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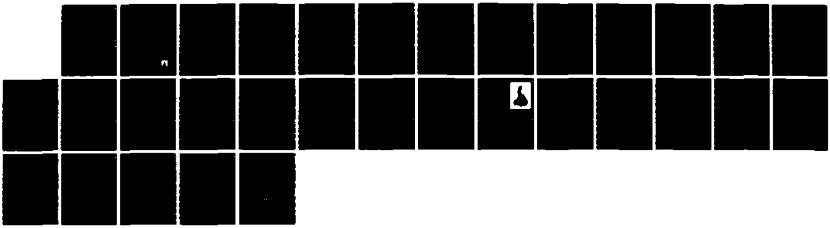

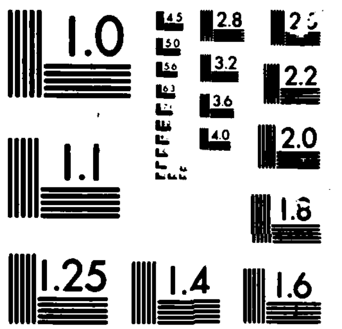

MICROCOPY CHART

ANNUAL REPORT
Joint Services Electronics Program
DAAG29-84-K-0024
January 1, 1985 - December 31, 1985

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

JANUARY 1986

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

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This is an annual report on research conducted under the auspices of the Joint Services Electronics Program. Specific topics covered are: digital signal processing, parallel processing architectures, two-dimensional optical storage and processing, hybrid optical/digital signal processing, electromagentic measurements in the time domain, and automatic radiation measurements for near-field and far-field transformations.

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ANNUAL REPORT

Joint Services Electronics Program

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January 1, 1985 - December 31, 1985

TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE
AND
THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

January 1, 1986

Georgia Institute of Technology
School of Electrical Engineering
Atlanta, Georgia 30332

TABLE OF CONTENTS

I. OVERVIEW

This annual report covers the second year of research carried out under Contract DAAG29-84-K-0024. The research is part of the Joint Services Electronics Program and is administered by the U. S. Army Research Office. Research activities are concentrated in two areas: (1) Two-Dimensional Signal Processing and Storage, and (2) Theory and Application of Electromagnetic Measurements.

The research in two-dimensional signal processing and storage is concentrated in five major areas. These areas overlap and the research activities interact and reinforce one another. Research in Work Unit Number 1, *Multidimensional Digital Signal Processing*, is concerned with the theory, design, and implementation of digital signal representations and digital signal processing algorithms and systems. Work Unit Number 2, *Multiprocessor Architectures for Digital Signal Processing*, focusses upon hardware and software problems in the use of multiport memories and multiple processors for high-speed implementations of digital signal processing algorithms. The research in Work Unit Number 3, *Two-Dimensional Optical Storage and Processing*, is concerned with problems of using holographic information storage as the basis for multiport memories and for optical computation. Work Unit Number 4, *Two-Dimensional Optical/Electronic Signal Processing*, is concerned with the theory, implementation, and application of combined optical and electronic digital signal processing techniques. Work Unit Number 5 is directed toward problems in the design of VLSI implementations of digital signal processing systems.

The other two work units in the JSEP program are concerned with electromagnetic measurements. In Work Unit Number 6, *Electromagnetic Measurements in the Time- and Frequency-Domains*, research is concerned with both theoretical and experimental investigations of the use of time-domain and frequency-domain methods for measuring the characteristics of materials and electromagnetic systems. Work Unit Number 7, *Automated Measurements for Near- and Far-Field Transformations*, is concerned with assessing the accuracy of computed fields on the surface of lossy radomes and with compensating for probe effects when near-field measurements are made on spherical and arbitrary surfaces.

The report begins with a summary of the most significant accomplishments (in the judgement of the lab directors) during the period January 1, 1985 to December 31, 1985. Following this are brief reports on the individual work units. These reports list personnel supported and discuss in general terms the research that was carried out during the reporting period. Also included in each work unit report is a complete list of publications on the research during this period. Complete copies of these publications are available in the Annual Report Appendix.

II. SIGNIFICANT RESEARCH ACCOMPLISHMENTS

The following accomplishments are, in the judgement of the laboratory directors, of particular significance and potential and are therefore worthy of special mention.

2.1 Experimental Demonstration of Parallel Logic Operations

A major achievement of the continuing research in Work Unit Number 3 was the experimental demonstration of both parallel EXCLUSIVE OR and parallel NAND logic operations to achieve content addressability and thus digital parallel truth-table look-up processing. This work was published in the invited paper in *Optical Engineering*.

This result provides practical experimental demonstrations of optical digital parallel processing using array logic. It is highly significant since it demonstrates that large scale parallel digital processors can be implemented optically. Potential applications include remote sensing, air traffic control, synthetic aperture radar imaging, missile guidance, and adaptive antenna array beamforming.

2.2 A Unified Theory of Translation-Invariant Image Processing Systems

A major achievement of the research in Work Unit Number 1 is the development of a new theory for representing images and image processing systems. Maragos, in his Ph.D. thesis, has developed a new theory of translation-invariant systems in which both signals and systems are fundamentally represented by sets rather than by functions. This leads to a new theory of signals and systems in which geometric structure is prominent. The theory has already been applied to gain new insight into the properties and implementation of many common image transformations and it potentially can serve as the basis for the design and implementation of new image transformations specifically directed toward enhancing, detecting, and coding of geometric structure in images.

2.3 Monostatic Near-Field Radar Cross-section Measurement

A monostatic near-field radar cross-section measurement of a simple target (a square flat plate) was performed on a planar surface near-field measurement system. The far-field monostatic radar cross-section was correctly determined from the near-field measurements. This demonstration was an important step in the process of developing the monostatic near-field radar cross-section technique. Should this technique become fully developed, the monostatic scattering of large (full scale) targets could be accurately measured. The near-field, intermediate field and far-field scattering properties are determined in one measurement set. Radar ananoloies such as glint can be accurately predicted from these measurements.

WORK UNIT NUMBER 1

TITLE: Multidimensional Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATOR: R. W. Schafer, Regents' Professor

SCIENTIFIC PERSONNEL:

M. H. Hayes, Assistent Professor
R. M. Mersereau, Professor
C. Au Yeung, Graduate Research Assistant (Ph. D. candidate)
J. E. Bevington, Graduate Research Assistant (Ph. D. candidate)
C. C. Davis, Graduate Research Assistant (Ph. D. candidate)
L. Hertz, Graduate Research Assistant (Ph. D. candidate)
E. Karlsson, Graduate Research Assistant (Ph. D. candidate)
A. K. Katsaggelos, Ph. D. recipient Sept. 1985
P. A. Maragos, Ph. D. recipient, June 1985
D. M. Wilkes, Graduate Research Assistant (Ph. D. candidate)

SCIENTIFIC OBJECTIVE:

The long term scientific objective of this research is to understand the means by which multidimensional signals such as images should be modelled and represented to facilitate the encoding, enhancement, and automatic extraction of information from such signals, and to develop, analyze, and extend computer algorithms for these purposes.

PROPOSED RESEARCH:

A. Image Segmentation by Texture

This work has focused on the use of two-dimensional linear prediction coefficients as features characterizing texture in an image. A maximum likelihood detector of the boundary between two textured regions has been found and some simple segmentation procedures based on standard clustering algorithms have been explored. To date our results have been limited by the block sizes involved. If the blocks over which statistics are gathered are too large, performance is limited. If the blocks are too small our algorithms require inordinate time. Research is focused on more intelligent methods for forming blocks, the size of which can vary with content and whose shape can be irregular. Our computational methods have been generalized to deal with these irregularly shaped blocks.

B. Constrained Signal Estimation

The problems of constrained deconvolution and the problem of power spectrum estimation both involve the estimation of an unknown function given measurements of a linear functional based on that function. In this study we have been extending some of the formalism of the power spectrum estimation problem to the problem of estimating a positive signal from blurred observations. Our intent has been to use the resulting techniques for image restoration. Initially we have chosen our restoration to be that feasible solution which has the maximum entropy. Based on an analogous derivation for the power spectrum estimation problem, we have shown that such a signal must satisfy a parametric model whose number of free parameters equals the number of measurements. Algorithms for finding those parameters have been found. Efficient computational procedures have been developed for solving this problem and these results have been prepared for publications. Procedures have been developed for determining whether a feasible solution exists and they have been formulated as a test.

C. Reconstruction of Multidimensional Signals from Projections

We have looked into the use of iterative signal restoration algorithms applied to the reconstruction of multidimensional signals from their projections, a problem which forms the basis for computer-aided tomography and NMR imaging. A new algorithm has been developed which shows promise as a faster converging iterative procedure. This algorithm has been implemented and the simulations confirm our expectations on some synthetic examples.

D. Signal Modeling and Power Spectrum Estimation

This work has focused on the problem of signal modeling and the use of these models in power spectrum estimation. We have considered the problem of modeling a signal as a sum of sinusoids whose frequencies may vary as a function of time. A fast and efficient procedure for estimating the sinusoidal frequencies has been developed and analyzed for nonstationary signals. Although the work so far has been restricted to one-dimensional signals, our efforts are now focused on the extension of this model and algorithm to two-dimensional signals. We have also looked at the problem of modeling a linear time-varying system with an ARMA lattice filter. A new ARMA lattice filter realization has been developed which is fully consistent with the geometrical characteristics of the well-known AR and MA lattice filters, i.e., it is realized in terms of a fully orthogonal lattice basis and it evaluates all ARMA lattice filters of lower order. A new fast RLS algorithm for the evaluation of the ARMA lattice filter coefficients has also been developed.

E. Constrained Iterative Image Restoration

A general formulation has been developed for constrained adaptive and nonadaptive iterative image restoration algorithms. In this formulation, deterministic and/or statistical information about the undistorted image and statistical information about the noise are directly incorporated into the iterative procedure by what we have called "soft constraints." Spatial adaptivity is introduced by a soft constraint operator that incorporates properties of the response of human vision. The resulting image restoration algorithms are general and can be used for any type of linear constraint and distortion operators.

F. Unified Theory of Translation-Invariant Image Processing Systems

The theory of mathematical morphology seeks to quantitatively represent geometrical structure in images and in image transformations. The principles of mathematical morphology have been appied to develop a new general theory for translation invariant image processing systems. The key to this new theory is the representation of signals as sets rather than as functions. With this representation of signals, systems are represented as set transformations. A major new result is that systems also can be represented by sets, in a way that leads to new implementations and new understanding of image processing systems. This theory has been applied to obtain new insight into such classes of systems as morphological filters, rank-order filters, median filters, matched filters for shapes, and an interesting class of linear systems. The theory is potentially the basis for new approaches to the synthesis of image transformations with specific desired properties. Another result of this research is new insight into skeleton transformations of images. The skeleton has been applied to binary image coding, and it is currently being studied as a means for detecting shapes in images.

PUBLICATIONS

Theses:

1. P. A. Maragos, "A Unified Theory of Translation-Invariant Systems with Applications to Morphological Analysis and Coding of Images", Ph. D. Thesis, Georgia Institute of Technology, July 1985.

2. A. K. Katsaggelos, "Constrained Iterative Image Restoration Algorithms", Ph. D. Thesis, Georgia Institute of Technology, August 1985.

Books or Chapters in Books

1. M. H. Hayes, "The Unique Reconstruction of Multidimensional Sequences from Fourier Transform Magnitude or Phase", to appear in *Image Recovery: Theory and Application*, (H. Stark, ed.), Academic Press, 1986.

2. R. M. Mersereau, "Iterative Algorithms for Deconvolution and Reconstruction of Multidimensional Signals from their Projections", pp. 563-579 in *Adaptive Methods in Underwater Acoustics*, (H. G. Urban, ed.) Reidel, 1985.

Journal Articles (published or accepted)

1. A. Guessoum and R. M. Mersereau, "Fast algorithms for the multidimensional discrete Fourier transform", accepted, *IEEE Trans. Acoustics, Speech, Signal Processing*.

2. M. H. Hayes and M. C. Clements, "An efficient algorithm for computing Pisarenko's harmonic decomposition using Levinson's recursion", accepted, *IEEE Trans. Acoustics, Speech, Signal Processing*.

3. P. A. Maragos and R. W. Schafer, "Morphological skeleton representation and coding of binary images," accepted, *IEEE Trans. Acoustics, Speech and Signal Processing*.

Papers in Conference Proceedings

1. C. AuYeung and R. M. Mersereau, "Maximum entropy signal restoration", *19th Asilomar Conf. on Circuits, Systems, and Computers*.

2. A. Guessoum and R. M. Mersereau, "Solution to the indexing problem of multidimensional DFTs on arbitrary sampling lattices", *Proc. 1985 IEEE Int. Conf. Acoustics, Speech, Signal Processing*, pp. 1535-1538.

3. M. H. Hayes, M. A. Clements, and D. M. Wilkes, "Iterative harmonic decomposition of nonstationary random processes: theory and application", *Proc. Int. Conf. on Math. in Signal Processing*.

4. A. K. Katsaggelos, J. Biemond, R. M. Mersereau, and R. W. Schafer, "Non-stationary iterative image restoration", *Proc. 1985 IEEE Int. Conf. Acoustics, Speech, Signal Processing*, pp. 696-699.

5. A. K. Katsaggelos, J. Biemond, R. M. Mersereau, and R. W. Schafer, "A general formulation of constrained iterative restoration algorithms", *Proc. 1985 IEEE Int. Conf. Acoustics, Speech, Signal Processing*, pp. 700-703.

6. P. A. Maragos and R. W. Schafer, "A unification of linear, median, order-statistics, and morphological filters under mathematical morphology," *Proc. 1985 IEEE Int. Conf. Acoustics, Speech Signal Processing*, pp. 1329-1332.

Papers Submitted:

1. C. AuYeung, R. M. Mersereau, and R. W. Schafer, "Maximum entropy deconvolution", *1986 IEEE Int. Conf. Acoustics, Speech, Signal Processing.*

2. E. Karlsson and M. H. Hayes, "Modeling of time-varying systems with ARMA lattice filters", *1986 IEEE Int. Conf. Acoustics, Speech, Signal Processing.*

3. D. M. Wilkes and M. H. Hayes, "Spectral line tracking for nonstationary random processes", *1986 IEEE Int. Conf. Acoustics, Speech, Signal Processing.*

4. P. A. Maragos and R. W. Schafer, "Application of Morphological filtering to image processing and analysis," *1986 IEEE Int. Conf. Acoustics, Speech and Signal Processing.*

5. E. Karlsson and M. H. Hayes, "ARMA modeling of linear time-varying systems: Lattice filter structures and fast RLS algorithms", *IEEE Trans. on Acoustics, Speech, Signal Processing.*

WORK UNIT NUMBER 2

TITLE: Multiprocessor Architectures for Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATOR:

T. P. Barnwell, III, Professor

SCIENTIFIC PERSONNEL:

C. J. M. Hodges, Research Engineer
D. A. Schwartz, (Ph.D. candidate)
S. H. Lee, (Ph.D. candidate)
V. Owei (Ph.D. candidate)

SCIENTIFIC OBJECTIVES:

The objective of this research is to develop techniques for the automatic generation of optimal and near-optimal implementations for a large class of Digital Signal Processing (DSP) algorithms on digital machines composed of multiple processors.

RESEARCH ACCOMPLISHMENTS:

This research is centered on the problem of generating highly efficient implementations for a large class of DSP algorithms using multiple programmable processors. This problem is fundamental to many areas of activity, including VLSI design; implementations using arrays of state machines, signal processing chips, or microprocessors; and implementations using networks of general purpose computers.

DSP algorithms are unique in the sense that they usually are both highly structured and highly computationally intense. For this reason, it is often possible to achieve extremely efficient multiprocessor implementations in which the data precedence relations (that is to say the control functions) are maintained through the system synchrony and the system architecture, and every cycle of every arithmetic processor is applied directly to the fundamental operations of the algorithm. The basic goal of this research is to develop automatic techniques for the generation of such synchronous multiprocessor implementations from intrinsically non-parallel algorithm descriptions in such a way that the resulting implementations are both definably and meaningfully optimal. In short, we are developing multiprocessor compilers for DSP algorithms which can be used to generate optimal multiprocessor implementations for both discrete component and VLSI implementations.

Historically, this research has emphasized a set of techniques which we have named Skewed Single Instruction Multiple Data, or SSIMD, realizations. SSIMD implementations are generally realized on synchronous multiprocessors systems composed of many identical programmable processors. In SSIMD implementations, all of the processors execute exactly the same program using a computational mode in which the instruction execution times on the individual processors are skewed. SSIMD implementations have proven to have many desirable properties for DSP implementations. First, since all SSIMD implementations involve only one program, the problem of finding the best multiprocessor implementation reduces to the task of finding the best single processor implementation. Second, given any single processor program suitable for SSIMD implementations, it is possible to compute bounds for the full multiprocessor realization, thereby measuring in very fine grain the quality of the realization. These bounds include the SSIMD sample period bound, which is the minimum achievable time between the processing of input points; the SSIMD delay bound, which is the minimum achievable latency between the arrival on an input and the generation of the corresponding output; and the SSIMD processor bound, which it the minimum number of processors required to achieve the SSIMD sample period bound. Third, and more important, these bounds are not only easily computable, but also easily achievable. In particular, all SSIMD realizations which utilize less processors than the processor bound are perfectly efficient (processor optimal) in the sense that an N processor implementation is exactly N time faster than a one processor realization. Finally, the communications architecture required by SSIMD implementations is completely controllable through the specification of the delay (pipeline register) structure within the algorithm itself. For SSIMD realizations, it is always possible to realize the algorithm using a unidirectional nearest neighbor communications structure, but more complex communications architectures can be easily used to advantage if they are available. SSIMD realizations have many advantages for DSP realizations, particularly when compared to such approaches as systolic arrays, wavefront processors, SIMD and general MIMD solutions. In particular, SSIMD solutions tended to be faster, more efficient, and easier to find than the competing techniques. Most of the important results obtained over the past three years have resulted from a systematic attempt to understand the nature of the advantages which seemed to be inherent in the SSIMD approach.

We now know that SSIMD realizations are a special case of a more general class of synchronous multiprocessor implementations which we have named Cyclo-static realizations. The SSIMD results were all derived using a formalism which dealt with programs, that is to say sets of instructions for the control of arithmetic processors. We have now developed a similar formalism which deals not with programs, but with algorithms. In particular, we have introduced a three level formalism which allows for the simultaneous description and manipulation of a very large class of DSP algorithms. The three levels of the formalism -- called the graph theoretic level, the matrix level, and the link-list level -- are all mathematically equivalent formalisms each of which is particularly appropriate to understanding or implementing different parts of the theory. The graph theoretic level is most appropriate for conceptualizing the basic techniques. The matrix level is most appropriate to conceptualizing the associated automation techniques. And the link-list level is most appropriate to the actual computer realizations of the optimization techniques.

The algorithms addressed by this theory are those which can be described using fully-specified shift-invariant flow graphs. These graphs are similar to the more familiar shift-invariant signal flow graphs except that the nodes can contain any operators which can be realized by the processors to be used in the final realization. Given such a flow graph, and given the operation timings for the constituent processor which is to be used in the multiprocessor implementation of the flow graph, it is possible to compute absolute bounds on the multiprocessor realization. In particular, three bounds can be computed. The sample period bound is the smallest sample period at which the algorithm may be implemented. The delay bound is the shortest achievable period between an input and a corresponding output. And the processor bound is the fewest processors which can be used to achieve the sample period bound. These bounds give rise to a very fine-grained definition of optimallity. An implementation is rate-optimal if it achieves the sample period bound. An implementation is delay-optimal if it achieves the delay bound. An implementation is processor-optimal if it is either perfectly efficient (factor N speedup) or if it achieves the sample period bound using the number of processors specified by the processor bound.

Two years ago, the application of our new formalism to the SSIMD approach resulted in the development of an SSIMD compiler for signal flow graphs. This compiler, which can be configured to generate code for a large class of discrete and VLSI multiprocessor machines, is currently configured to generate code for the eight-processor, LSI-11 based multiprocessor which has been designed and implemented as part of this research. This compiler always finds a rate-optimal SSIMD implementation if it exists, and finds the best SSIMD implementation if it does not. Because of the great insight attained in the computation of the bounds, it is fairly simple to find a rate-optimal solution if it exists. It is less efficient to find the best sub-optimal solution if that is what is required. SSIMD realizations are always processor-optimal, often rate-optimal, and seldom delay-optimal.

The application of our new formalism to the systolic approach resulted in a rigorous procedure for transforming shift-invariant flow graphs into systolic realizations. This procedure, which can be fully automated, constitutes a formal procedure for both the generation and the verification of systolic implementations. But more important, this procedure showed very clearly the relationship between SSIMD and systolic implementations. Whereas systolic implementations constituted a full parsing of the algorithm in space, the SSIMD approach constituted a full parsing of the algorithm in time, followed by a mapping of time into space. Both the SSIMD and the systolic approach are limited special cases of synchronous multiprocessor implementations, and both have the virtue that they simplify the problem to the point at which it may be solved. Both have the disadvantage that, in simplifying the problem, they have over-constrained the resulting implementations.

Last year and this year, major advances were made two areas. The first, and most important, is the area of the automatic generation of rate-optimal, delay-optimal, and processor-optimal cyclo-static realizations for fully specified recursive shift-invariant flow graphs. Cyclo-static implementations have all of the advantages of SSIMD implementations without most of the disadvantages. In particular, at least one (often many) rate optimal implementation is always attainable, whereas for SSIMD a rate-optimal implementation was not always achievable. Likewise, at least one rate-optimal, delay-optimal implementation is always attainable. Delay-optimal implementations are seldom attainable for SSIMD. Like SSIMD, cyclo-static implementations are always processor-optimal. Also like SSIMD, so long as only optimal implementations are sought, cyclo-static solutions can be found using efficient tree-searching procedures. Unlike SSIMD, however, optimal solutions for cyclo-static schedules always exist.

Based on the above results (this is mostly the Ph.D. research of David A. Schwartz), a program for the automatic generation of cyclo-static solutions from shift-invariant flow graphs has been demonstrated. This program is the essential part of a 'cyclo-static compiler' which can generate control code for a broad class of synchronous MIMD machines. David Schwartz completed his Ph.D. research in June, 1985, and is continuing in the same general area as faculty member.

The second area in which results have been attained is in developing a multiprocessor compiler which operates from a non-parallel algorithm specification, and efficiently generates optimal constrained multiprocessor implementations for synchronous MIMD machines. The compiler is basically composed of four parts. The first part is a graph generator, which uses a serial algorithm specification to generate a generic flow graph with the minimum potential iteration period bound. The second part is a graph transformation which generates a fully specified flow graph with the minimum possible iteration period bound from the generic flow graph. The third and forth parts combine to efficiently find the best SSIMD, PSSIMD, or static PSSIMD under communications constraints imposed by a processor adjacency map. The major advance in this area is the extension of the concept to bounds so that the optimal implementations can be efficiently found even when a full cyclo-static implementation is excluded. The total effect of this work is a compiler in which the user specifies the desired algorithm serially, and the optimal multiprocessor implementation is generated automatically. This is largely the Ph.D. research of S. H. Lee.

Another major development, which is not really part of this research but will impact it greatly in the future, is the funding by DARPA of a DSP supercomputer project based on the principles developed in this research. This multiprocessor system, called the Optimal Synchronous Cyclo-static Array, or OSCAR, will be developed over a five year period, the first two years of which are currently funded. The OSCAR will be the target of all future multiprocessor compiler development.

PUBLICATIONS:

Thesis:

1. D. A. Schwartz, "Synchronous Multiprocessor Realization of Shift-Invariant Flow Graphs," Ph.D. Thesis, Georgia Institute of Technology, June 1985.

Papers in Conference Proceedings:

1. D. A. Schwartz and T. P. Barnwell III, "Cyclo-static Multiprocessor Scheduling for the Optimal Realization of Shift-Invariant Flow Graphs," *Proc. 1985 Int. Conf. Acoustics, Speech and Signal Processing*, pp. 1834-1387, March 1985.

2. S. H. Lee, C. J. M. Hodges, and T. P. Barnwell III, "An SSIMD Compiler for the Implementation of Linear Shift-Invariant Flow Graphs," *Proc. 1985 Int. Conf. Acoustics, Speech and Signal Processing*, pp. 1664-1667, March 1985.

3. M.J.T. Smith and T.P. Barnwell, III, "A New Formalism for Describing Analysis/Reconstruction Systems based on Maximally Decimated Filter Banks," *Proc. 1985 Int. Conf. Acoustics, Speech and Signal Processing*, pp. 521-524, March 1985.

Papers Submitted:

1. Mark J. T. Smith and Thomas P. Barnwell, III, "A Unifying Filter Bank Theory for Frequency Domain Coding", (submitted) *IEEE Transactions on Acoustics, Speech and Signal Processing*.

2. S. H. Lee and T. P. Barnwell III, "A Topological Sorting and Loop Cleansing Algorithm for a Constrained MIMD Compiler of Shift-Invariant Flow Graphs", *Proc. 1986 Int. Conf. Acoustics, Speech and Signal Processing*, Tokyo, Japan, April, 1986.

3. D. A. Schwartz, T. P. Barnwell III, and C. J. M. Hodges, "The Optimal Synchronous Cyclo-Static Array: A Multiprocessor Supercomputer for Digital Signal Processing", *Proc. 1986 Int. Conf. Acoustics, Speech and Signal Processing*, Tokyo, Japan, April, 1986.

WORK UNIT NUMBER 3

TITLE: Two-Dimensional Optical Storage and Processing

SENIOR PRINCIPAL INVESTIGATOR: T. K. Gaylord, Regents' Professor

SCIENTIFIC PERSONNEL:

M. G. Moharam, Associate Professor
E. I. Verriest, Assistant Professor
M. M. Mirsalehi, Assistant Professor
E. N. Glytsis, Graduate Research Assistant (Ph.D. candidate)
A. Knoesen, Graduate Research Assistant (Ph.D. candidate)
R. S. Weis, Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The long-term scientific objective of this research is to develop broadly based, theoretical and experimental knowledge of high-capacity, high-troughput, two-dimensional optical information storage and two-dimensional optical signal processing. This would bring together a range of concepts from basic physics to signal processing in its most generalized form. An optical digital parallel processor based on truth-table look-up processing implemented in the form of a content-addressable memory would be developed and tested.

RESEARCH ACCOMPLISHMENTS:

A. Optical Data Processing Instrumentation

Routine passive techniques such as temperature and air current control are not adequate to provide interference fringe stabilization in holographic optical data proce-sing experiments. A successful active phase stabilization system that can be adapted to a variety of experimental configurations was developed. It utilizes a synchronous lock-in amplifier and an electro-optic phase modulator to provide real-time stabilization of the interference fringe pattern. Both a video detection method and a direct optical detection were evaluated in conjunction with the phase stabilization system.

This work was published in *Applied Optics*.

B. Lithium Niobate Properties

In optical signal processing, lithium niobate is widely used due to its favorable electro-optic and photorefractive properties. This ferroelectric material also has important piezoelectric, elastic, and photoelastic properties. The important tensor physical properties and their mathematical descriptions were compiled. The essential features of its crystal structure were deduced and illustrated. Numerous errors in property values and crystal structure dimensions appearing in the literature were corrected.

The results of this work appeared in an invited review paper in *Applied Physics*.

C. Integrated Optical Anisotropic Waveguide Analysis

The surface impedance/admittance approach was shown to be very useful in describing the reflection and refraction of electromagnetic waves in an anisotropic medium incident upon a boundary with another anisotropic material. This valuable approach was reviewed and extended to the case of anisotropic dielectric slab waveguides used in integrated optical signal processing.

This work was published in *Applied Physics*.

D. Grating Diffraction

The rigorous coupled-wave analysis of grating diffraction developed under JSEP support by us is the first unified treatment that applies to both dielectric and metallic materials and to both planar (slab) and surface-relief (corrugated) structures. The exact formulation was presented along with the details of the solution in terms of state variables. Then using a series of assumptions, the rigorous theory is shown to reduce to the various existing approximate theories in the appropriate limits. The effects of these fundamental assumptions in the approximate theories were quantified.

This work was published in the *Proceedings of the IEEE*.

E. Optical Digital Parallel Processing

It was shown that digital parallel processing could be implemented using optical truth-table look-up techniques. With optical-logic-based pattern recognition, a content-addressable memory can be constructed. The use of the EXCLUSIVE OR and NAND logic operations to achieve content addressability were quantified. This memory system can be used to perform digital truth-table look-up processing and the requirements for 4-, 8-, 12-, and 16-bit addition and multiplication were given. The use of a binary-coded residue number system dramatically reduces the required storage capacity.

This work was published in *Optical Engineering*.

PUBLICATIONS:

Thesis:

1. M. M. Mirsalehi, "Two-Dimensional Optical Storage and Processing," Ph.D. Thesis, Georgia Institute of Technology, August, 1985.

Journal Articles:

1. C. C. Guest and T. K. Gaylord, "Phase stabilization system for real-time image subtraction and logical EXCLUSIVE OR processing," *Applied Optics*, vol. 24, pp. 2140-2144, July 15, 1985.

2. R. S. Weis and T. K. Gaylord, "Lithium niobate: Summary of physical properties and crystal structure," *Applied Physics A*, vol. 37, pp. 191-203, August 1985. (invited)

3. A. Knoesen, M. G. Moharam, and T. K. Gaylord, "Surface impedance/admittance approach for solving isotropic and anisotropic propagation problems," *Applied Physics B*, vol. 38, pp. 171-178, November 1985.

4. T. K. Gaylord and M. G. Moharam, "Analysis and applications of optical diffraction by gratings," *Proceedings of the IEEE*, vol. 73, pp. 894-937, May 1985. (invited)

5. T. K. Gaylord, M. M. Mirsalehi, and C. C. Guest, "Optical digital truth-table look-up processing," *Optical Engineering*, vol. 24, pp. 45-58, January/February 1985. (invited)

6. T. K. Gaylord and M. M. Mirsalehi, "Truth-table look-up processing: Number representation, multilevel coding, and logical minimization," *Optical Engineering*, vol. 25, pp. 22-28, January/February 1986. (invited)

Journal Papers Accepted:

1. M. M. Mirsalehi and T. K. Gaylord, "Comments on direct implementation of discrete and residue-based functions via optimal encoding: A programmable array logic approach," *IEEE Transactions on Computers*, vol. C35, pp. xxx-xxx, July 15, 1986.

2. M. M. Mirsalehi and T. K. Gaylord, "Multilevel coded residue-based content-addressable memroy optical computing," *Applied Optics*, vol. 24, pp. xxx-xxx, 1986.

3. M. M. Mirsalehi, T. K. Gaylord, and E. I. Verriest, "Integrated optical givens rotation device," *Applied Optics*, vol. 25, pp. xxx-xxx, May 15, 1986.

INTERACTIONS AND TECHNOLOGY TRANSFER:

The use of truth-table look-up content-addressable memory optical computing for adaptive antenna beamforming was discussed with the US Army MICOM Research Directorate in Huntsville, Alabama.

The analysis of interdigitated-electrode produced electric fields in integrated optical anisotropic waveguides was discussed with the US Army Research and Development Center in Dover, New Jersey.

WORK UNIT NUMBER 4

TITLE: Two-Dimensional Optical/Electronic Signal Processing

SENIOR PRINCIPAL INVESTIGATOR: W.T. Rhodes, Professor

SCIENTIFIC PERSONNEL:

R.W. Stroud, Graduate Research Assistant (Ph.D. candidate)
J.M. Hereford, Graduate Research Assistant (Ph.D. candidate)
J.T. Sheridan, Graduate Research Assistant (M.S. candidate)

SCIENTIFIC OBJECTIVE:

The long term scientific objective of this research is to gain a good understanding of the capabilities and limitations of hybrid optical/electronic methods for high throughput processing of 2-D signal information and to develop new and widely applicable techniques based on such methods. Emphasis is placed on establishing the capabilities of systems that mate well with digital signal processing systems.

RESEARCH ACCOMPLISHMENTS:

A. Bipolar Incoherent Spatial Filtering

Our original objective in this area was to develop effective methods for bipolar spatial filtering using incoherent optical systems that are simple to implement and efficient with respect to light utilization. That objective was augmented with the additional goal of maximizing overall system dynamic range in the case where optical and digital subsystems are combined with a scanning operation in between.

Research in this area was essentially completed during 1984 and the early part of 1985. During the term of this report the writing of a doctoral dissertation was completed and three papers prepared for publication.

B. Morphological Shape Transformations.

Investigations were begun this past fall on highspeed opto-electronic methods for implementing morphological shape transformations (e.g., erosions, dilations, openings, closings, and general rank-order processes) on binary images and nonlinear filtering operations (e.g., median filtering) on gray-scale images. Morphological transformations, which involve the interaction of a shape under study with a structuring element, are being used more and more in pattern recognition and classification for such things as quality control and robotic vision. Some of the basic operations are quickly performed using binary digital logic circuitry. Others, however (e.g., skeleton decomposition, where the pattern under study is reduced to primitive components), are sufficiently complex that TV-frame-rate processing is difficult to achieve. The schemes we are investigating perform the necessary operations in parallel. Real-time operation depends on finding a device that, like high contrast film, will perform a hard limiting operation on an image, but essentially instantaneously. Such devices are currently under development (e.g., at GTE laboratories), and the methods we are investigating appear to have good potential for success in a real-time environment.

Figure 1 illustrates how the operation is performed. A binary input pattern is presented to a shift-invariant imaging system and a blurring operation performed (Fig. 1a). In the figure the blur function, which plays the role of the structuring element in the transformation, is a disk, though other shapes are easily accommodated. The resultant blurred image is then hard limited. If the threshold is set for a high intensity, an erosion results (Fig. 1b); with a low intensity threshold, a dilation results (Fig. 1c). Setting the threshold at the 50% level results (with binary input and blur functions) in a median operation. Other threshold levels can be used to obtain other rank-order processing operations, assuming the input and blur functions are binary. These simple operations have been successfully demonstrated in the laboratory and will be presented at a conference in April 1986.

C. Time-Integration Optical Processing Research

Work that began under this program in connection with a Fourier transform scanning hybrid image processing system has evolved to center on the general problem area of bias buildup, signal-to-bias ratio, and signal-to-noise ratio in time-integration optical processing. This is a generic problem that affects several important classes of optical signal processing, including time-integration acousto-optic processing of radar and communication signals and incoherent holography.

In a mathematical study we have considered the implications of an image synthesis operation of the form

$$I(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(u,v)\cos^2[2\pi(ux+vy) + \theta(u,v)]dudv,$$

which can be written as

$$I(x,y) = \frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(u,v)\{1 + \cos[2\pi(2ux+2vy) + 2\theta(u,v)]\}.$$

The first form suggests the name "raised cosine" synthesis. The elemental components of this synthesis, though similar to Fourier components, are biased, each component having the necessary and sufficient bias to assure nonnegativity. The relationship to a normal Fourier transform is emphasized by writing

$$I(x,y) = \frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(u,v)dudv + \frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A(u,v)\cos[2\pi(2ux+2vy) + 2\theta(u,v)]dudv.$$

The second term, although in unconventional form, is essentially a real-valued Fourier synthesis integral and can represent any real-valued function f(x,y) satisfying the usual conditions. The first term is a bias that depends on the entire range of spatial frequencies in the image. Details of the relationship between A(u,v) and the 2-D Fourier transform of f(x,y) have been studied, both in continuous and sampled versions.

This particular synthesis is of considerable practical interest to us because it represents the minimum-bias image that can be recorded using time integration optical processing methods. Its properties and characteristics have been studied in connection with image synthesis, incoherent holography, and more general time-integration optical signal processing where an output distribution is built up of biased cosine fringe patterns.

Of particular use in numerical studies has been the relationship between a conventional Fourier series representation for an image,

$$I(x,y) = \{ \sum_{m,n} F_{m,n} \exp[j2\pi(mx+ny)] \} \mathrm{rect}(x,y),$$

and the corresponding raised cosine synthesis,

$$I_{rc}(x,y) = 2 \sum_{m,n} |F_{m,n}| (1 + \cos[2\pi(mx+ny) + \theta_{m,n}]) \mathrm{rect}(x,y),$$

where $\theta_{m,n}$ is the phase of $F_{m,n}$ and the summation excludes the 0,0 component. This relationship allows us to simulate on the computer a number of important optical signal processing operations that would be difficult for us to set up in the laboratory.

In this general area we have also considered characteristics of the output plane detector that can improve overall processor signal-to-noise ratio. The problem generally is that in such processing bias uses up a large fraction of the detector dynamic range. Of special interest to us for certain applications is the optimum use of photographic film for the detector. We have showed how optimum performance can be obtained in the particular case of bleached silver halide holograms made with low-contrast exposures. The results of our work will be presented at a holography conference in April 1986, and a manuscript for publication is in preparation.

D. Opto-Electronic Processor Architectures

We have continued our study of linear algebraic optical processing, giving an invited review paper on the subject at a recent SPIE Critical Review of Technology in the area of Highly Parallel Signal Processing Architectures. Work in this area has been frustrated by largely negative conclusions about the ability of optical algebraic processors to compete with their all-electronic counterparts. Our studies have extended to architectural concepts exploiting ultrashort optical pulses and their interactions in appropriate nonlinear optical media. Some preliminary conclusions, dealing largely with the difficulties associated with such methods, have been presented at a recent SPIE conference on Optical Computing.

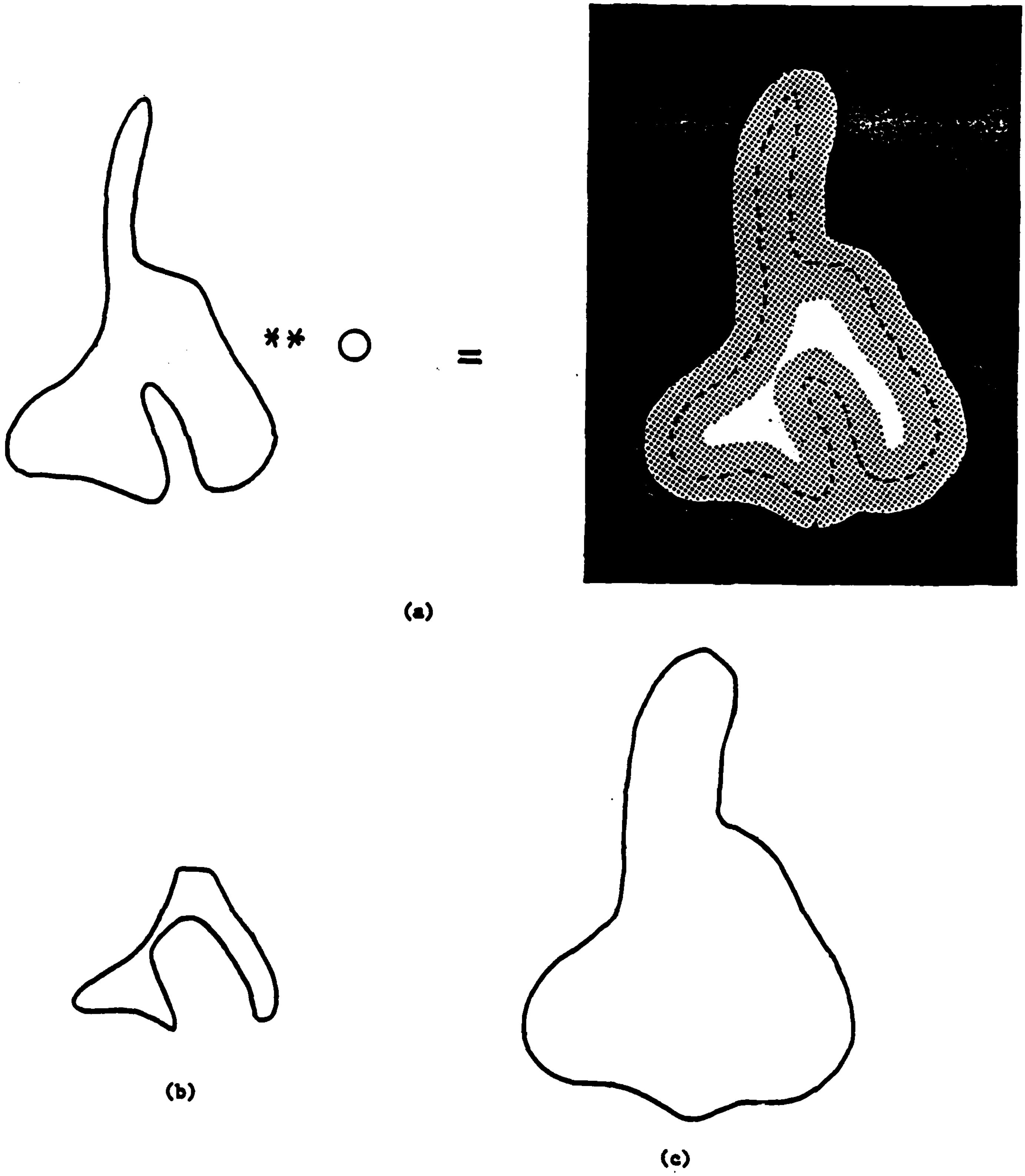

Figure 1. Morphological transformation by binary image blurring and hard limiting: (a) blurring operation (here with a disk; blurring represented by convolution) produces an image that is bright in the center, dark at edges, with a transition region in between; (b) erosion results from hard limiting at a high threshold; (c) dilation results from hard limiting at a low threshold.

PUBLICATIONS:

Dissertations:

1. Joseph N. Mait, "Pupil Function Optimization for Bipolar Incoherent Spatial Filtering," Ph.D. Thesis, Georgia Institute of Technology, June, 1985.

Journal Articles:

1. Joseph N. Mait, "Existence Conditions for Two-Pupil Synthesis of Bipolar Incoherent Pointspread Functions," (accepted) *Journal of the Optical Society of America A*, vol. 3, pp. xxx-xxx (1986).

Papers at Conferences without Proceedings:

1. W. T. Rhodes and R. W. Stroud, "Forming Parallel Fringes of Variable Spatial Frequency," presented at 1985 Annual Meeting of the Optical Society of America, Washington, D.C., October 1985.

2. E. S. Gaynor and W. T. Rhodes, "Exposure Optimization for Incoherent Computer Holography," presented at 1985 Annual Meeting of the Optical Society of America, Washington, D.C., October 1985.

Papers Submitted:

1. W. T. Rhodes and K. S. O'Neill, "Morphological Transformations by Hybrid Optical-Electronic Methods," in *Hybrid Image Processing*, D. Casasent and A. Tescher, eds. (Proc. SPIE, vol. 638, 1986).

2. W. T. Rhodes, "Optical Matrix-Vector Processors: Basic Concepts," in *Highly Parallel Signal Processing Architectures*, K. Bromley, ed. (Proc. SPIE, vol. 614, 1986).

3. W. T. Rhodes and J. A. Buck, "Optical Computing and Nonlinear Optics," in *Optical Computing*, J. Neff, ed. (Proc. SPIE, vol. 625, 1986).

4. J. N. Mait and W. T. Rhodes, "Two-Pupil Synthesis of Optical Transfer Functions: Pupil Function Relationships," submitted to *Optics Letters*.

5. J. N. Mait, "Pupil Function Design for Bipolar Incoherent Spatial Filtering," submitted to *Journal of the Optical Society of America A*.

6. W. T. Rhodes, "The Optical Margin," to be published in *Optics News*.

INTERACTIONS WITH DOD LABS:

Met with Dr. Jacques Ludmann, RADC, Hanscom Field, June 1985.

Met with Captain Greg Swietek, HQ FASC/DLAC, Andrews AFB, November 1986, for discussions on optical computing.

Met with P. Denzil Stilwell, Radar Division, Naval Research Laboratory, November 1986, for discussions on optical processing for fiber-optic-feed phased array radar system.

WORK UNIT NUMBER 5

TITLE: Optimal Multiprocessor Structures for the Implementation of Digital Signal Processing Algorithms on High Density Integrated Circuits

SENIOR PRINCIPAL INVESTIGATOR: J. H. Schlag and D. A. Schwartz

SCIENTIFIC PERSONNEL:

H. Forren, (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

To develop techniques for the automatic generation of optimal or highly efficient implementations of digital signal processing algorithms for synchronous multiprocessor VLSI architectures.

RESEARCH ACCOMPLISHMENTS:

In April of 1985 this work unit was split off from Work Unit 2 (Multiprocessor Architectures for Digital Signal Processing). Due to the initial overlap in personnel (D. A. Schwartz) there has been an overlap in research areas. While both units are interested in the problem of generating highly efficient implementations for a large class of DSP algorithms using multiple synchronous processors, this unit specifically focuses on the issues related to VLSI implementation constraints. The emphasis is on complexity tradeoffs and interprocessor communications. The multiprocessor systems are being analyzed in the context of cyclo-static solutions to DSP algorithms. This is due to the powerful ability to draw broad formal conclusions of the optimality of the resulting system with respect to several optimality criteria of interest (i.e. processor utilization optimal, delay optimal, rate optimal and communications optimal), in the case of cyclo-static solutions.

In the research area of cyclo-static solutions, the ability to find solutions has been expanded from the class of recursive filter-like algorithms to general iterative non-recursive algorithms. It has also been noted that the numerical solution of ordinary differential equations is a special case of the recursive filter-like class.

Simple sufficient conditions for a recursive algorithm to have a hardware realization that is rate optimal, processor optimal and delay optimal have been established. Simple sufficient conditions have also been found for the fully-static class of cyclo-static solutions to exist. This has come from the Ph.D research of H. Forren.

Previous work on cyclo-static solutions has focused on a more general purpose homogeneous multiprocessor. Statements about processor (utilization) optimality have been with respect to processor, as an atomic unit, utilization. When examined in the area of algorithmically specialized processor to be realized in VLSI, for a specific task, it becomes apparent that though processors may be ideally utilized, internally the processor may be only partially utilized. For example, in the filtering problems previously examined, it was assumed that the homogeneous processor could perform a (floating point) multiply or a (floating point) addition. While a processor may be doing one of theses operations at all times, resulting in a processor optimal solution, internally the processor may be only partially utilized is the different functions (addition and multiplication) use disjoint resources. Cyclo-static solutions have therefore been expanded to non-homogeneous processors, i.e. adders and multipliers. This was accomplished by associating a separate principal lattice vector with each type of processor.

A new cyclo-static compiler is under development that will incorporate the capacity for inhomogeneous processor solutions as well as applying some new ideas on methods for increasing the efficiency of the compiler in order to handle more complex problems.

The basic ideas of cyclo-static systems from this work unit and from work unit 2 has led to a technology transfer to develop a small scale supercomputer signal processor under contract from the Defense Agencies Research Projects Administration (DARPA). The small scale model is called OSCAR (Optimal Synchronous Cyclo-static ARray), and will be a four by four square array of special floating point processor with and expected throughput of approximately 80 MFLOPS. OSCAR will provide a test bed architecture for real time algorithm development in areas such as image processing, moving image processing etc. as well as a test bed for the development of compilers and other tools for the automatic determination of highly parallel realizations of digital signal processing algorithms. In additions OSCAR has been designed to support several models of architectures for which there are currently no formal tools for finding parallel realizations to, but which appear to be promising research areas.

OSCAR promises to be an important test vehicle for validating the current classes of cyclo-static solutions and to provide a direct mechanism for comparison to other approaches to multiprocessing such as systolic and wavefront array processing. The architectual design of OSCAR's communications has clarified many aspects that had been previously overlooked and has led to a clearer understanding of some of the theoretical tradeoffs in communications complexity. The design of OSCAR has amplified the importance of the tradeoff between the communications complexity, for a given performance goal, and the ability to design a processor that can be effectively programed.

Research is still in the start-up phase of examining a complexity theory approach to determining a minimum communications support for a given algorithm. Given a communications support (that is minimal or is fixed in a target machine), work is continuing on efforts to find more efficient algorithms to map applications algorithms onto the communications support. Binary tree communications support are know to embed efficiently in a planar constraint (VLSI chip), however they do not correspond well to current cyclo-static solutions. Work is continuing to find extensions of cyclo-static solutions that have better planar communications embedding. Initial results from a method that maps communications distance into communications delay appear promising.

WORK UNIT NUMBER 6

TITLE: Electromagnetic Measurements in the Time and Frequency Domains

SENIOR PRINCIPAL INVESTIGATOR: G. S. Smith, Professor

SCIENTIFIC PERSONNEL:

J. D. Nordgard, Professor
W. R. Scott, Jr., Graduate Research Assistant (Ph.D. candidate)
C. E. Davis, Graduate Research Assistant (M.S. Candidate)

SCIENTIFIC OBJECTIVE:

The broad objective of this research is to develop new methodology for making electromagnetic measurements directly in the time domain or over a wide bandwidth in the frequency domain. This research includes the development of the theoretical analyses necessary to support the measurement technqiues. One aspect of the research is the systematic study of radiating structures placed near or embedded in material bodies. In a practical situation the radiator might serve as a diagnostic tool for determining the geometry, composition or electrical constitutive parameters of the body.

RESEARCH ACCOMPLISHMENTS:

The research conducted during the last year was concentrated on the topic "Measurement of the Electrical Constitutive Parameters of Materials Using Antennas." This research involved the study of three separate configurations for measuring the constitutive parameters of a material:

A. the open-circuited coaxial line of general electrical length;

B. the monopole antenna of moderate electrical size;

C. the monopole antenna of general electrical length.

The research involving all three configurations is now complete, and journal articles describing the results have been published or submitted for publication.

A brief description of the research accomplishments for these topics follows.

A. Open-Circuited Coaxial Line

The open-circuited coaxial line of general length was studied as a sample holder for broadband measurements of the dielectric permittivity. The multivalued nature of the inverse function was described in detail. The error that results from passing onto the wrong branch was developed. The error in the measured permittivity due to the inaccuracies in the instrumentation was also analyzed. Contour graphs were constructed that quantify the effects of these two errors on the measured permittivity. The measurement technique was tested by measuring several alcohols with know permittivity. The study of the open-circuited coaxial line provided valuable experience that was applied to the measurement of the electrical constitutive parameters of materials using monopole antennas.

B. and C. Monopole Antennas

Two general procedures were developed for measuring the electrical constitutive parameters of materials using monopole antennas.

In the first procedure, a normalized impedance that is only a function of the dimensionless parameter kh (wave number • length) is defined for the antenna. The normalized impedance is expressed as a rational function, and the coefficients in this function are determined from a measurement of the impedance in a standard medium. The impedance measured in a material with unknown constitutive parameters is used with the rational function to form a polynomial in kh. The constitutive parameters of the medium are determined from a root of this polynomial. The measurement technique was implemented for a rational function of order three. The constitutive parameters of the alcohol 1-butanol and saline solutions were measured over a range of frequencies using the technique with cylindrical and conical monopole antennas. The measured constitutive parameters are in good agreement with those determined by previous investigators.

The second procedure, like the first, makes use of the normalized impedance of the antenna and a calibration of the antenna in a standard material with known constitutive parameters. However, in this procedure a numerical inverse is constructed from the calibration data and used to obtain the unknown permittivity of a material from the measured input impedance of the antenna. This procedure can be used with any size monopole antenna. The measurement technique was used to measure the constitutive parameters of the alcohol 1-butanol and saline solutions over broad frequency ranges (f to 200 f) with a single antenna. The antenna was as long as three wavelengths in the medium at the highest frequencies. The measured parameters for these materials were not good agreement with the expected values.

PUBLICATIONS:

Theses:

1. W. R. Scott, Jr., "Dielectric Spectroscopy Using Shielded Open-Circuit Coaxial Lines and Monopole Antennas of General Length," *Ph.D. Thesis, School of Electrical Engineering, Georgia Institute of Technology*, Atlanta, Georgia, October 1985.

Journal Articles (published or accepted):

1. G. S. Smith and J. D. Nordgard, "Measurement of the Electrical Constitutive Parameters of Materials Using Antennas," *IEEE Trans. Antennas and Propagat.*, Vol. AP-33, pp. 783-792, July 1985.

2. W. R. Scott, Jr., and G. S. Smith, "Error Analysis for Dielectric Spectroscopy Using Shielded Open-Circuited Coaxial Lines of General Length," accepted *IEEE Trans. Instrumentation and Meas.*.

Papers at Conferences with Proceedings:

1. G. S. Smith, "Measurement of the Permittivity of Materials Using Monopole Antennas," *1985-IEEE Antennas and Propagation Society, International Symposium*, Vancouver, Canada, pp. 517-520, June 1985.

2. W. R. Scott, Jr. and G. S. Smith, "Dielectric Spectroscopy Using Open-Circuited Coaxial Lines of General Length," *1985 North American Radio Science Meeting*, Vancouver, Canada, pg. 37, June 1985.

Papers Submitted for Publication:

1. W. R. Scott, Jr. and G. S. Smith, "Error Corrections for an Automated Time-Domain Network Analyzer," submitted for publication.

2. W. R. Scott, Jr. and G. S. Smith, "Dielectric Spectroscopy Using Monopole Antennas of General Electric Length," submitted for publication.

INTERACTION WITH DOD LABS

During the year, a study entitled "Hardened Antenna Technology Assessment" was begun for the Air Force (RADC, Griffis, AFB). This study makes use of analyses of buried antennas performed on the Joint Services Electronics Program.

WORK UNIT NUMBER 7

TITLE: Automated Radiation Measurements for Near- and Far-Field Transformations

SENIOR PRINCIPAL INVESTIGATOR: E.B. Joy, Professor

SCIENTIFIC PERSONNEL:

W.M. Leach, Jr., Professor
J.M. Rowland, Graduate Research Assistant (Ph.D. candidate)
R.E. Wilson, Graduate Research Assistant (Ph.D. candidate)
A.J. Julian, Jr., Graduate Research Assistant (Ph.D. candidate)
Y. Kanai, Graduate Research Assistant (M.S. candidate)

SCIENTIFIC OBJECTIVE:

The long term objective of this research is to understand the near field and far field coupling between antennas in the presence of scatterers. Special emphasis is placed on determination of limits of accuracy in the measurement of the fields radiated or scattered by an antenna-under-test by a second antenna and to develop techniques and computer algorithms for compensation of such measurements due to known geometrical or electromagnetic anomalies.

RESEARCH ACCOMPLISHMENTS:

A. Near-Field Radar Cross-Section Measurement Technique

Initial work has been completed on the plane wave scattering description of near-field coupling among three antennas. Antenna number one is viewed as the source of electromagnetic radiation, antenna number two is viewed as a scatterer of electromagnetic energy and the third is viewed as the receiver of electromagnetic radiation. This general formulation can model both bistatic and monostatic radar cross section measurement systems, both in the near-field and far-field. The model is capable of predicting both far-field bistatic and monostatic radar cross-sections from near-field measurements. The model has been verified for a single plane wave illumination, bistatic measurement. A monostatic near-field radar cross-section measurement was performed using a planar surface near-field measurement system with good results. These measurements were made on a simple (a flat plate) target. Measurements of other targets which will more fully test the technique are planned. These results were presented at the 1985 Meeting of the Antenna Measurement Techniques Association.

B. Sampling Requirements for Spherical Surface Near-Field Measurements

A sample spacing requirement was developed in the spherical surface near-field measurement technique. The rate of decay of evanscent energy storage near an antenna was investigated and found to be bounded by a Hankel function of the second kind of order N. The order N also specifies the theta and phi orders and thus sampling in theta and phi. Results were presented at the 1985 Meeting of the Antenna Measurement Techniques Association. These results showed that the sampling depended on the electrical size of the antenna under test and the distance from the antenna under test to the measurement sphere. Results were also presented which showed that the sampling requirement for spherical surface measurement approaches the well known sampling requirement for the planar surface as the radius of the spherical surface becomes large.

This result is important in the correct measurement of near-field or far-field patterns of antennas. Under-sampling causes aliasing and measurement error. Previous sampling requirements resulted in inaccuracies. Large amounts of redundant data were often collected and processed to overcome the lack of a sampling criterion.

This sampling criterion will be used in the measurement, testing, aligning and accepting of ground/ship based, air based and space based radar and communications antennas.

PUBLICATIONS:

Short Course Texts:

1. J. Frank and E.B. Joy, *Phased Array Antenna Technology*, Technology Service Corporation, 1984.

2. E. B. Joy, A.L. Maffett and J. Frank, *Radar Cross-Section Measurement Techniques*, Technology Service Corporation, 1984.

Editor of Meeting Proceedings:

1. E. B. Joy (Editor), Proceedings of the 1985 Meeting of the Antenna Measurement Techniques Association Meeting, Melbourne, FL, October 29-31, 1985, p. 421.

Papers in Conference Proceedings:

1. E. B. Joy and J. B. Rowland, Jr., "Sample Spacing and Position Accuracy Requirements for Spherical Surface Near-Field Measurements," *Proceedings of the 1985 IEEE/AP-S International Symposium*, Vancouver, B.C., June 17-21, 1985, pp. 682-692.

2. E. B. Joy, Near-Field Radar Crossection Measurement," *Proceedings of the Antenna Measurement Techniques Association Workshop on RCS Measurement Techniques*, Vancouver, B.C., June 21, 1985.

3. E. B. Joy and J. B. Rowland, Jr., "Sample Spacing Requirements for Spherical Surface Near-Field Measurements," *Proceedings of the 1985 Antenna Measurement Techniques Association Meeting*, Melbourne, FL, October 29-31, 1985, pp. 2-1, 2-10.

4. K. W. Cozad and E. B. Joy, "An Outdoor VHF Cylindrical Surface Near-Field Range," *Proceedings of the 1985 Antenna Measurement Techniques Association Meetings*, Melbourne, FL, October 29-31, 1985, pp. 4-1, 4-8.

5. E. B. Joy, O. D. Asbell and R. C. Johnson, "Feasibility of a Large Outdoor Compact Range," *Proceedings of the 1985 Antenna Measurement Techniques Association Meeting*, Melbourne, FL, October 29-31, 1985, pp. 11-1, 11-6.

6. E. B. Joy, B. K. Rainer and B. L. Shirley, "Monostatic Near-Field Radar Cross-Section Measurement," *Proceedings of the 1985 Antenna Measurement Techniques Association Meeting*, Melbourne, FL, October 29-31, 1985, pp. 24-1, 24-11.

Papers Submitted:

1. W.M. Leach, Jr., "A Plane-wave Spectrum Development of the Spherical Surface Near-Field Coupling Equation," (submitted) *IEEE Transactions on Antennas and Propagation*.

TECHNOLOGY TRANSFER

1. U.S. Navy: M.I.T. Lincoln Laboratory is developing a high performance surveillance radar system which incorporates a shipboard mounted ultra-low sidelobe planar phased array antenna. The array has a 5-meter by 10-meter aperture and -55 dB rms sidelobe levels. M.I.T. Lincoln Laboratory will install a multi-million dollar plane-polar near-field measurement system to test and align the phased array. To achieve the desired measurement and alignment accuracies, the K-correction probe position error compensation technique and algorithm developed under JSEP sponsorship will be transferred to M.I.T. Lincoln Laboratory. (The request for proposal on the facility specifies use of this technique).

2. Harris Corporation: A cylindrical surface near-field measurement system was designed and constructed at Harris Corporation, Quincy, IL, using the error analysis simulation developed under JSEP sponsorship for the specification of the required electrical and mechanical apparatus.

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