Using Gaussian Quadrature," accepted and to be published in *IEEE Trans Signal Proc* (1994).

K. Aas and C. T. Mullis, "Minimum Mean-Squared Error Transform Coding and Subband Coding," submitted to *IEEE Trans Signal Proc* (January 1993).

L. L. Scharf and S. T. Voran, "Noise Rejecting Quantizers," submitted to *IEEE Trans Signal Proc* (January 1993).

J. K. Thomas, L. L. Scharf, and D. W. Tufts, "Probability of Subspace Swap in the SVD," submitted to *IEEE Trans Signal Proc* (July 1993).

C. Fajre and C. T. Mullis, "The Application of the Spectral Decomposition of Hankel Matrices to L^∞ Extension and Approximation Problems," submitted to *IEEE Trans Signal Proc* (December 1991).

b. **Papers published in refereed journals:**

L. T. McWhorter and L. L. Scharf, "Cramer-Rao Bounds for Deterministic Modal Analysis," *IEEE Trans Signal Proc* **41**, pp. 1847–1862 (May 1993).

S. D. Voran and L. L. Scharf, "Polar Coordinate Quantizers, *IEEE Trans Signal Proc* **42**:6, pp. 1559–1563 (June 1994).

L. L. Scharf and B. Friedlander, "Matched Subspace Detectors,"*IEEE Trans Signal Proc* **SP-42**:8, pp. 2146–2157 (August 1994).

R. T. Behrens and L. L. Scharf, "Signal Processing Applications of Oblique Projection Operators," *IEEE Trans Signal Proc* **42**:6, pp. 1413–1424 (June 1994).

M. P. Clark and L. L. Scharf, "Two-Dimensional Modal Analysis Based on Maximum Likelihood," *IEEE Trans Signal Proc* **SP-42**:6, pp. 1443–1452 (1994).

M. P. Clark and C. T. Mullis, "Quadratic Estimation of the Power Spectrum using Orthogonal Time-Division Multiple Windows," *IEEE Trans on Signal Proc* **SP-41**:1 (January 1993).

L. L. Scharf and L. T. McWhorter, "Geometry of the Cramer-Rao Bound," *Signal Processing* **31**:3, pp. 1–11 (April 1993).

M. P. Clark and L. L. Scharf, "On the Complexity of IQML Algorithms," *IEEE Trans Signal Proc* **40**, pp. 1811–1813 (July 1992).

L. L. Scharf, "The SVD and Reduced-Rank Signal Processing," *Signal Processing* **24**, pp. 111–130

(November 1991).

B. Derras and C. T. Mullis, "A Unified Approach to System Approximation," *AMSE Journ* **23**:1, 29-48 (1991).

W. P. Burleson and L. L. Scharf, "A VLSI Design Methodology for Distributed Arithmetic," *Journ VLSI Signal Proc* **2**, pp. 235–252 (1991).

c. **Books** (and sections thereof) **submitted for publication:**

None.

d. **Books** (and sections thereof) **published:**

C. T. Mullis and L. L. Scharf, "Quadratic Estimators of the Power Spectrum," Chapter One in *Advances in Spectrum Analysis* (Prentice-Hall, 1991).

C. T. Mullis, *Digital Signal Processing*, Second Edition, (Englewood Cliffs, NJ: Prentice Hall, 1991).

e. **Technical reports and nonrefereed papers:**

M. L. Vis and L. L. Scharf, "CR Bounds for System Identification and Modal Analysis in Colored Noise," *ECE Technical Report* DSP-513 (June 1994).

L. T. McWhorter and L. L. Scharf, "Quadratic Estimators of Covariance," *ECE Technical Report* DSP-512 (December 1993).

L. T. McWhorter and L. L. Scharf, "Geometry of the Cramer-Rao Bound," *ECE Technical Report* DSP-505 (December 1991).

f. **Patents filed:**

None (one in preparation, disclosure filed 12/93).

g. **Patents granted:**

None.

h. **Invited presentations at topical or scientific/technical society conferences:**

L. L Scharf, "Geometrical Ideas in Detection, Estimation, and Time Series Analysis," *Proc 7th SP Workshop on Statistical Signal and Array Processing*, Quebec City (June 1994).

L. L. Scharf and B. Friedlander, "Matched Subspace Detectors," 1993 Workshop on Underwater Acoustic Signal Processing, Kingston, RI (September 1993).

L. L. Scharf, "Keynote Speech," 1991 IEEE Workshop on Underwater Acoustic Signal Processing, Kingston, RI (October 1991).

i. **Contributed presentations at topical or scientific/technical society conferences:**

M. Spurbeck and L. L. Scharf, "Least Squares Filter Bank Design," *Proc 28th Annual Asilomar Conf on Signals, Systems, and Computers*, Asilomar, CA (November 1994).

L. T. McWhorter and L. L. Scharf, "Exact Maximum Likelihood Estimation of Autoregressive Time Series," *Proc 28th Annual Asilomar Conf on Signals, Systems, and Computers*, Asilomar, CA (November 1994).

L. T. McWhorter and L. L. Scharf, "Multiwindow Estimators of Correlation," *Proc 28th Annual Asilomar Conf on Signals, Systems, and Computers*, Asilomar, CA (November 1994).

L. L. Scharf and L. T. McWhorter, "Quadratic Estimators of Correlation," *Proc 7th IEEE Workshop on SSAP*, Quebec (July 1994).

M. Spurbeck and L. L. Scharf, "Least Squares Filter Design for Periodically Correlated Time Series," *Proc 7th IEEE Workshop on SSAP*, Quebec (July 1994).

L. T. McWhorter and L. L. Scharf, "Quadratic Performance Bounds for Parametric Estimators," *Proc 27th Annual Asilomar Conf on Signals, Systems, and Computers*, Asilomar, CA (November 1993).

L. L. Scharf and B. Friedlander, "Matched Subspace Detectors," *Proc 27th Annual Asilomar Conf on Signals, Systems, and Computers*, Asilomar, CA (November 1993).

J. Thomas, L. L. Scharf, and D. W. Tufts, "Probability of a Subspace Swap," *Proc 27th Annual Asilomar Conf on Signals, Systems, and Computers*, Asilomar, CA (November 1993).

M. Spurbeck and L. L. Scharf, "Causal Wiener Filtering of Periodically Correlated Sequences," Proc SIAM Conf on Linear Algebra, Signal Systems, and Controls, Seattle (August 1993).

L. T. McWhorter and L. L. Scharf, "Variance Bounds for Modal Analysis," *Proc SIAM Conf on Linear Algebra, Signal Systems, and Controls*, Seattle (August 1993).

M. P. Clark and L. L. Scharf, "Frequency-Wavenumber Spectrum Analysis," *Proc 1992 Workshop on Statistical and Array Processing*, Victoria, BC (October 1992).

L. L. Scharf and T. McWhorter, "Geometry of the Cramer-Rao Bound," *Proc 1992 Workshop on Statistical and Array Processing*, Victoria, BC (October 1992).

M. P. Clark and L. L. Scharf, "Efficient Frequency-Wavenumber Spectrum Estimation using Sliding Time-Division Windows," *Proc 1992 Asilomar Conf on Signals, Systems, and Computers*, Pacific Grove, CA (November 1992).

T. McWhorter and L. L. Scharf, "Cramer-Rao Bounds for Deterministic Modal Analysis," *Proc 1991 Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA (November 1991).

M. P. Clark and L. L. Scharf, "Exact Maximum-Likelihood DOA Estimation Using Generalized IQML," *Proc 1991 Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA (November 1991).

C. Fajre and C. T. Mullis, "The L^∞ Wiener Problem: An Application of the L^∞ Extension Problem," EUSIPCO 92 Conference, Brussels, Belgium (August 1992).

j. Honors/awards/prizes:

C. T. Mullis promoted to full Professor effective January 1, 1993.

L. L. Scharf appointed National Distinguished Lecturer for IEEE Society for Signal Processing (1993–1994).

k. Graduate students and post-doctorals supported under the contract for the three years ending 1 October 1993: (no female/minority)

Knut Aas
Richard T. Behrens
Michael P. Clark
Mark Spurbeck
John K. Thomas
Fred Ziel

l. Graduate Theses Submitted:

K. Aas, "Analysis and Synthesis of Filter Banks for Wavelet Decompositions and Subband Coding," Ph.D. Dissertation, University of Colorado at Boulder (May 1993).

M. P. Clark, "Estimation Techniques for Sensor Array Processing," Ph.D. Dissertation, University of Colorado at Boulder (May 1992).

M. Spurbeck, "Filter Bank Analysis and Design," Ph.D. Dissertation, University of Colorado at Boulder (December 1994).

F. Ziel, "MIMO Filters with Redundancy: Connections with Channel Coding and Frames," Ph.D. Dissertration, University of Colorado at Boulder (May 1995).

m. Work in Progress:

F. Ziel and C. T. Mullis, "Discrete Wavelet Frames and Filter Banks," to be submitted to *IEEE Trans Signal Proc.*

J. K. Thomas, "Automatic Bandwidth Estimation in Spectral Analysis," to be submitted.

M. Spurbeck, "Wavelet Decompositions of ℓ^2," to be submitted.

L. L. Scharf and M. Vis, "Signal Subspace MUSIC Algorithm," to be submitted.

J. K. Thomas, "Nonstationary Spectrum Analysis," to be submitted.

C. T. Mullis, Text on "Advanced Linear Systems," to be submitted.

END

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