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This is the final report on research carried out under this contract. There has been significant progress in the research areas of multidimensional signal processing, optical information storage and processing, and electromagnetic measurements. This reports lists degrees awarded and publications for the three year contract period. Specific research results are contained in the Annual Reports submitted prior to this final report.

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Contract DAAL-03-90-C-0004
April 15, 1990 - April 14, 1993

TWO-DIMENSIONAL SIGNAL PROCESSING, OPTICAL INFORMATION STORAGE AND PROCESSING, AND ELECTROMAGNETIC MEASUREMENTS

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1 Overview

This is the Final Report on research carried out under Contract DAAL-03-90-C-0004. The period of the contract is from April 15, 1990 through April 14, 1993. The research is part of the Joint Services Electronics Program (JSEP) and is administered by the U.S. Army Research Office. The report is concerned with basic research in the following broad areas of electronics:

- Multidimensional signal processing,
- Optical information storage and processing,
- Electromagnetic measurements.

The three year period covered by the contract has produced significant progress in all these areas. Detailed discussion of progress during the contract period is given in the three preceding annual reports. This report lists only degrees granted and publications during the contract period. The main topics of research are given in the following subsections for each of the three main areas of research.

1.1 Research in Multidimensional Signal Processing

During the past three years the research in this area has been carried out in five work units. These work units have focused on multidimensional signal processing and modeling, signal restoration and detection, morphological (nonlinear) signal processing systems, array processing, and multiprocessing for digital signal processing. Specific research topics include blur identification and removal from images, knowledge-based image analysis, multiresolution representation of images, new approaches to vector quantization of images and video, multidimensional recursive filtering with boundary values, implementation of filterbanks using cosine transforms, video segmentation and motion estimation, multidimensional multirate filterbanks, detection and classification of events using 2-D arrays, symbolic representation of signals, iterated function systems in image processing, robust image multilevel image thresholding for automated scene analysis, symbolic representation and analysis of linear and nonlinear signal processing systems, decomposition of structuring elements for morphological systems, image segmentation by iterative multi-resolution smoothing, min-max implementation of linear filters, the theory of connected morphological filters, image segmentation using connected filters, design and calibration of nonuniform and minimum redundancy sensor arrays, dual-form adaptive filtering, optimal multiprocessor architectures and compilers, compilers for fixed-point DSP machines, and design and analysis of exact reconstruction multidimensional filter banks.

1.2 Research in Optical Information Storage and Processing

In the optical storage and processing part of the contract, the research was carried out in three work units which focused on linear and nonlinear optical processing of images, the

use of optical techniques for digital information storage and processing, and on new ideas in semiconductor quantum wave devices. Specific research topics include three dimensional image processing, nonlinear optical image processing via threshold decomposition, partially coherent image processing, the exploitation of coupled magnitude-phase spatial light modulators, analysis of light propagation in anisotropic media, determination of the eigenstates of polarization in gyrotropic media, description of hybrid modes in biaxial planar waveguides, characterization of magneto-optic spatial light modulators, optical characterization of ferroelectric liquid crystal/silicon VLSI spatial light modulators, special issues in grating diffraction, rigorous 3-D coupled-wave analysis of anisotropic grating diffraction, performance analysis of Givens rotation integrated optical interdigitated-electrode cross-channel Bragg diffraction devices, antireflection grating surfaces, multi-layer waveguides, structured targets for enhanced absorption and X-ray emission in femtosecond laser-produced plasmas, solid-state quantum mechanical electron and hole wave devices, semiconductor quantum well electron and hole waveguides, ballistic electron transport in semiconductor heterostructures, electron waveguiding in quantum wells, ballistic electron emission microscopy, semiconductor biased superlattice tunable interference filter/emitters, and nanostructure optical emitters.

1.3 Research in Electromagnetic Measurements

In this area of the contract, the work was carried out in two work units that focused on electromagnetic measurements in the time and frequency domains and on near- and far-field antenna measurements. Specific research topics in this area include millimeter wave substrate mounted antennas, pulse excited antennas, circular half-loop antennas with coaxial feed, electrical properties of materials, finite-difference time-domain methods for solving EM problems, spherical back transforms for near-field-to-far-field transformation, techniques for evaluation of antenna measurement ranges, spherical microwave holography, new "flower petal" reflector antenna configurations, antenna measurement range enhancement and compensation, and antenna and radome electromagnetic diagnostics using spherical near-field measurements.

1.4 Organization of Report

The next section gives a list of the work units and their principal investigators. Following that is a list of doctoral degrees awarded. Twenty-one Ph.D. degrees were awarded to students who were supported by this contract. Thesis topics spanned the complete range of topics covered by the contract. Finally, the last section consists of a complete list of publications that resulted from the research during the period of the contract.

2 Work Units and Principal Investigators

Work Unit One: *Multidimensional Digital Signal Processing and Modeling*

Principal Investigator: Russell M. Mersereau, Regents' Professor

Work Unit Two: *Signal Restoration and Detection*

Principal Investigator: Monson H. Hayes, Professor

Work Unit Three: *Morphological Systems for Multidimensional Signal Processing*

Principal Investigator: Ronald W. Schafer, Institute Professor

Work Unit Four: *Multidimensional Processing for Sensor Arrays*

Principal Investigator: James H. McClellan

Work Unit Five: *Multiprocessor Systems and Tools for Digital Signal Processing*

Principal Investigators: James H. McClellan and Thomas P. Barnwell

Work Unit Six: *Linear and Nonlinear Image Processing*

Principal Investigator: William T. Rhodes

(This work unit was phased out after the first year of the contract.)

Work Unit Seven: *Two-Dimensional Optical Storage and Processing*

Principal Investigators: T. K. Gaylord and E. N. Glytsis

Work Unit Eight: *Semiconductor Quantum Wave Devices*

Principal Investigators: K. F. Brennan and T. K. Gaylord

Work Unit Nine: *Electromagnetic Measurements in the Time and Frequency Domains*

Principal Investigator: Glenn S. Smith

Work Unit Ten: *Automated Radiation Measurements for Near- and Far-Field Transformations*

Principal Investigator: Edward B. Joy

3 Doctoral Degrees Awarded

J. M. Hereford - Ph.D., May 1990

Thesis Title: *Optical Implementation of Morphological Transformations*

D. Y. Suh - Ph.D., June 1990

Thesis Title: *Knowledge-Based Boundary Detection System: on MRI Cardiac Image Sequences*

T. A. Maldonado - Ph.D., September 1990

Thesis Title: *Analysis of Electro-Optic/Gyrotropic Biaxial Crystals for Bulk and Waveguide Applications*

S. J. Reeves - Ph.D., September 1990

Thesis Title: *A Cross-Validation Approach to Image Restoration and Blur Identification*

L. Hertz - Ph.D., November 1990

Thesis Title: *Robust Image Thresholding Techniques for Automated Scene Analysis*

K. Nayebi - Ph.D., December 1990

Thesis Title: *A Time Domain Framework for the Analysis and Design of FIR Multirate Filter Bank Systems*

D. N. Sitter - Ph.D., June 1991

Thesis Title: *Space Invariant Modeling in Three-Dimensional Optical Image Formation*

J. van der Gracht - Ph.D., June 1991

Thesis Title: *Partially Coherent Image Enhancement by Source Modification*

G. Zhou - Ph.D., November 1991

Thesis Title: *A New Model for the Half-Loop Antenna and its Application to Multiturn Structures*

F. J. Malassenet - Ph.D., November 1991

Thesis Title: *Self-Affine Signals and Weighted Multiresolution Processes*

B. M. Kim - Ph.D., November 1991

Thesis Title: *Compilation Techniques for Multiprocessors Based on DSP Microprocessors*

C. P. Hong - Ph.D., November 1991

Thesis Title: *Implementation of Recursive Shift-Invariant Flow Graphs in Parallel/Pipelined Processing Environments*

C. H. Richardson - Ph.D., December 1991

Thesis Title: *The Symbolic Representation, Analysis, and Manipulation of Morphological Algorithms*

- A. Kittel** - Ph.D., March 1992
Thesis Title: *A Symbolic Representation for Signals*
- D.-W. Lee** - Ph.D., April 1992
Thesis Title: *Extracting Multiple Frequencies from Phase-Only Data*
- F. A. Sakarya** - Ph.D., June 1992
Thesis Title: *Passive Source Location Estimation*
- K. Baudendistel** - Ph.D., September 1992
Thesis Title: *Compiler Development for Fixed-Point Processors*
- J. G. Maloney** - Ph.D., November 1992
Thesis Title: *Analysis and Synthesis of Transient Antennas Using the Finite-Difference Time-Domain (FDTD) Method*
- P. R. Gelabert** - Ph.D., December 1992
Thesis Title: *Optimal Synchronous Multiprocessor Compiler for Fully Specified Flow Graphs*
- K. K. Truong** - Ph.D., December 1992
Thesis Title: *Large Vector Quantizer Design for Images Based on Hierarchical Structures*
- H.-K. Kim** - Ph.D., March 1993
Thesis Title: *A Design Synthesis Environment for DSP Algorithms Represented by Shift-Invariant Flow Graphs*

4 Publications

4.1 Work Unit One – Multidimensional Digital Signal Processing and Modeling

1. D. Y. Suh, *Knowledge-Based Boundary Detection System: on MRI Cardiac Image Sequences*, Ph.D. Thesis, Georgia Institute of Technology, June 1990.
2. S. J. Reeves, *A Cross-Validation Approach to Image Restoration and Blur Identification*, Ph.D. Thesis, Georgia Institute of Technology, Sept. 1990.
3. J. Biemond, R. L. Lagendijk, and R. M. Mersereau, "Iterative methods for image deblurring," *Proc. IEEE*, vol. 78, No. 5, pp. 856-883, May 1990.
4. S. J. Reeves and R. M. Mersereau, "Optimal estimation of the regularization parameter and stabilizing functional for regularized image restoration," *Optical Engineering*, vol. 29, No. 5, pp. 446-454, May 1990.
5. S. J. Reeves and R. M. Mersereau, "Identification of image blur parameters by the method of generalized cross-validation," *Proc. 1990 IEEE Int. Symp. Circuits Syst.*, pp. 223-226.
6. D. Y. Suh and R. M. Mersereau, "Automatic boundary detection on cardiac magnetic resonance image sequences for four-dimensional visualization of the left ventricle," *First Conference on Visualization in Biomedical Computing*.
7. S. J. Reeves and R. M. Mersereau, "Optimal constraint parameter estimation for constrained image restoration," *SPIE Conf. on Visual Communications and Image Processing, '90*, pp. 1372-1380.
8. François J. Malassenet, *Self-Affine Signals and Weighted Multiresolution Processes*, Ph.D. Thesis, Georgia Institute of Technology, December, 1991.
9. A. K. Katsaggelos, J. Biemond, R. W. Schafer, and R. M. Mersereau, "A regularized iterative image restoration algorithm," *IEEE Trans. on Signal Processing*, vol. 39, no. 4, pp. 914-929, April 1991.
10. C. Auyeung and R. M. Mersereau, "A dual approach to signal restoration," Ch. 2 in *Iterative Image Restoration*, (A. K. Katsaggelos, ed.), New York:Springer-Verlag, pp. 21-56, 1991.
11. T. R. Gardos and R. M. Mersereau, "FIR filtering on a lattice with periodically deleted samples," *Proc. 1991 IEEE Int. Conf. on Acoustics, Speech, and Signal Processing*, pp. 2873-2876, Toronto, Canada, May 14-17, 1991.

12. J. Huang and R. M. Mersereau, "Displacement estimation along contours in image sequency analysis," *Proc. 1991 IEEE Int. Conf. on Acoustics, Speech, and Signal Processing*, pp. 2421-2424, Toronto, Canada, May 14-17, 1991.
13. F. J. Malassenet and R. M. Mersereau, "Wavelet representations and coding of self-affine signals," *Proc. 1991 IEEE Int. Conf. on Acoustics, Speech, and Signal Processing*, pp. 677-680, Toronto, Canada, May 14-17, 1991.
14. S. A. Martucci, "Signal extension and noncausal filtering for subband coding of images," *SPIE Visual Communications and Image Processing '91: Visual Communication*, vol. 1605, pp.137-148, 1991.
15. S. J. Reeves, "Assessing the validity of constraint sets in image restoration," *Proc. 1991 IEEE Int. Conf. on Acoustics, Speech, and Signal Processing*, pp. 2929-2932, Toronto, Canada, May 14-17, 1991.
16. S. J. Reeves and R. M. Mersereau, "Optimal regularization parameter estimation for image restoration," *SPIE Conf. on Electronic Imaging, 1991*, vol. 1452, pp. 127-138.
17. K. K. Truong, "Multilayer Kohonen image codebooks with a logarithmic search complexity," *Proc. 1991 IEEE Int. Conf. on Acoustics, Speech, and Signal Processing*, pp. 2789-2792, Toronto, Canada, May 14-17, 1991.
18. T. S. Rao and R. M. Mersereau, "2-D zero phase rational filters: design and boundary-valued realization," *1991 Allerton Conference on Circuit and System Theory*.
19. T. S. Rao, *Random field modeling with applications to M-D zero-phase rational filtering and image coding*, Georgia Institute of Technology, Dec. 1992.
20. K. K. Truong, *Large vector quantizer design for images based on hierarchical structures*, Ph.D. Thesis, Georgia Institute of Technology, Dec. 1992.
21. S. J. Reeves and R. M. Mersereau, "Automatic assessment of constraint sets in image restoration," *IEEE Trans. Image Processing*, pp. vol. 1, pp. 119-123, Jan. 1992.
22. S. J. Reeves and R. M. Mersereau, "Blur identification by the method of generalized cross-validation," *IEEE Trans. Image Processing*, pp. vol. 1, pp. 301-311, July 1992.
23. T. R. Gardos, K. Nayebi, and R. M. Mersereau, "Time domain analysis of multi-dimensional multi-rate filter banks in the context of periodically time-varying systems," *1992 Princeton Conf. Info. Science Syst.* pp. 369-374.
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25. J. Huang, S. Liu, M. H. Hayes, and R. M. Mersereau, "A multi-frame pel-recursive algorithm for varying frame-to-frame displacement estimation," *1992 IEEE Int. Conf. on Acoustics, Speech, and Signal Processing*, vol. 3, pp. 241-244.

26. S. Lucke, T. Rao, and R. M. Mersereau, "Three-source boundary interpolating image coder," *1992 IEEE Int. Conf. on Acoustics, Speech, and Signal Processing*, vol. 3, pp. 489-492.
27. S. A. Martucci, "Convolution-multiplication properties for the entire family of discrete sine and cosine transforms," *1992 Princeton Conf. Info. Science Syst.* pp. 399-404.
28. S. A. Martucci and R. M. Mersereau, "Support constraints for M-band alias-free filter banks," *1992 IEEE Int. Conf. on Acoustics, Speech, and Signal Processing*, vol. 5, pp. 85-88.

4.2 Work Unit Two – Signal Restoration and Detection

1. W. S. Kim and M. H. Hayes, "Phase retrieval using two Fourier transform intensities," *Journal Optical Society of America: A, Special Issue on Signal Recovery*, vol. 7, no. 3, pp. 441-449, March 1990.
2. M. H. Hayes and W. S. Kim, "Using a second intensity measurement in the phase retrieval problem," *Proc. SPSE 43rd Annual Conference*, pp. 126-128, Rochester, NY, May 1990.
3. F. A. Sakarya and M. H. Hayes, "Estimating 2-D angles of arrival from a pair of linearly displaced planar arrays," *Communications, Control, and Signal Processing, Proc. 1990 Bilkent Int. Conf. on New Trends in Comm., Control, and Signal Proc.*, pp. 1575-1582, July 1990.
4. W. S. Kim, *Phase Retrieval Using Two Fourier Transform Intensities with Application to X-Ray Crystallography*, Ph.D. Thesis, Georgia Institute of Technology, August 1991.
5. W. Kim and M. H. Hayes, "Phase retrieval in x-ray crystallography," *Proc. 1991 IEEE Int. Conf. on Acoustics, Speech, and Signal Processing*, pp. 1765-1768, Toronto, Canada, May 14-17, 1991.
6. F. A. Sakarya and M. H. Hayes, "Estimating 2-D angles of arrival using overlapping volume arrays," *Proc. 1991 IEEE Int. Conf. on Acoustics, Speech, and Signal Processing*, pp. 3353-3356, Toronto, Canada, May 14-17, 1991.
7. A. Kittel, "A Symbolic Representation for Signals", Ph.D. Thesis, Georgia Institute of Technology, March, 1992.
8. F.A. Sakarya, "Passive Source Location Estimation", Ph.D. Thesis, Georgia Institute of Technology, June, 1992.
9. W.S. Kim and M.H. Hayes, "Phase retrieval using a window function," *Proc. 1992 Int. Conf. on Signal Processing*, pp. IV 149-152, March 1992.
10. A. Kittel and M.H. Hayes, "Monitoring rotating machine signals," *Proc. 1992 Int. Conf. on Signal Processing*, pp. V 65-68, March 1992.

11. S. Liu and M.H. Hayes, "Segmentation-based coding of motion difference and motion field images for low bit-rate video compression," *Proc. 1992 Int. Conf. on Signal Processing*, pp. III 525-528, March 1992.
12. J. Huang, S. Liu, M.H. Hayes, and R.M. Mersereau, "A multi-frame pel-recursive algorithm for varying frame-to-frame displacement estimation," *Proc. 1992 Int. Conf. on Signal Processing*, pp. III 241-244, March 1992.
13. F.A. Sakarya and M.H. Hayes, "Partial discharges in high-voltage transformers", *Proc. Sixth SSAP Workshop on Stat. Sig. and Array Proc.*, pp. 473-476, Oct. 1992.

4.3 Work Unit Three – Morphological Systems for Multidimensional Signal Processing

1. L. Hertz, *Robust Image Thresholding Techniques for Automated Scene Analysis*, Ph.D. Thesis, Georgia Institute of Technology, November 1990.
2. P. A. Maragos and R. W. Schafer, "Morphological systems for multidimensional signal processing," *Proc. IEEE*, Vol. 78, No. 4, April 1990, pp. 690-710.
3. C. H. Richardson and R. W. Schafer, "An environment for the automatic manipulation and analysis of morphological expressions," *Proceedings of SPIE, Image Algebra and Morphological Image Processing*, Vol. 1350, pp. 262-273, July 1990.
4. C. H. Richardson, *The Symbolic Representation, Analysis, and Manipulation of Morphological Algorithms*, Ph.D. Thesis, Georgia Institute of Technology, December 1991.
5. C. H. Richardson and R. W. Schafer, "A lower bound for structuring element decompositions," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 13, no. 4, April 1991, pp. 365-369.
6. L. Hertz and R. W. Schafer, "Edge coincidence-based multilevel image thresholding." *Twenty-fifth Annual Conference on Information Sciences and Systems*, Johns Hopkins University, Baltimore, March 1991.
7. A. K. Katsagglos, J. Biemond, R. W. Schafer, and R. M. Mersereau, "A regularized iterative image restoration algorithm," *IEEE Trans. on Signal Processing*, vol. 39, no. 4, pp. 914-929, April 1991.
8. L. Hertz and R. W. Schafer, "On The Use of Morphological Operators in a Class of Edge Detectors," *Computer Vision and Image Processing*, pp. 25-54, Academic Press, Inc., 1992.
9. C. H. Richardson and R. W. Schafer, "The Symbolic Manipulation and Analysis of Morphological Algorithms," *Symbolic and Knowledge-Based Signal Processing*, ed. by A. V. Oppenheim and H. Nawab, Prentice-Hall, Inc., 1992.

10. J. Crespo and R. W. Schafer, "Image Partition Using an Iterative Multi-Resolution Smoothing Algorithm," *Proc. 1992 Int. Conf. on Acoustics, Speech, and Signal Processing*, pp. III-561-III-564, San Francisco, CA, March 1992.
11. J. Crespo and R. W. Schafer, "An Efficient Image Partition Algorithm Based on Edge Information," submitted for publication in *Proceedings of 1992 SPIE Conference on Visual Communications and Image Processing*, vol. 1818, pp. 1230-1242, Boston, MA, November 1992.

4.4 Work Unit Four – Multidimensional Processing for Sensor Arrays

1. D. Lee & J. H. McClellan, "Decomposition of the focusing transformation in coherent signal-subspace DOA estimation", *Proc. ISCAS-90*, New Orleans, LA, May 1-3, 1990, pp. 238-241.
2. J. H. McClellan & D. Lee, "Exact equivalence of iterative pre-filtering and IQML", *Proc. ISCAS-90*, New Orleans, LA, May 1-3, 1990, pp. 621-624.
3. L. B. Fertig & J. H. McClellan, "Dual form adaptive filters with norm constraints", *Proc. DSP Workshop*, Mohonk, NY, Sept. 16-19, 1990, pp. 4.6.1-4.6.2.
4. G. C. Brown, J. H. McClellan, and E. J. Holder, "Eigenstructure approach for array processing and calibration with general phase and gain perturbations," *Proc. 1991 Int. Conference on Acoustics, Speech, and Signal Processing*, pp. 3037-3040, paper E1.3, May 1991, Toronto, Canada.
5. K. A. Blanton and J. H. McClellan, "New search algorithm for minimum redundancy linear arrays," *Proc. 1991 Int. Conference on Acoustics, Speech, and Signal Processing*, pp. 1361-1364, paper U3.5, May 1991.
6. J. H. McClellan and D. Lee, "Exact equivalence of the Steiglitz-McBride iteration and IQML," *IEEE Trans. on Signal Processing*, vol. SP-39, Feb. 1991, pp. 509-512.
7. D.-W. Lee, *Extracting Multiple Frequencies from Phase-Only Data*, Ph.D. Thesis, Georgia Institute of Technology, April 1992.
8. G. C. Brown, J. H. McClellan and E. J. Holder, "A Homotopy Continuation Approach for Self-Calibration of Arrays with General Phase Perturbations," *Sixth SP Workshop on Statistical Signal and Array Processing*, Victoria, British Columbia, CANADA, Oct. 1992.

4.5 Work Unit Five – Multiprocessor Systems and Tools for Digital Signal Processing

1. Kambiz Nayebi, *A Time Domain Framework for the Analysis and Design of FIR Multirate Filter Bank Systems*, Ph.D. Thesis, Georgia Institute of Technology, December, 1990.
2. K. Nayebi, T. P. Barnwell, and M. J. T. Smith, "A general time domain analysis and design framework for exactly reconstructing FIR analysis/synthesis filter banks," *International Symposium on Circuits and Systems*, New Orleans, Louisiana, May 1-3, 1990.
3. T. P. Barnwell and M. J. T. Smith, "Filter banks for analysis-reconstruction of systems: A tutorial," *International Symposium on Circuits and Systems*, New Orleans, Louisiana, May 1-3, 1990. (invited)
4. B. M. Kim and T. P. Barnwell, "Resource allocations and code generation for pointer based pipelined DSP multiprocessors," *International Symposium on Circuits and Systems*, New Orleans, Louisiana, May 1-3, 1990.
5. C. P. Hong and T. P. Barnwell, "The implementation of shift-invariant flow graphs on clock-skewed multiprocessors," *International Symposium on Circuits and Systems*, New Orleans, Louisiana, May 1-3, 1990.
6. B. Evans and J. H. McClellan, "Symbolic transforms with applications to signal processing," *The Mathematica Journal*, vol. 1, no. 2, Fall, 1990, pp. 70-80.
7. B. M. Kim, *Compilation Techniques for Multiprocessors Based on DSP Microprocessors*, Ph.D. Thesis, Georgia Institute of Technology, November 1991.
8. C. P. Hong, *Implementation of Recursive Shift-Invariant Flow Graphs in Parallel/Pipelined Processing Environments*, Ph.D. Thesis, Georgia Institute of Technology, November 1991.
9. C. P. Hong and T. P. Barnwell, "Compilation for interprocessor communications in clock-skewed parallel processing systems," *Proc. 1991 IEEE Conference on Acoustics, Speech, and Signal Processing*, pp. 1249-1252, Toronto, Canada, May 14-17, 1991.
10. K. Nayebi, T. P. Barnwell, and M. J. T. Smith, "The design of perfect reconstruction non-uniform band filter banks," *Proc. 1991 IEEE Conference on Acoustics, Speech, and Signal Processing*, pp. 1781-1784, Toronto, Canada, May 14-17, 1991.
11. B. L. Evans, J. H. McClellan, and K. A. West, "Mathematica as an Educational Tool for Signal Processing," *IEEE Southeastern Conference*, April 1991, pp. 1162-1166.
12. B. L. Evans, J. H. McClellan, and L. J. Karam, "Transforms for signal processing," *1991 Mathematica Conference*, Jan. 1991.

13. Kurt Baudendistel, *Compiler Development for Fixed-Point Processors*, Ph.D. Thesis, Georgia Institute of Technology, September 1992.
14. Pedro R. Gelabert, *Optimal Synchronous Multiprocessor Compiler for Fully Specified Flow Graphs*, Ph.D. Thesis, Georgia Institute of Technology, December 1992.
15. B. L. Evans and J. H. McClellan, "Symbolic analysis of signals and systems," Chapter 3 in *Knowledge-Based Signal Processing* edited by A. V. Oppenheim and S. H. Nawab. Prentice-Hall: Englewood Cliffs, NJ, 1992.
16. K. Nayebi, T. P. Barnwell, and M. J. T. Smith, "Time-domain filter bank analysis: a new design theory, *IEEE Transactions on Signal Processing*, vol. 40, no. 6, June 1992, pp. 1412-1429.
17. K. Nayebi, T. P. Barnwell, M. J. T. Smith, "Analysis-synthesis systems with time varying filter bank structures," *Proceedings of the International Conference on Acoustics, Speech, and Signal Processing*, March 1992, pp. IV-617 to IV-620.
18. P. Gelabert and T. P. Barnwell III, "Optimal automatic periodic compiler for multi-bus networks," *Proceedings of the International Conference on Acoustics, Speech, and Signal Processing*, March 1992, pp. V-593 to V-596.
19. H. K. Kim and T. P. Barnwell, III, "A chip compiler for rate-optimal multiprocessor schedules," *Proceedings of the International Symposium on Circuits and Systems*, May 1992.
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2. David N. Sitter and William T. Rhodes, "Three-dimensional imaging: a space invariant model for space variant systems," *Applied Optics*, vol. 29, no. 26, Sept. 10, 1990, pp. 3789-3794.

3. James M. Hereford and William T. Rhodes, "Optical asymmetrical median filtering using gray-scale convolution kernels," *Optics Letters*, vol. 15, No. 12, June 15, 1990, pp. 697-699.
4. David N. Sitter and William T. Rhodes, "Space variance in optical sectioning microscopy," OSA Annual Meeting, 1990 Technical Digest Series, Vol. 15, Optical Society of America, Washington, DC, 1990, paper TuDD2.
5. J. Van der Gracht and William T. Rhodes, "New masks for complementary source-pupil filtering," OSA Annual Meeting, 1990 Technical Digest Series, Vol. 15, Optical Society of America, Washington, DC, paper MX3.
6. James M. Hereford and William T. Rhodes, "Non-ideal thresholding effects in the optical implementation of median filtering," OSA Annual Meeting, 1990 Technical Digest Series, Vol. 15, Optical Society of America, Washington, DC, paper MX5.
7. David N. Sitter, *Space Invariant Modeling in Three-Dimensional Optical Image Formation*, Ph.D. Thesis, Georgia Institute of Technology, June 1991.
8. Joseph van der Gracht, *Partially Coherent Image Enhancement by Source Modification*, Ph.D. Thesis, Georgia Institute of Technology, June 1991.
9. J. van der Gracht, "Noise performance of a partially coherent sinusoid notching system," (abstract) *1991 Annual Meeting of the Optical Society of America*, ThMM11, Technical Digest, p. 180, San Jose, November 1991.

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4.7 Work Unit Seven – Two-Dimensional Optical Storage and Processing

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2. E. I. Verriest, E. N. Glytsis, and T. K. Gaylord, "Performance analysis of Givens rotation integrated optical interdigitated-electrode cross-channel Bragg diffraction devices: intrinsic accuracy," *Applied Optics*, vol. 29, no. 17, pp. 2556-2563, June 10, 1990.
3. N. F. Hartman and T. K. Gaylord, "Coherent optical characterization of magneto-optical spatial light modulators," *Applied Optics*, vol. 29, no. 29, pp. 4372-4383, October 10, 1990.
4. T. A. Maldonado and T. K. Gaylord, "Light propagation characteristics for arbitrary wavevector directions in biaxial media by a simple coordinate-free approach," *Applied Optics*, vol. 30, pp. 2465-2480, June 20, 1991.

5. E. N. Glytsis and T. K. Gaylord, "Review and applications of rigorous coupled-wave analysis of grating diffraction," in *Diffraction Optics: Design, Fabrication, and Applications*, vol. 9, pp. 38-40, April 1992.
6. E. N. Glytsis and T. K. Gaylord, "High-spatial-frequency binary and multilevel staircase gratings: Polarization-selective mirrors and broadband antireflection surfaces," *Applied Optics*, vol. 31, pp. 4459-4470, Aug. 1, 1992.
7. D. W. Wilson, E. N. Glytsis, N. F. Hartman, and T. K. Gaylord, "Beam diameter threshold for polarization conversion photoinduced by spatially oscillating bulk photovoltaic currents in Fe:LiNbO₃," *Journal of the Optical Society of America B*, vol. 9, pp. 1714-1725, September 1992.
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3. T. K. Gaylord, E. N. Glytsis, G. N. Henderson, K. P. Martin, D. B. Walker, D. W. Wilson, and K. F. Brennan, "Quantum interference effects in semiconductors: a bibliography," *Proceedings of the IEEE*, vol. 79, pp. 1159-1180, Aug. 1991. (invited)

4. G. N. Henderson, E. N. Glytsis, and T. K. Gaylord, "Electron wave diffraction by semiconductor gratings: rigorous analysis and design parameters," *Applied Physics Letters*, vol. 59, pp. 440-442, July 22, 1991.
5. D. W. Wilson, E. N. Glytsis, and T. K. Gaylord, "Quantum well, voltage-induced quantum well, and quantum barrier electron waveguides: mode characteristics and maximum current," *Applied Physics Letters*, vol. 59, pp. 1855-1857, Oct. 7, 1991.
6. G. N. Henderson, T. K. Gaylord, E. N. Glytsis, P. N. First, and W. J. Kaiser, "Ballistic electron emission testing of semiconductor heterostructures," *Solid State Communications*, vol. 80, no. 8, pp. 591-596, 1991.
7. T.K. Gaylord, G.N. Henderson, E.N. Glytsis, D.W. Wilson, P.N. First, and D.B. Walker, "Semiconductor ballistic electron reflection, refraction, interference, and diffraction effects: modeling and quantum device applications," *Integrated Photonics Research*, vol. 10, pp. 178-179, April 1992.
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9. G.N. Henderson, T.K. Gaylord, and E.N. Glytsis, "Ballistic electron diffractive switches: design and performance analysis," *Integrated Photonics Research*, vol. 10, pp. 74-75, April 1992.
10. G.N. Henderson, P.N. First, T.K. Gaylord, and E.N. Glytsis, "Low-temperature BEEM testing of quantum semiconductor heterostructures," *Ballistic Electron Emission Microscopy Workshop 1992 Abstracts*, January 27, 1992.
11. E. Anemogiannis, E.N. Glytsis, and T.K. Gaylord, "Electronic bound and quasi-bound states and lifetimes in semiconductor quantum heterostructures," (Abstract) *Optical Society of America Annual Meeting Technical Digest Series*, vol. 23, pg. 99, September 1992.

4.9 Work Unit Nine – Electromagnetic Measurements in the Time and Frequency Domains

1. J.G. Maloney, G.S. Smith, and W.R. Scott, "Accurate computation of the radiation from simple antennas using the finite-difference time-domain method," *IEEE Transactions on Antennas and Propagation*, vol. AP-38, pp. 1059-1068, July, 1990.
2. G.S. Smith, "On the skin effect approximation," *Am. J. Phys.*, vol. 58, pp. 996-1002, October 1990.

3. J.G. Maloney and G.S. Smith, "Implementation of surface impedance concepts in the finite-difference time-domain (FD-TD) technique," *1990 IEEE AP-S Symposium*, pp. 1628-1631, Dallas, TX, May 1990.
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5. M. A. Gouker, *Studies of Dipole Antennas on Finite Thickness Substrates with Planar Integrated Focusing Elements*, Ph.D. Thesis, Georgia Institute of Technology, May 1991.
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10. M. A. Gouker and G. S. Smith, "A millimeter-wave integrated-circuit antenna based on the Fresnel zone plate," *1991 IEEE International Microwave Symposium*, Boston, MA, pp. 157-160, June 1991.
11. J. G. Maloney, *Analysis and Synthesis of Transient Antennas Using the Finite-Difference Time-Domain (FDTD) Method*, Ph.D. Thesis, Georgia Institute of Technology, November 1992.
12. J. G. Maloney and G. S. Smith, "The use of surface impedance concepts in the finite-difference time-domain method," *IEEE Trans. Antennas Propagat.*, vol. 40, pp. 38-48, Jan. 1992.
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17. W. R. Scott and G. S. Smith, "Measured electrical nproperties of soil as functions of frequency and moisture content," *IEEE Trans. Geoscience Remote Sensing*, vol. 30, pp. 621-623, May 1992.
18. W. R. Scott, Jr., "Accurate modeling of axisymmetric two-port junctions in coaxial lines using the finite-element method," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 1712-1716, August 1992.
19. W. R. Scott, Jr., "A new technique for measuring the constitutive parameters of planar materials," *IEEE Trans. Instrum. Meas.*, vol. 41, 639-645, October 1992.
20. J.G. Maloney and G.S. Smith, "A discussion of efficient methods for including material sheets in th FDTD technique," *1992 International IEEE AP-S Symposium*, Chicago, IL, pp. 1666-1669, July 1992.
21. J.G. Maloney and G.S. Smith, "Optimization of a resistively loaded conical antenna for pulse radiation," *1992 International IEEE AP-S Symposium*, Chicago, IL, pp. 1968-1971, July 1992.
22. J.G. Maloney and G.S. Smith, "Accurate modeling of antennas for radiating short pulses, FDTD analysis and experimental measurements," *International Conference on Ultra-Wideband Short-Pulse Electromagnetics*, New York, NY, October 1992.

4.10 Work Unit Ten – Automated Radiation Measurements for Near- and Far-Field Transformations

1. H. Nehme and E. B. Joy, "Range amplitude error effects on the measurement of low sidelobe levels and gain," *Proceedings of the 1990 Antenna Measurement Techniques Association Meeting*, Philadelphia, PA, pp. 6-13 through 6-18, October 8-11, 1990.
2. D. N. Black and E. B. Joy, "Spherical probing of spherical ranges," *Proceedings of the 1990 Antenna Measurement Techniques Association Meeting*, Philadelphia, PA, pp. 14-19 through 14-24, October 8-11, 1990.
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7. D. N. Black, E. B. Joy, M. G. Guler, and R. E. Wilson, "Improving Source Detection in Spherical Probing," *Proceedings of the 1992 Antenna Measurement Techniques Association Meeting*, Columbus, OH, pp. 7-16 through 7-21, October 19-23, 1992.
8. M. G. Guler, E. B. Joy, D. N. Black, and R. E. Wilson, "Far-Field Spherical Microwave Holography," *Proceedings of the 1992 Antenna Measurement Technique Association Meeting*, Columbus, OH, pp. 8-3 through 8-7, October 19-23, 1992.
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5 Reportable Patents

1. T.K. Gaylord, K.F. Brennan, and E.N. Glytsis, "Solid state quantum mechanical electron and hole wave devices," U.S. Patent No. 4,985,737 assigned to Georgia Tech Research Corporation, January 15, 1991.
2. T.K. Gaylord, E.N. Glytsis, and K.F. Brennan, "Semiconductor biased superlattice tunable interference filter/emitter," U.S. Patent No. 4,987,458, assigned to Georgia Tech Research Corporation, January 22, 1991.
3. T.K. Gaylord, E.N. Glytsis, M.G. Moharam, and W.E. Baird, "Technique for producing antireflection grating surfaces on dielectrics, semiconductors, and metals," U.S. Patent No. 5,007,708 assigned to Georgia Tech Research Corporation, April 16, 1991.
4. G.N. Henderson, T.K. Gaylord, and E.N. Glytsis, "Quantum mechanical semiconductor device with electron/hole diffractive grating," U.S. Patent Application 07/734,300, filed July 18, 1991.