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Joint Services Electronics Program

Contract DAAL-03-90-C-0004

January 1, 1991 - December 31, 1991

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

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July 15, 1992

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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: multidimensional digital signal processing, signal restoration and detection, morphological systems for multidimensional signal processing, multidimensional processing for sensory arrays, multiprocessor systems and tools for digital signal processing, linear and nonlinear image processing, two-dimensional optical storage and processing, semiconductor quantum wave devices, electromagnetic measurements in the time and frequency domains, and automated radiation measurements for near- and far-field transformations.			
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ANNUAL REPORT

Joint Services Electronics Program
Contract DAAL-03-90-C-0004
January 1, 1991 - December 31, 1991

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

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July 15, 1992

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

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Contents

1 Overview

1.1 Technical Program	1
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2 Significant Accomplishments

2.1 Passive Detection and Localization of Sources	3
2.2 Semiconductor Quantum Electron Wave Devices	4
2.3 FDTD Methods for Transient Analysis of Antennas	5
2.4 "Flower Petal" Reflector Antennas	5

3 Two-dimensional Signal Processing

WU#1 Multidimensional Digital Signal Processing and Modeling	7
WU#2 Signal Restoration and Detection	16
WU#3 Morphological Systems for Multidimensional Signal Processing	21
WU#4 Multi-Dimensional Processing for Sensor Arrays	32
WU#5 Multiprocessor Systems and Tools for Digital Signal Processing	40

4 Optical Information Storage and Processing

WU#6 Linear and Nonlinear Image Processing	54
WU#7 Two-Dimensional Optical Storage and Processing	59
WU#8 Semiconductor Quantum Wave Devices	65

5 Electromagnetic Measurements

WU#9 Electromagnetic Measurements in the Time and Frequency Domains	77
WU#10 Automated Radiation Measurements for Near- and Far-Field Transformations	85

1 Overview

This Annual Report covers second full year of research carried out under Contract DAAL-03-90-C-0004. The research is part of the Joint Services Electronics Program (JSEP) at Georgia Tech, which is administered by the U.S. Army Research Office. The research activities are concentrated in the following areas: (1) Multidimensional Digital Signal Processing, (2) Optical Storage and Information Processing, and (3) Electromagnetic Measurements. The details of the contributions of these work units during the period January 1, 1991 to December 31, 1991, are summarized in the individual reports.

Preceding those individual reports is a brief summary of the technical program and a discussion of some of the significant accomplishments during the reporting period.

1.1 Technical Program

Research in the Multidimensional Digital Signal Processing area focuses on digital representation and processing of signals and the information that they represent. Advances in integrated circuit technology are making it possible to implement digital signal processing systems of unprecedented sophistication and power. With this increased capability comes an increasing need to expand the underlying theoretical base, to learn how to apply the theory innovatively to solve fundamental problems, to develop new approaches to implementing systems, and to learn how to design complex systems effectively and efficiently.

The research in this area is organized into the following research units:

- *Multidimensional Digital Signal Processing and Modeling*
PI: R. M. Mersereau
Work Unit One
- *Signal Restoration and Detection*
PI: M. H. Hayes
Work Unit Two
- *Morphological Systems for Multidimensional Signal Processing*
PI: R. W. Schafer
Work Unit Three
- *Multidimensional Processing for Sensor Arrays*
PI: J. H. McClellan
Work Unit Four
- *Multiprocessor Systems and Tools for Digital Signal Processing*
PI: T. P. Barnwell III, and J. H. McClellan
Work Unit Five

In spite of the tremendous advances in speed and complexity of digital integrated circuits, many problems in multidimensional signal processing and in general information processing require orders of magnitude more computation than can presently be provided economically by digital integrated circuits. For this reason, the research program contains a major effort in optical information storage and processing. The goal of this research is to learn how to utilize the inherent speed and parallelism of optics to increase the speed and capacity of information processing

systems, including especially multidimensional signal processing systems. The research program in this area is designed to explore a wide range of options including optical implementation of digital computation and storage and hybrid optical/electronic digital processing.

The Optical Storage and Information Processing area is comprised of the following three research units:

- *Linear and Nonlinear Image Processing*
PI: W. T. Rhodes
Work Unit Six
- *Two-Dimensional Optical Storage and Processing*
PI: T. K. Gaylord and E. N. Glytsis
Work Unit Seven
- *Semiconductor Quantum Wave Devices*
PI: K. F. Brennan, T. K. Gaylord, and E. N. Glytsis
Work Unit Eight

Work Unit Six has been phased out during the past year, and will not continue.

Problems of generation, propagation, coupling, and scattering of electromagnetic radiation are of fundamental concern in the theory and application of electronic/optical information processing systems. Measurement and modeling of electromagnetic phenomena is crucial to advancing knowledge in this field. Thus, the research program contains a significant effort directed at development of basic knowledge and definition of advanced techniques for performing measurements of electromagnetic phenomena. These techniques for making electromagnetic measurements rely heavily on computer control, digital signal processing, and numerical simulation. Thus, research in this area is closely related to other parts of the research program. Applications of the research include antenna design, radome design, alignment of phased-array antennas, measurement of electrical properties of materials, detection of buried objects, and design of buried antenna systems.

Research in the area of Electromagnetic Measurements is organized into the following two research units:

- *Electromagnetic Measurements in the Time and Frequency Domains*
PI: G. S. Smith
Work Unit Nine
- *Automated Radiation Measurements for Near- and Far-Field Transformations*
PI: E. B. Joy
Work Unit Ten

2 Significant Accomplishments

2.1 Passive Detection and Localization of Sources

The passive detection and localization of sources in a three-dimensional space is a problem of importance in a number of applications including radar, sonar, seismology, and non-destructive testing. In some cases, such as nondestructive testing or machine monitoring, the sources are confined to a compact region of 3-D space. Therefore, our work has looked at the use of two-dimensional and three-dimensional *master arrays* that are composed of two translationally equivalent *subarrays*. Recently, we developed a *Modified Direction of Arrival Matrix* (MDOAM) method and reported that there are many important advantages with this approach including increased detectability, efficient computation, and improved performance. In addition, we have tested modified DOA matrix method and have looked at the effect of rotational equivalencies in the two-dimensional and three-dimensional master array. The highlights of some of our results are as follows:

1. Since certain array processing applications involving passive source localization require the use of volume arrays, the MDOAM method was extended to include volume arrays. Volume arrays have enabled us to relax certain geometrical constraints imposed by planar arrays for unique source localization.
2. A new subspace rotation based technique called the SSM Method was developed that is able to detect more sources than the MDOAM method for the same number of sensors. Like the MDOAM Method, the SSM Method may be used for any non-linear array as long as there are two translationally equivalent subarrays.
3. In analyzing the performance of the MDOAM and SSM methods, it was observed that they outperform other subspace rotation based techniques such as ESPRIT, the SR Method, and the DOAM Method as summarized in Table 1.
4. The applicability of the MDOAM and SSM methods to arrays composed of rotationally equivalent subarrays were investigated. It was shown that unique DOA angle estimation with these methods is possible only when only a single source exists.

Algorithm	Automatic pairing of 2-D arrival angles	High detectability in 2-D applications	Insensitivity to subarray separation	Removing search procedure
ESPRIT (LS, TLS)	No	No	No	Yes
SR Method	No	No	No	Yes
DOAM Method	Yes	No	No	No
MDOAM Method	Yes	Yes	Yes	Yes
SSM Method	Yes	Yes	Yes	Yes

Table 1: Comparison of the MDOAM Method and the SSM Method to other subspace rotation based methods.

2.2 Semiconductor Quantum Electron Wave Devices

The following is a quotation from the "Prolog" written by M. J. Riezenman describing the paper G. N. Henderson, T. K. Gaylord, and E. N. Glytsis, "Ballistic Electron Transport in Semiconductor Heterostructures and its Analogies in Electromagnetic Propagation in General Dielectrics," *Proceedings of IEEE*, vol. 79, pp. 1643-1659, November 1991.

"For well over twenty years, progress in the semiconductor industry has been largely a matter of miniaturization. Power consumption, speed, and – most of all – circuit density have improved enormously as a direct result of the steady reduction in feature sizes. Interestingly, although the engineering details of the successive generations of integrated circuits have undergone a great deal of change during that time, the underlying physics has not. IC's are, and always have been, diffusive devices – that is, the electron transport within them has always been dominated by scattering.

"But diffusive transport will remain the dominant mode of electron transport only so long as device dimensions remain large with respect to the electron coherence length – the average distance an electron moves between collisions. And the time is rapidly approaching when that criterion will not be met. In fact, with today's technology, coherence length and device dimensions are of roughly the same size – about a micron. When device dimensions decrease further, semiconductor devices will find themselves operating under a new set of rules: the rules of ballistic transport, which apply when propagation takes place without collisions, or nearly so.

"How will operation under those new rules affect device behavior? And what can device manufacturers do to exploit ballistic transport in a positive manner instead of just learning to live with it? To help answer those questions, this paper describes a set of exact analogies between the behavior of ballistic electrons and electromagnetic waves. It thus allows semiconductor researchers to understand electron behavior at small dimensions in terms of established principles with which they are already familiar.

"An appreciation of the implications of ballistic transport may make possible whole new classes of semiconductor devices – if the fabrication technology needed to exploit the concepts is up to the job. Wave-type devices long familiar to microwave and optical engineers – lenses, waveguides, prisms, etc. – are possible. The challenge is that electron wavelengths are about a hundred times shorter than those of visible light. Hence the dimensions of such electron wave devices will have to be exceedingly small. Still, with molecular beam epitaxy being refined to the point where single atomic layers with differing compositions can be grown, the task may well be within our abilities. The possibilities are enormous: notebooks computers with the power of supercomputers, computational speeds hundreds of times higher than today's fastest devices."

2.3 FDTD Methods for Transient Analysis of Antennas

One objective of this research program is to study the mechanism of transient radiation by various antennas. The theoretical portion of this research uses the finite-difference time-domain (FDTD) method. Several extensions of this method were required before it could be used for practical antenna structures.

Many of the various antennas used to radiate transient pulses incorporate regions of resistive material in their structure. The resistive material used falls into two broad categories; electrically thick and electrically thin.

Electrically-thick, lossy materials are traditionally modelled using surface impedance concepts. Our work on incorporating surface impedance concepts into the FDTD method was recently accepted for publication in the *IEEE Transactions on Antennas and Propagation*. Our surface impedance FDTD formulation has been used to study a canonical resistive antenna (the lossy, open-ended parallel-plate radiator). Briefly, our research is driven towards finding antennas that can radiate pulses without distortion. An optimum resistive loading was found for the resistively loaded parallel-plate antenna that minimized pulse distortion while maximizing radiated amplitude and minimizing internal reflections. This work has been accepted for publication in the *Journal of Optical and Microwave Letters*.

Work on incorporating electrically-thin, lossy materials into the FDTD method has also been completed and been accepted for publication in the *IEEE Transactions on Antennas and Propagation*. Our electrically-thin material formulation has been used to successfully model the performance of a resistively loaded cylindrical monopole. This formulation is currently being used in the design of a transient radiator, the hollow, conical monopole loaded with resistive cards and driven by a coaxial line. The preliminary results are very promising. We have found that studying the FDTD results for the electric field surrounding the antenna on a graphic workstation is allowing us to gain a better understanding of the transient radiation mechanisms and to successfully design transient radiators.

2.4 "Flower Petal" Reflector Antennas

JSEP research is currently underway and promising results have been obtained on a new type of reflector antenna. Through the use of "flower petal" shaped edge serrations the performance of any type of reflector antenna (paraboloidal, corner, flat plate, shaped, spherical, etc.) can be improved. Specifically, sidelobe levels can be reduced while retaining gain. The use of the "flower petal" shaped edge serrations produces many of the advantages attainable through the use of a subreflector, at greatly reduced cost. The edge serrations give the reflector antenna designer an additional degree of freedom in shaping the aperture distribution of the reflector to achieve desired sidelobe level performance. This work is an outgrowth of the new type of JSEP sponsored flower petal shaped edge treatment for compact range reflectors that was implemented at the U.S. Army Fort Huachuca Electronic Proving Ground new Compact Range. One commercial company now manufactures this type of reflector for use on compact ranges. One paraboloidal reflector antenna using the flower petal shaped edge serrations, for use in point-to-point communications, has been designed, constructed, and tested. It is thought that this antenna type will find applications in radar antennas, satellite antennas, compact range antennas and point-to-point communications antennas.

Unusual Citations of "Flower Petal" Edged Reflector Invention

1. *Defense News*, November 4, 1991, "Sunflower Inspires Radar Dish," article.
2. *Business Week Magazine*, November 11, 1991, "Better-Looking Radar Dishes May Work Better, Too," article and drawing.
3. *Associated Press*, Nationwide, November 28, 1991, "Prof Puts Petal to the Metal," article and photo.
4. *Design News*, December 1, 1991, "Flower Petal Edge Enhances Satellite Dishes," article.
5. *Chicago Tribune*, December 1, 1991, "Better Satellite Dishes Have Flowery Edge," article and photo.
6. *National Public Radio*, December 5, 1991, Fort Huachuca, Flower Petal Edge Reflector Compact Range.
7. *CNN Headline News*, December 5, 1991, Fort Huachuca, Flower Petal Edge Reflector Compact Range.
8. *Wall Street Journal*, December 16, 1991, "Cutting Edge Sharpens Antenna Performance," article and photo.
9. *Johnny Carson Monologue*, December 19, 1991, "An electrical engineer in Atlanta, Georgia says that you can improve the performance of your satellite dish by shaping the edge of it like the petals of a flower. The problem is that your dish is then attacked by these enormous bees."
10. *New York Times*, January 19, 1992, "Dish with a Difference," article and photo.
11. *Poetry of Facts*, vol. 7, Arno Reinfrank, to be published in 1993, "Radar-Blumen," a poem in German about a flower-like radar antenna.

Technology Transfer

1. In process of transferring spherical backward transform to Texas Instruments, McKinney, Texas.
2. In process of transferring several JSEP techniques to U.S. Navy, NWSCC, Crane, Indiana, proposed planar near-field antenna measurement facility.
3. Jet Propulsion Laboratory, Pasadena, CA, is incorporating several JSEP Techniques in the design and construction of a new cylindrical near-field range.

Work Unit One

TITLE:

Multidimensional Digital Signal Processing and Modeling

SENIOR PRINCIPAL INVESTIGATOR:

R. M. Mersereau, Regents' Professor

SCIENTIFIC PERSONNEL:

F. J. Malassenet, (Ph.D. received, Dec. 1991)
T. R. Gardos, (Ph.D. Candidate)
J. Huang, (Ph.D. Candidate)
S. A. Martucci, (Ph.D. Candidate)
T. S. Rao, (Ph.D. Candidate)
K. K. Truong, (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The primary long term scientific objective of this research is to understand the means by which multidimensional signals, such as images, can be modeled and represented to facilitate their encoding, enhancement, and automatic extraction of information. A second objective is the development and analysis of algorithms for these tasks. These should work with real data and permit implementation in a reasonable amount of time in a multiprocessor environment.

RESEARCH ACCOMPLISHMENTS:

Students Gardos, Martucci, Rao, and Truong were partially supported using funds supplied by Georgia Tech, supplemented with JSEP funds. Their work is included in the summaries below. In those summaries the references refer to the publications which were published or submitted under this work unit during the period covered by this report. These are listed at the end and copies are included in the microfilm appendix to this report.

• *Weighted Multiresolution Representations for Images*

A number of models have been developed to model or code images. The approach followed in the thesis by Malassenet [1,6] assumes that a textured region of an image can be modeled as a deterministic correlated process. He called this model a weighted multiresolution process (WiMP).

The WiMP model is a generalization of a fully deterministic model that can generate random looking images, the iterated function system (IFS) model of Barnsley. Signals generated from IFS codes are not regular square integrable functions; they belong to the set of normalized Borel measures. While the behavior of continuous attractors of IFS systems was known, hardly

anything could specify the properties of their sampled versions. This thesis presented a generalization of the sampling transformation for square integrable functions that can be applied to the set of measures. It studied manipulations and transformations of sampled measures. For example, contractions in the continuous case may not be defined in the discrete case, and when they are they may not be contractions, which limits the performance of discrete implementations. The thesis developed a relationship between sampled measures and sampled functions. The functional and measure points of view were combined to study sampled measures. This allowed us to test some classical inverse filtering techniques to solve the inverse problem of IFS coding.

The WiMP model combines the flexibility of the IFS model at the expense of introducing more parameters. This increase in the number of parameters allowed more control of the sensitivity of the signal to the parameters. Indeed, the inverse problem showed that the continuity associated with the IFS transformation did not help the generation of simple robust algorithms.

The thesis also presented coding examples using WiMPs on real textures. These indicated that the assumption that all images do not have relationships between levels of the sub-band decomposition is not totally true. Since there is redundancy between the levels of decomposition, the bit-allocation procedures of subband coding methods may be redundant and better coding methods may be available.

• *Implementing Filter Banks Using Discrete Cosine Transforms*

The recent acceptance of standards for image coding employing the discrete cosine transform has led to a commercial demand for DCT chips and a renewed interest in this transform. This research began as an exploration of *multidimensional filter banks* for images.

In [7] and [16] we developed a framework for analyzing the effect of non-causal analysis filtering on the aliasing cancellation properties of the two-band filter bank system. A general solution was presented for the problem of how to extend finite-length signals before filtering so that expansion of the subband signal size could be avoided, while preserving perfect reconstruction. Circular convolution and symmetric extension are two techniques for providing this solution. It was shown that when using the symmetric extension method, the way in which the signal is extended and the amount of delay that the analysis filters may impart are highly constrained. Either even-length or odd-length filters can be used but the extension is different for the two cases. With proper implementation, an analysis/synthesis system with an overall constant transfer function is possible while maintaining a constant sample rate. These results were extended to the M -band case in [19].

Using symmetric extension to minimize edge effects is equivalent to filtering using discrete cosine transforms. In effect the symmetric convolution of two 2-D signals can be accomplished by calculating the discrete cosine transforms of the two signals, multiplying the two transforms, and calculating the inverse transform of the result. This property is complicated, however, by the fact that the discrete cosine transform assumes different forms when the signals are of even length or of odd length. In fact there are four discrete cosine transforms and four sine transforms. They must be used in the proper combinations if the convolution is to be performed correctly. These results were presented in [17] and the complete implementation of nonexpansive perfect reconstruction filter banks for images using discrete cosine transforms will be presented in [18].

• *Vector Quantizer Design for Video Coding*

One problem with using vector quantizers for image coding has always been the fact that the encoding operation is computationally intensive. (The decoding by contrast is done by a table lookup and is quite straightforward.) This complexity grows with the size of the codebook. This is unfortunate, because the achievable compression also grows with the size of the codebook. The goal of the research in this project has been to reduce the time required to encode an image or sequence of images. Our approach has been to design codebooks that are structured so that the best codeword match to a presented vector can be found in a reduced number of searches.

Part of this structure was imposed using a type of neural net called a *Kohonen self-organizing feature map*, which is arranged in a hierarchy. When used to design vector quantizers for still images, it could design codebooks that were only slightly inferior to the optimal designs obtained using the Linde-Buzo-Gray (LBG) procedure, but they could be trained and accessed in approximately 1% of the time. These results are summarized in [11].

A particularly exciting result during the past year was the discovery of an alternative hierarchical structure that could be imposed on top of the earlier one that offered impressive gains in compression when applied to video. The structure resembles a cache memory. The cache is a very small codebook containing the most recently used vectors from a large codebook. Whenever a new vector needs to be coded, the cache is searched and if a sufficiently close fit is found (measured by comparing a distance metric to a threshold) that vector is used again. If no good fit is found, a larger codebook is searched and the resulting vector replaces one in the cache. In our implementation three codebooks of increasing sizes were used and the largest codebook was implemented using the structured Kohonen feature map. In our video coder the cache VQ was used to encode displacement vectors. It could encode a black and white 352×240 video sequence at approximately 4K bits/frame with very high quality (36 dB PSNR). Furthermore, the complexity of the algorithm is such that we believe that a real-time video coder can be built to run on a single printed circuit card. Details of this coder can be found in [22].

• *Video Segmentation and Motion Estimation*

This research is concerned with one of the major issues that arises in the analysis of image sequences, image segmentation and the estimation of the motion of the isolated segments. Both gradient-based and block-matching approaches to displacement estimation assume that the image motion field varies slowly. This constraint is valid everywhere except at object boundaries, where nearby pixels can have very different motion. While the number of pixels that might be affected is often relatively small, they are perceptually very important, and they are responsible for the largest samples in a frame difference image.

We have been developing a scheme for simultaneously segmenting an image sequence and estimating the motion of the various segments. Initial estimates of the motion aid in the segmentation and initial guesses of segments aid in the estimation of the motion. An early version of our system was described in [5]. The algorithm involved moving edge detection, edge token extraction, edge matching, and displacement parameter estimation.

In [14] we describe a multi-frame gradient based algorithm for estimating displacement, which uses three or more frames from the image sequence. The procedure is quite robust in the presence of noise and it is suitable for object motion with acceleration, since it places no

constraints on the displacement vectors among consecutive frames. To the best of our knowledge this is the first multi-frame algorithm that does not assume constant object motion.

• *Non-causal Filtering and Modeling of Images*

Many one- and two-dimensional signal processing algorithms are characterized, in one form or another, by an underlying difference equation. Although derived in a number of application dependent ways, the difference equations are invariably realized by an initial condition based recursion. There is an implication of causality associated with recursive difference equations.

There are a number of reasons why algorithms created from causal (or semicausal) difference equations do not always work well. One of these is the fact that causal difference equations introduce a nonlinear phase shift to an input signal when used as frequency selective filters. Another concerns system stability. The absence of a factorization theorem for multivariate polynomials makes it extremely difficult to test the stability of a system characterized by a causal difference equation. Noncausal difference equations can alleviate many of the difficulties associated with causal models. They can always be made to form zero-phase filters and, when constructed in certain ways, can always be guaranteed to be stable. This research is developing a framework for developing, solving, and applying noncausal difference equation models to multidimensional signals.

In [8] we described a procedure for the design of 2-D zero-phase IIR filters based on McClellan transformations. The McClellan transformation technique is well-known for the design of 2-D FIR filters. We applied separate transformations to the numerator and denominator polynomials of the squared magnitude function of a 1-D IIR filter, such as an elliptic filter. This filter cannot be realized as a causal filter, because it is not stable, but it possesses a stable non-causal implementation based on a boundary-value realization, which was also described in that paper.

Additional effort has been expended to apply non-causal image models to image coding. The formalism used is that of recursive block coding that was originally introduced by Farrelle and Jain. Their coder used a restrictive class of non-causal models, however, and the coder was not adaptive. We have removed both of these restrictions. An early version of our image coder is described in [15].

• *Multi-Dimensional Multi-Rate Filter Banks*

Recent research by Cheung and Marks has shown that a period sampling lattice is not the most efficient lattice for sampling isotropically bandlimited multidimensional signals. Certain samples in the periodic lattice contain redundant information and can be deleted. At this time it is not clear for most applications whether the reduction in the number of samples justifies the increased complexity of the resulting systems. In an attempt to begin to answer this question we showed that it is possible to implement multidimensional, linear, periodically time-varying digital filters on signals that have been sampled in this fashion and that the total number of multiplications that are required is slightly less than would be required when the signals are sampled using a complete periodic lattice. These results are summarized in [4].

In related research we have built upon earlier research performed by Barnwell and Nayebi (in Work Unit 5), to develop a new context in which to analyse one-dimensional multirate filter banks and extended this analysis to the multidimensional case. These filter banks have

potential applications for image and video coding, motion estimation, and image restoration. We showed that a filter bank can be viewed as a periodically time-varying (PTV) system and that the necessary and sufficient conditions for perfect reconstruction in the time domain can be read directly from the PTV impulse response. These conditions are exactly the same as those derived by Nayebi by another approach. The advantage of our formulation is that the properties of the filter bank can be shown to coincide with the more intuitive properties of PTV systems. For example, bounds on system delay can be read directly from the PTV impulse response. Furthermore, the interaction of analysis/synthesis filter length and the resampling factor can be easily seen from the PTV impulse response. This point of view also makes the multidimensional extension more straightforward. Perfectly reconstructing analysis and synthesis filters were derived and presented for a multidimensional multirate filter bank. This work was summarized in [12]. It was extended to the case of non-uniform filter banks in [13].

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The publications by C. Auyeung and S. J. Reeves represent JSEP sponsored research from previous years.

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Work Unit Two

TITLE:

Signal Restoration and Detection

SENIOR PRINCIPAL INVESTIGATOR:

M. H. Hayes, Professor

SCIENTIFIC PERSONNEL:

W. Kim, (Ph.D. Graduate)
F. A. Sakarya, (Ph.D. Candidate)
A. Kittel, (Ph.D. Candidate)
S. Liu, (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

Signals generally carry information that is to be extracted and used in a particular signal processing system or application. In many cases of practical interest, these information-bearing signals become distorted or corrupted. In most applications, the recovery of the signal is not the primary concern but rather the extraction of the information that is contained within the signal. The signal may, for example, contain target classification information, the status or condition of a piece of equipment or machinery, or a high resolution image of a star in a distant galaxy, and it is this information that is to be extracted from the signal.

The objective of the research that is proposed in this unit is to look at the problem of recovering *information* from signals that have been distorted or incompletely specified. There are two specific problems that will be investigated during this research period. The first begins with an investigation into techniques for recovering the information in an image from a sequence of images that contain only Fourier magnitude information. This problem represents a new approach to the long-standing phase retrieval problem and will launch an effort in the general area of information extraction from a sequence of images. The second problem is concerned with the detection and classification of targets or sources that are known to originate within a closed (compact) environment. A particular application would be to monitor the status or condition of a machine.

RESEARCH ACCOMPLISHMENTS:

Signals generally carry information that is to be extracted and used in a particular signal processing system or application. In many cases, these information-bearing signals become distorted or corrupted. In most applications, the recovery of the signal is not the primary concern but rather the extraction of the information that is contained within the signal. The signal may, for example, contain target classification information, the status or condition of a piece of equipment or machinery, or a high resolution image of a star in a distant galaxy and it is this information that is to be extracted from the signal.

The work performed during the current reporting period, summarized in the following paragraphs, continues to build upon the results obtained during the first year of this contract. In addition, two new avenues of research have been explored in order to define some new, exciting, and potentially fruitful research directions for the forthcoming years. In the following sections, our work in four different areas is summarized: (1) the detection and classification of events using 2-D and 3-D arrays, (2) phase retrieval, (3) the symbolic representation of signals, and (4) video image coding using variable sampling and quantization.

• *Detection and classification of events using 2-D arrays*

The passive detection and localization of sources in a three-dimensional space is a problem of importance in a number of applications including radar, sonar, seismology, and non-destructive testing. In some cases, such as nondestructive testing or machine monitoring, the sources are confined to a compact region of 3-D space. Therefore, our work has looked at the use of two-dimensional and three-dimensional *master arrays* that are composed of two translationally equivalent *subarrays*. In the first year of work we developed the *Modified Direction of Arrival Matrix* (MDOAM) method and reported that there are many important advantages with this approach including increased detectability, efficient computation, and improved performance [1]. In the current year, we have continued testing the modified DOA matrix method and have, in addition, looked at the effect of rotational equivalencies in the two-dimensional and three-dimensional master array. A summary of our results is as follows:

1. Since certain array processing applications involving passive source localization, such as non-destructive testing, require the use of volume arrays, the MDOAM developed for planar arrays was extended to include volume arrays. Volume arrays have enabled us to relax certain geometrical constraints imposed by planar arrays for unique source localization.
2. We developed a new subspace rotation based technique that we call the SSM Method. This technique is able to detect more sources than the MDOAM method for the same number of sensors. Like the MDOAM Method, the SSM Method is applicable to any non-linear array as long as two of the subarrays are translationally equivalent.
3. In analyzing their performance, it was observed that the MDOAM and SSM methods outperform other subspace rotation based techniques such as ESPRIT, the SR Method, and the DOAM Method. A summary of our findings is illustrated in Table 1.
4. Finally, the applicability of the MDOAM and SSM methods to arrays composed of rotationally equivalent subarrays were investigated. It was shown that unique DOA angle estimation with these methods is possible only when only a single source exists [2].

• *Phase Retrieval*

Phase retrieval is concerned with the recovery of a 2-D signal from the intensity of its Fourier transform along with a set of signal constraints or assumptions. In our first year's work, we focussed exclusively on the extraction of phase information from a pair of Fourier intensities where a second intensity is derived by the addition of a known reference signal [4]. In addition,

the application of this approach to x-ray crystallography using real and simulated data was investigated [5]. In the current year, the phase retrieval problem has been considered for the case in which additional intensity measurements are obtained by using an object mask function [6,7]. This investigation has considered both the question of the uniqueness of the solution as well as a reconstruction algorithm for restoring the signal from the intensities. It has been shown, in particular, that if a signal, $x(n)$ or $x(m, n)$, is written as the sum of two signals that have complementary regions of support,

$$x(n) = y(n) + z(n)$$

then $x(n)$ is, in most cases, uniquely defined by the three intensities, $|X(e^{j\omega})|$, $|Y(e^{j\omega})|$, and $|Z(e^{j\omega})|$. In addition, a computationally efficient iterative reconstruction algorithm that is similar to the Gerchberg-Saxton algorithm was developed and analyzed [6,7].

• *Symbolic Representation of Signals*

One of the applications for our research in the detection and classification of events using 2-D and 3-D sensor arrays is to monitor the status or condition of a machine or, more generally, to monitor the state of some environment. In such applications, it is often not necessary to record and process the signals exactly as they are received. It is often sufficient, for example, to reduce the signal into a symbolic representation that preserves the signal features that are necessary for the extraction or detection of the events of interest. Therefore, we have looked at the problem of transforming 1-D waveforms recorded by sensors into a symbolic representation [8,9,10,11]. In this work, a symbol alphabet was defined for capturing the "physical appearance of signals." The signals were decomposed into simpler subcomponents described by different parametric models and combined under an object-oriented hybrid signal representation. A robust, event-synchronous system capable of transcribing a given signal into a symbolic representation was developed and analyzed for a number of different types of signals including drill monitoring signals, electrocardiograms, helicopter noise, and speech.

• *Video Image Coding*

In order to efficiently represent and store an image or a sequence of images, it is necessary to remove the redundancy inherent in the image or images. Although many different techniques have been explored for image and video coding, a new approach has been explored that relies on adaptively sampling and quantizing image sequences on a block-by-block basis. Using a recursive tree structure for adaptively partitioning an image, a coding algorithm has been developed that performs about as well as a DCT coder but with less computation [12]. As an offshoot of this work, some collaboration with Work Unit #1 led to a multi-frame pel-recursive algorithm for varying frame-to-frame displacement estimation [13].

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4. W. Armin Kittel, C. M. Epstein, and M. H. Hayes, "Monitoring of the EEG based on fuzzy classification," submitted for publication in *IEEE Trans. on Biomedical Engineering*.
5. W. Armin Kittel and M. H. Hayes, "Detecting changes in process monitoring signals," submitted for publication in *ASME Journal Engineering for Industry*.
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Work Unit Three

TITLE:

Morphological Systems for Multidimensional Signal Processing

SENIOR PRINCIPAL INVESTIGATOR:

R. W. Schafer, Institute Professor and John O. McCarty Chair

SCIENTIFIC PERSONNEL:

J. Crespo, (Ph.D. Candidate)
C. H. Richardson, (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

This research unit is concerned with morphological systems and their application in multi-dimensional signal processing. Specific goals of the research are the following: (1) to extend the theory of morphological systems, (2) to develop a new design methodology for morphological systems, (3) to develop techniques for symbolic representation of morphological systems, and (4) to study applications of morphological systems such as their use in edge detection, thresholding, and automatic image analysis.

RESEARCH ACCOMPLISHMENTS:

Morphological systems are nonlinear systems that are particularly well suited to problems in image filtering, image analysis, and image segmentation. The theory of such systems is based upon the representation of signals as sets of points rather than by functions and the representation of systems (image transformations) as set transformations. This set-based representation is particularly useful for images, since object shapes and geometric structure are naturally expressed in such a representation.

Morphological systems usually involve combinations of nonlinear operations that are applied to the image over the finite region of support of the structuring elements of the system. The design of such systems involves the choice of component subsystems, the strategy for combining outputs of the component subsystems, and the structuring elements of the component subsystems. Since few formal design procedures exist, most system configurations are obtained heuristically. This lack of formal design procedures has motivated our work in symbolic representation and manipulation of morphological systems.

Research during the past year has focused on three areas: (1) the use of morphological systems for image thresholding, (2) symbolic representation and manipulation of morphological systems, and (3) new approaches to image segmentation using nonlinear filtering. The results of this work are summarized below.

• Use of an Edge Coincidence Measure in Multilevel Thresholding

Thresholding is often used to create a simplified image that preserves the geometric structures and spatial relationships found in the original greyscale image.[1] For images consisting of solid objects in a solid background, the edges of the greyscale image are a good representation of these properties. For many applications, one way to ensure that these structures and relationships have been preserved is to ensure that the edges of the original image are maintained in the thresholded image. To numerically measure the degree to which the edges in the original image and the edges in the thresholded image coincide, an *edge matching* metric was developed. This edge-matching measure was designed to meet the following criteria:

1. If the edges in the original image and the edges in the thresholded image completely agree, the value of the edge measure should be 1.0.
2. If the edges in the original image and the edges in the thresholded image have no pixels in common, the value of the edge measure should be 0.0.
3. The measure should make it possible to associate more penalty to either missing or extraneous edges or to weigh them equally.
4. The measure should also weigh the distance between a correct edge in an incorrect location and an extraneous edge. Intuitively, if an edge in the thresholded image is uniformly offset by one pixel, its edge coincidence is higher than a thresholded edge that is offset by two or more pixels.
5. Finally, all edge pixels should contribute equal weight to the edge measure.

The first step necessary to measure edge coincidence is the actual extraction of the edges of both the thresholded and the original greyscale image. One of the simplest methods to extract edges from the thresholded image is to use combination of morphological erosions and dilations. The resultant edges are two pixels wide. (Single pixel wide edges may be extracted but they tend to be directionally biased.) Direct comparison of the thresholded edge set to the original edges, requires that the extracted edges of the original image also be two pixels wide. This can be ensured using the morphological PSTP method of edge extraction on the original greyscale image (with a 3x3 square structuring element).[2]

Once the edges have been extracted from both the original and thresholded image, the edge pixels are separated into three classes. Each edge class is defined in the following manner: Given the edge images of the original greyscale image, OE , and the thresholded image, TE , define the subtracted edge image, SE as $SE = OE - T$. Since a binary edge image may contain only the values $[0,1]$, the subtracted edge image pixels have the values $[-1,0,1]$. For each pixel in the subtracted image,

$SE_{ij} = 0$ indicates that pixel (i, j) belongs to either the edge set of both images (the *common* edge set) or the edge set of neither image (the *nonedge* set),

$SE_{ij} = 1$ indicates that pixel (i, j) is an edge pixel in the original image only (the *excess original* edge set) or

$SE_{ij} = -1$ indicates that pixel (i, j) is an edge pixel in the thresholded image only (*the excess thresholded edge set*).

Finally, an additional definition is needed. The fourth criterion requires incorporating into the edge measure the distance from an excess edge to a correct edge. To achieve this requirement, a distance measure, $|d_e|$ is used. Let $|d_e|$ be the distance from the excess edge pixel e to the nearest complementary edge pixel¹. Then a distance function is defined as

$$F(e) = \begin{cases} |d_e| & \text{if } |d_e| < \text{maxdist} \\ P_{\text{max}} & \text{otherwise} \end{cases}$$

where *maxdist* is a predetermined maximum search size. If a complementary edge pixel is not found within this maximum search area, the edge pixel is assumed to be in isolation and is assigned the maximum penalty, P_{max} . If

$$D = \sqrt{\text{number of pixels in the image}},$$

a reasonable search area is 2.5% of D . This is the value chosen for *maxdist*. If the image size is 300 x 300 pixels, the maximum search area will be a circular region with a radius of 2.5% of 300 or 8 pixels. The maximum penalty may be set to a distance of 10% of D or 30 for a 300 x 300 image. With these definitions and criteria in mind, the following edge measure was defined:

$$|E| = \frac{CC}{CC + W \left[\sum_{k \in \{EO\}} F(k) + \alpha \sum_{l \in \{ET\}} F(l) \right]}$$

where

- CC = The number of common edge pixels found in the image,
- {EO} = the set of all excess original edge pixels,
- {ET} = the set of all excess thresholded edge pixels,
- W = the penalty associated with an excess original edge pixel,
- α = the ratio of the penalties associated with an excess thresholded edge pixel to an excess original edge pixel.

This edge measure satisfies all of the requirements set forth:

1. If the edges of the original and thresholded images agree completely, there will be no excess edge pixels of either type and $|E| = CC/CC = 1$.
2. If the edges completely disagree, $CC = 0$ and $|E| = 0$.
3. The penalties associated with each type of excess edge pixel may be weighted simply by setting α to the desired scaling. If $\alpha = 1$, the penalties are assessed equally. Assigning $\alpha = 2$ would assign more penalty to an excess thresholded edge. This would compensate for slight variations in the edge widths in the original image, and would highlight noise points, incorrect transitions between adjacent regions and inserted regions. Setting $\alpha = 0.5$ would accentuate missing edges. The variability of α provides the flexibility for a large number of applications.

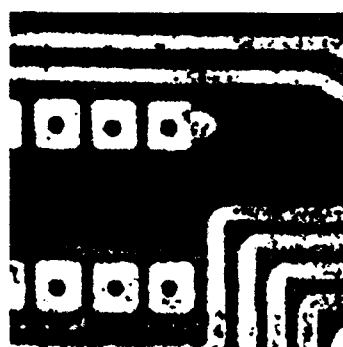
¹The complement to an excess original edge pixel is either a common edge pixel or an excess thresholded edge pixel. Similarly, the complement to an excess thresholded edge pixel is either a common edge pixel or an excess original edge pixel

4. By design, $|d_e|$ allows for the incorporation of the distance from excess edges to correct edge location.
5. Setting $W = (P_{max})^{-1}$, will help ensure that the contribution of all types of edge pixels will be of the same order of magnitude.

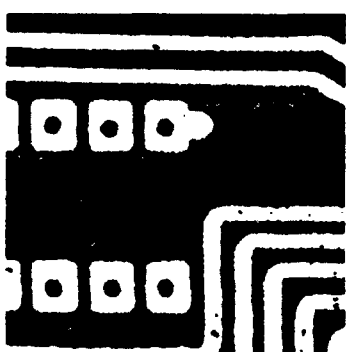
Figure 1 shows how this edge-matching metric may be used to determine the quality of a thresholded image. The greyscale image in (a) was thresholded using two global thresholds selected by three different methods: (b) the Moment Preserving method[3], (c) the Discriminant Analysis method[4] and (d) the Edge Preserving method.[1] Visually the results in (d) are far superior to the other methods, and this is clearly reflected in the respective values of the edge measure for the three thresholded images.



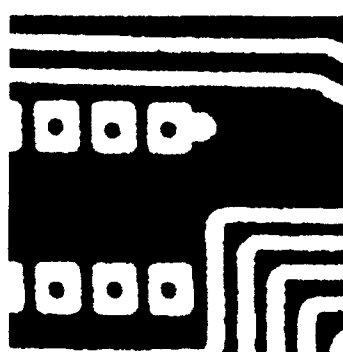
a. Original Greyscale



b. Moment Preserving:
0.316



c. Discriminant
Analysis: 0.215



d. Edge Preserving:
0.725

Figure 1: Greyscale image threshold computed using three methods and the resulting edge measures.

• Structuring Element Decompositions

Decomposition of structuring elements is an important issue in designing efficient algorithms for implementing morphological systems. This is so because the fundamental operations of erosion and dilation have an associative property such that erosion or dilation by a structuring element that can be represented as the dilation of two or more structuring elements

$$B = B_1 \oplus B_2 \oplus \dots \oplus B_N$$

is equivalent to cascaded erosions or dilations by the individual structuring elements. If the individual structuring elements are simple, significant computational savings can result.

A lower bound was derived that defines the limits of computation saving available through a structuring element decomposition implementation of the fundamental morphological operators of erosion and dilation. By setting the problem in a linear programming framework, a solution was found for the lower bound of $\lceil 3 \frac{\ln N}{\ln 3} \rceil$ points, where N is the number of points in the original structuring element. Thus any N -point set will have at least $\lceil 3 \frac{\ln N}{\ln 3} \rceil$ points in its decomposition.[5]

Combining this lower bound theory with integer programming techniques permitted the generation of optimal decompositions of 1-D connected lines of any length and near optimal decompositions of all L-D rectangular structuring elements. By defining the number of unions performed in a dilation operation with structuring element B as $|B| - 1$, the decomposition that requires the fewest number of unions was found. Changing the optimality criterion made it possible to find the decompositions that have the fewest number of points and either the minimum or maximum number of sets to represent these points. Integer programming techniques were chosen because of the ease of changing optimality criteria and the associated constraints. A mapping of the integer solution into sets produced the decomposition components that satisfied the specified optimality conditions. Although the decompositions are not unique, the optimality of the solution guarantees that no better decompositions exist.[5]

• Symbolic Representation and Manipulation of Morphological Systems

Craig H. Richardson has completed the work for a Ph.D. degree with a thesis on symbolic representation and manipulation of morphological systems. This thesis, which will be submitted for graduation in the spring quarter, 1992, presents, for the first time, symbolic manipulations and automatic analysis techniques applied to morphological signal processing. The major results are summarized below.

The research in this area has addressed many issues associated with automating the analysis and manipulation of morphological algorithms. In particular, symbolic representations of signals, systems, and system properties have been considered from a structured programming perspective that emphasizes an object-oriented paradigm. METAMORPH, a manipulation and analysis environment built to demonstrate these ideas, has shown how the representations of systems can be combined with rule-based programming techniques to generate symbolic simplifications and equivalent forms for morphological algorithms automatically. By introducing detailed cost measures, it was possible to rank the generation of equivalent forms according to the computational cost. The class of operations that are represented within METAMORPH is shown in Table 1. The elemental transformations consist of operations such as erosion, dilation, set theoretic

Table 1: The types of morphological algorithms that are represented within METAMORPH.

<i>Type</i>	<i>Example</i>	<i>METAMORPH representation</i>
Elemental	Erosion	Complete
Composite	Opening	Complete
Feed-forward	Skeleton	Partial
Feed-back		
Image recursive	Conditional-dilate	Partial

operations, and algebraic operations. For these operations there is a complete representation in terms of signal property propagation and manipulation rules. The composite transformations include any system composed of elemental operations and other composite systems such as the opening and closing. As with the elemental transformations, composite systems also have a complete representation in terms of signal property propagation and manipulation rules. The third class of operations consists of feed-forward iterative systems such as the skeleton or size distributions. A partial representation exists that allows one to work with a specified number of the subsets that form the operation. This same level of representation is present for image recursive operations such as the conditional dilation where the entire image is fed back into the input until some convergence criteria is satisfied.

Major contributions of this research include the specification and determination of the properties of morphological systems and system classes and the related signal property analysis procedures. An active representation of system properties permits relationships between system properties such as dual properties, implied properties, and excluded properties to be made explicit. In a generalization of signal property analysis, "meta-systems" were defined to describe the interconnection of systems and permit simpler system property analysis.

As part of the representation of signals, multi-dimensional regions were used to describe arbitrary regions of support and signal ranges, while deferred regions were used to permit infinite extent signals to have functional forms associated with them. Within METAMORPH, multi-dimensional regions extend the one-dimensional interval representation in E-SPLICE[6] and ADE[7], while deferred regions generalize Myers' extended deferred array.[6] Algorithms were presented that permitted logical operations such as intersection and Minkowski addition to be performed within the recursive representation of the regions. Also, a specification of computational cost of the fundamental operators of morphology and the generalization of this cost to different types of architectures was described. In addition to operation counts, a cost weighting mechanism was used to allow different types of costs to be compared according to a user-defined weighting function.

Finally, simplification and equivalent form rule-bases were defined that quantified the relationships that exist among morphological systems. About 100 manipulation rules have been found applicable to morphological systems and incorporated within METAMORPH. Equivalent form manipulations were performed for a collection of morphological algorithms including the morphological skeleton analysis and reconstruction algorithms. Immediately, the problem of combinatorial explosion became evident as the complexity of the input algorithm increased. By exploiting and extending Covell's work on manipulation constraints[7] to morphol-

ogy, METAMORPH was able to find automatically several equivalent forms for the morphological skeleton, including efficient forms found by Maragos[8,9] (in previous JSEP-supported research) and a new efficient form that had not been previously presented.

• *Image Partition Using Iterative Multi-Resolution Smoothing*

A new algorithm has been developed for determining variable resolution piece-wise constant representations of images.[10] At each iteration, a local 3 by 3 weighted average is computed at each pixel. The weights in the mask are adapted at each pixel according to the rule that the weights are inversely proportional to an estimate of the gradient of the image at the weighted point. Thus, edge pixels are automatically deemphasized in the smoothing process. A scale-space parameter k of the adaption algorithm controls the resolution of the resulting smoothed output. This works well if the edges (boundaries between regions) are distinct, but earlier algorithms based on this principle (proposed by Perona and Malik[11] and Saint-Marc, et al.[12]), suffered from inter-region averaging across weak segments of the edges. To prevent this, our new algorithm uses edge information estimated from the original image to extend and replace edges in the smoothed image after each smoothing iteration. The keys to success are: (1) the development of an edge extension algorithm that is compatible with the multi-resolution behavior of the algorithm and (2) the development of an edge detector that extracts two-pixels wide edges exhibiting high connectivity. The details of these algorithms are given in [10].

Figure 2 shows some results comparing the new algorithm to Saint-Marc's algorithm. It is clear from this figure that: (1) the position of the edges is well maintained within the scale space and (2) the region boundaries of the output occur precisely at the places marked by the set of edge pixels computed from the original image.

A major problem of the iterative adaptive smoothing scheme is that it is very slow to converge, with or without the addition of the edge extension feature, which does not add appreciably to the computation. Future research will focus on improving the computational efficiency, utilization of morphological operators, and the application of the multi-scale smoothing approach to image analysis.

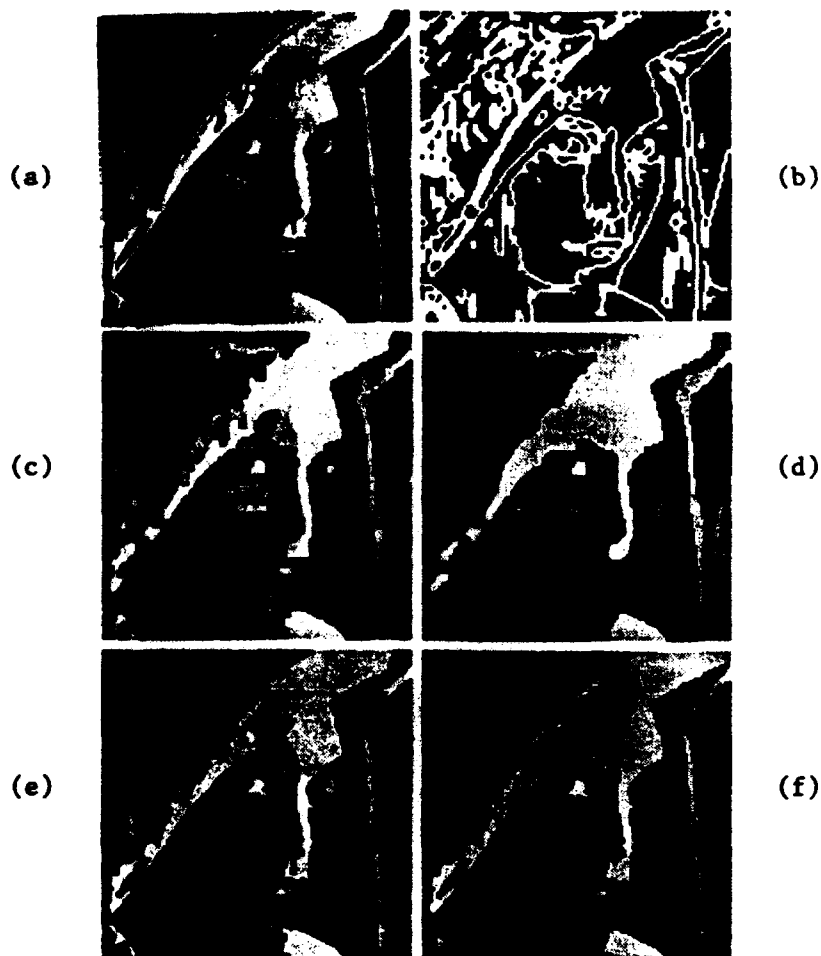


Figure 2: (a) Original image; (b) edges of original image (c) output of Saint-Marc's algorithm for $k = 6$; (d) output of Saint-Marc's algorithm for $k = 16$; (e) output of the new algorithm for $k = 6$; (f) output of the new algorithm for $k = 16$. For all cases, the number of iterations is 100. For (e) and (f) the edge information in (b) was used to prevent inter-region averaging.

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1. 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.
2. 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, pp. 365-369, April 1991.

Conference Presentations

1. 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.

Publications Submitted or Accepted

1. J. Crespo and R. W. Schafer, "Image partition using an iterative multi-resolution smoothing algorithm," accepted for publication in *Proc. 1992 Int. Conf. on Acoustics, Speech, and Signal Processing*, San Francisco, CA, March 1992.
2. L. Hertz and R. W. Schafer, "Measurement of edge coincidence in image thresholdings," accepted for publication in *Journal of Visual Communication and Image Representation*, December 1992.
3. C. H. Richardson and R. W. Schafer, "The symbolic manipulation and analysis of morphological algorithms," accepted for publication in *Symbolic and Knowledge-Based Signal Processing*, ed. by A. V. Oppenheim and H. Nawab, Prentice-Hall, Inc. to appear, May 1992.
4. 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*, Boston, MA, November 1992.

Work Unit Four

TITLE:

Multi-Dimensional Processing for Sensor Arrays

SENIOR PRINCIPAL INVESTIGATOR:

J. H. McClellan, Professor

SCIENTIFIC PERSONNEL:

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K. A. Blanton, (Ph.D. Candidate)
G. C. Brown, (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The objective of this research is to develop new methods of multi-dimensional spectrum estimation that are applicable to space-time data recorded from sensor arrays. Several major areas are being emphasized: adaptive algorithms for array beamforming, design techniques for non-uniform arrays, and calibration algorithms for robust processing in the presence of array imperfections.

RESEARCH ACCOMPLISHMENTS:

In the summaries below, some of the references are to publications that were published or submitted under this work unit during the period covered by this report. These are listed at the end and copies are included in the microfilm appendix to this report.

• *Dual Form Adaptive Filtering*

We have completed our work on the dual form constrained adaptive filter or beamformer. A paper on this subject has been accepted for publication. This adaptive filter is a new form of the classic LMS (Wiener) adaptive filter which applies when linear or norm constraints must be enforced on the filter coefficients. An extensive analysis of the algorithm, its convergence, and its misadjustment at convergence has been carried out.

The dual structure for constrained adaptive arrays is based on a gradient solution derived in the dual space of Lagrange multipliers [1]. Since the Lagrange multipliers are updated at each iteration, the dimension of the problem is equal to the number of constraints, which is usually much smaller than the number of weights.

The constrained LMS algorithm [2] solves a constrained Wiener filtering problem:

$$\min_{\mathbf{w}} \mathbf{w}^T \mathbf{R}_{xx} \mathbf{w} \quad \text{subject to: } \mathbf{C}^T \mathbf{w} = \mathcal{F} \quad (1)$$

In the dual approach, the problem is converted to an *unconstrained maximization* problem which is then solved via a gradient update for the Lagrange multipliers:

$$\lambda(j+1) = [\mathbf{I} - \mu \mathbf{C}^T \hat{\mathbf{R}}_{xx}^{-1}(j) \mathbf{C}] \lambda(j) - \mu \mathcal{F} \quad (2)$$

The actual weight vector for the adaptive array is a function of the Lagrange multiplier vector.

$$\mathbf{w}(j+1) = -\mathbf{R}_{xx}^{-1}(j) \mathbf{C} \lambda(j+1) \quad (3)$$

Our work has extended the dual structure to encompass norm constraints, which is sometimes referred to robust beamforming [3]. Thus the following problem is of interest:

$$\begin{aligned} \min_{\mathbf{w}} \quad & \mathbf{w}^H \mathbf{R}_{xx} \mathbf{w} \\ \text{subject to} \quad & \mathbf{C}^T \mathbf{w} = \mathcal{F} \quad \text{and} \quad \mathbf{w}^T \mathbf{w} \leq \delta^2 \end{aligned} \quad (4)$$

From the gradients with respect to the Lagrange multipliers, a steepest descent algorithm can be specified for the Lagrange multipliers:

$$\lambda_0(k+1) = \max \left\{ 0, \lambda_0(k) + \mu_{\lambda_0} \left[\lambda^H(k) \mathbf{C}^H \left(\frac{1}{1-\gamma} \hat{\mathbf{R}}_{xx}(k) + \lambda_0(k) \mathbf{I} \right)^{-1} \mathbf{C} \lambda(k) - \delta^2 \right] \right\} \quad (5)$$

$$\lambda(k+1) = [\mathbf{I} - \mu_{\lambda} \mathbf{C}^H \left(\frac{1}{1-\gamma} \hat{\mathbf{R}}_{xx}(k) + \lambda_0(k+1) \mathbf{I} \right)^{-1} \mathbf{C}] \lambda(k) - \mu_{\lambda} \mathcal{F} \quad (6)$$

The weight vector will be computed as

$$\mathbf{w} = -(\mathbf{R}_{xx} + \lambda_0 \mathbf{I})^{-1} \mathbf{C} \lambda \quad (7)$$

Since the norm constraint applies to $\mathbf{w}$, it may be necessary, in a numerical iteration, to enforce this constraint exactly on the true dual problem at each time step. Otherwise, the constraint may only be satisfied at convergence.

Finally, we see from the summary equations (2), (5), and (6), that the *dual* algorithm uses the inverse covariance matrix, and hence needs a recursive update of $\mathbf{R}_{xx}^{-1}$. On the other hand, we have conducted a number of simulations to show that its convergence characteristics are more like RLS than LMS even though the method is derived from a gradient point of view.

• Minimum Redundancy Array Design

This project is directed at the design of non-uniform arrays when the criterion of interest is to minimize the number of sensors, while maximizing the array aperture. A minimum redundancy linear array (MRLA) can measure all the correlation lags possible from 1 to L with many fewer than L sensors. In fact, an MRLA will have the maximum possible length for a given number of sensors. Compared to a uniform array of length $L = N-1$, an MRLA with the same number of sensors will have a length L in the range $\frac{1}{4}N(N+2) \leq L \leq \frac{1}{2}N(N-1)$ [4].

Finding a length- L MRLA, with N sensors, is equivalent to specifying a set of N distinct non-negative integers $\mathcal{S} = \{s_1 = 0, s_2, s_3, \dots, s_{N-1}, s_N = L\}$ such that any integer k , in the

range $0 \leq k \leq L$, can be represented as the difference of two elements of S . Such a set S is called a *restricted difference basis* [5].

Only a few theoretical results are available for designing MRLA's because the general case requires exhaustive enumeration. We have developed a relatively efficient search algorithm capable of finding all MRLA's of length L having exactly N sensors. It is based on the principles of combinatorial generating functions. To pare down the exhaustive search, certain constraints are imposed on the candidate arrays. For example, there must be a sensor at each end of the array (positions 0 and L) to get the spacing of L in the array. Furthermore, there are only two ways to have a spacing of $L-1$: a sensor must be present at position 1 or $L-1$. Continuing, there are three ways to obtain a spacing of $L-2$ in the array. This process can be implemented by creating a tree structure in which each template is represented by a node in the tree. The constraints allow many of the subtrees to be removed before being searched. At the same time, the tree is a complete representation of all valid arrays and is also efficient since no array will be represented by more than one template.

We have succeeded in generating, by this exhaustive search algorithm, optimal arrays larger than any previously published. The results obtained to date by the new algorithm go up through length 112. These results were published in a conference paper [6]. In the process of generating these arrays, errors in two earlier references were discovered and corrected. Such information, along with the array patterns themselves, should be extremely valuable in developing suboptimal searching techniques for still longer, but sparse, arrays.

• Array Calibration

This thesis project is directed at developing methods of self-calibration for array processing. The primary motivation for this research is the fact that high-resolution methods for angle-of-arrival (AOA) estimation do not work very well when the sensors are not ideal. This is especially true of methods based on eigen-analysis of the spatial correlation matrix. Techniques for self-calibration seek to compensate the sensor responses from measurements on "targets of opportunity", rather than known calibration sources.

Consider N distinct sources radiating narrowband signals, $s_j(t)$, received by an M -element array with arbitrary geometry. The k^{th} sensor has coordinates x_k and y_k . The signal received by the k^{th} sensor at time t is $z_k(t)$:

$$z_k(t) = \sum_{j=1}^N \gamma_k(\theta_j) f_k(\theta_j) s_j(t) v_k(\theta_j) + n_k(t) \quad (8)$$

where the data from the j^{th} source at time t is $s_j(t)$, the noise term is $n_k(t)$, the gain distortion term is $\gamma_k(\theta_j)$, the phase distortion term is $f_k(\theta_j)$, and $v_k(\theta_j)$ is the k^{th} element of the *ideal* steering vector given as the complex exponential: $v_k(\theta_j) = \exp[j\pi(x_k \sin(\theta_j) + y_k \cos(\theta_j))]$. Errors in the sensor positions can be modeled as angularly dependent phase distortions and can be incorporated into f_k .

A single vector equation can be written for the entire array. If the $M \times M$ diagonal matrix $F(\theta_j)$ represents phase distortions, and Γ the gain distortions, a *perturbed* steering vector, $w(\theta_j)$, can be written in terms of the ideal steering vector $v(\theta_j)$ as:

$$w(\theta_j) = \Gamma(\theta_j) F(\theta_j) v(\theta_j) \quad (9)$$

Then the data vector snapshot at time t can be written in vector notation as

$$\begin{aligned} \mathbf{z}(t) &= [\mathbf{w}(\theta_1) \cdots \mathbf{w}(\theta_N)] [s_1(t) \cdots s_N(t)]^T + \mathbf{n}(t) \\ &= \mathbf{W}(\boldsymbol{\theta}) \mathbf{S}(t) + \mathbf{n}(t) \end{aligned} \quad (10)$$

Techniques for self-calibration seek to determine $\mathbf{F}$ and $\mathbf{F}$ from measurements on "targets of opportunity." This obviously limits the calibration to discrete angles, although interpolation could be used to derived the complete angular dependence of the sensor imperfections.

The completely general calibration problem is impossible to solve, unless some restrictions are made. We have developed algorithms for two special cases: (1) angularly dependent phase errors plus gain errors that do not vary with AOA [8], (2) angularly dependent phase errors with a correct gain of one at each sensor. These cases could model phase errors due to incomplete knowledge of the sensor positions, or due to mutual coupling between the elements in a radar array.

In both cases, the approach is to compute the "perturbed steering vectors" in an eigen-decomposition of the correlation matrix. These perturbed steering vectors can then be decomposed into a linear phase term that represents the ideal steering vector, and a distortion term that represents $\mathbf{F}$ and $\mathbf{F}$. The difficult step is going from the signal subspace, extracted from the eigen-decomposition, to the set of perturbed steering vectors. Ordinarily, the steering vectors which make up the columns of the matrix $\mathbf{A}(\boldsymbol{\theta})$ have the form of perfect complex exponentials. When there are gain and phase perturbations, the steering vectors no longer have the form of perfect complex exponentials. However, the perturbed steering vectors will still span the signal subspace. Therefore, the following equation must hold:

$$\mathbf{W}(\boldsymbol{\theta}) = \mathbf{U}_{sig} \mathbf{X} \quad (11)$$

where $\mathbf{U}_{sig}$ is a matrix whose columns are the signal subspace eigenvectors of the correlation matrix, and the matrix $\mathbf{X}$ is a square matrix that determines the linear combinations of eigenvectors needed to create the perturbed steering vectors which are the columns of $\mathbf{W}(\boldsymbol{\theta})$. The objective of the calibration algorithm is now to determine the entries of the matrix $\mathbf{X}$. In order to accomplish this task, an error measure must be introduced, so that a numerical optimization method can be used to choose $\mathbf{X}$. The difficulty is that the problem is underconstrained when the most general case of angularly dependent phase errors is allowed.

In the first case, the following algorithm was developed:

- (i) Initialize: $j = 0$; select $\hat{\mathbf{X}}_0$

Perform an eigen-decomposition of $\mathbf{R}$: $\mathbf{Y} = \mathbf{U}_{sig}^H (\mathbf{R} - \sigma_n^2 \mathbf{J}) \mathbf{U}_{sig}$

- (ii) Map $\mathbf{Y}$ into feasible set: $\hat{\mathbf{X}}_j = \hat{\mathbf{X}}_j \sqrt{\hat{\mathbf{X}}_j^{-1} \mathbf{Y} \hat{\mathbf{X}}_j^{-H}}$

- (iii) Update signal power: for $k = 1 : N$

$$\hat{\sigma}_{k,j}^2 = \frac{1}{M^2} \left[\sum_{l=1}^N |[\mathbf{U}_{sig} \hat{\mathbf{x}}_{k,j}]_l|^2 \right]$$

- (iv) Update gains:

$$\hat{\gamma}_j^2 = \left[\sum_{q=1}^N \hat{\sigma}_{q,j}^4 \right]^{-1} \sum_{l=1}^N \hat{\sigma}_{l,j}^2 (\hat{\mathbf{x}}_{l,j}^H \mathbf{U}_{sig}^H)^T \odot (\mathbf{U}_{sig} \hat{\mathbf{x}}_{l,j})$$

(v) Update $\tilde{\mathbf{X}}$ via a Newton update, for $k = 1 : N$

$$\tilde{\mathbf{x}}_{k,j+1} = \tilde{\mathbf{x}}_{k,j} - \alpha \left[\frac{\partial^2 e(\tilde{\mathbf{x}}_{k,j})}{\partial \tilde{\mathbf{x}}_{k,j}^2} \right]^{-1} \frac{\partial e(\tilde{\mathbf{x}}_{k,j})}{\partial \tilde{\mathbf{x}}_{k,j}}$$

(vi) If $|e(\tilde{\mathbf{X}}_{j+1}) - e(\tilde{\mathbf{X}}_j)| > \epsilon$, then (* not finished *)

$j = j + 1$; goto (ii)

(vii) Estimate AOA : for $k = 1 : N$; $\hat{\theta}_k = h(\mathbf{U}_{sig} \tilde{\mathbf{x}}_k)$

This requires a non-linear fit of a linear phase term to the vector $\mathbf{U}_{sig} \tilde{\mathbf{x}}_k$.

(viii) Normalize the gain estimate: $\hat{\Gamma} = \sqrt{(\text{diag}(\hat{\gamma}^2))}$

(ix) Estimate phase error : for $k = 1 : N$, for $l = 1 : N$

$$[\hat{f}(\hat{\theta}_k)]_l = \frac{[\text{diag}(\mathbf{v}(\hat{\theta}_k))^{-1} \mathbf{U}_{sig} \tilde{\mathbf{x}}_k]_l}{|[\text{diag}(\mathbf{v}(\hat{\theta}_k))^{-1} \mathbf{U}_{sig} \tilde{\mathbf{x}}_k]_l|}$$

The proposed algorithm, based on Newton's method, iteratively minimizes an error that is a measure of the distance between the component magnitude of the estimated steering vectors of each source and average sensor gain estimate:

$$e(\hat{\mathbf{X}}) = \sum_{k=1}^N \|(\hat{\mathbf{x}}_k^H \mathbf{U}_{sig}^H)^T \odot (\mathbf{U}_{sig} \hat{\mathbf{x}}_k) - \hat{\sigma}_k^2 \hat{\gamma}^2\|^2 \quad (12)$$

where $\hat{\gamma}^2 = \text{diag}(\hat{\Gamma} \hat{\Gamma})$ and the hatted terms denote estimates. Here, the symbol $\odot$ denotes element-wise multiplication. The error has the following three properties: it is independent of the steering vector phase components; sources with larger power are more heavily weighted; it is minimized if components of all steering vectors have the same magnitude to within a scaling factor, $\hat{\sigma}_k$.

If the Newton step size, α , is chosen properly, the algorithm converges to a local minimum. To ensure convergence to the global minimum, the initial guess must be sufficiently close to the optimum; otherwise, the algorithm may not converge. Simulations show that this algorithm can extract the gain and phase perturbations, although there may be a linear-phase bias in $f_k(\theta)$ that cannot be recovered.

In the second case, where the gain is known to be unity, we have developed an algorithm based on the method of *Homotopy* [7]. This method of optimization yields a global minimum, but is restricted to situations with a small number of sources. Present work is directed at characterizing the different types of self-calibration scenarios that can be attacked via this algorithm, and analyzing the behavior of the basic algorithm when the number of available sources is small.

When this calibration problem is posed as the minimization of a cost function, it can be reduced to the rooting of a multi-dimensional cubic equation. This in turn can be written in terms of a real polynomial, and the method of *Polynomial Continuation* or *Homotopy* can be employed. One advantage of the homotopy is that it will find all solutions for a coupled system

of polynomials. The major disadvantage is that the computational load is related to the number of solutions, which grows exponentially with the number of sources. Consequently, even though a solution is at hand that will guarantee all solutions in a finite run time, the method only works effectively for small values of N .

To overcome this obstacle and obtain feasible run times, we are investigating a family of suboptimal cost functions that have fewer solutions. This still only reduces the number of solutions to $3 \times 2^{2N-3}$. Among these, the number of physically meaningful solutions will be only a very small set. We are studying characteristics of the solution for the cases of one or two sources to determine how to simplify the minimization algorithm when there are more sources.

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Conference Presentations/Publications

1. G. C. Brown, J. H. McClellan and E. J. Holder, "Eigenstructure Approach for Array Processing and Calibration with General Phase and Gain Perturbations," *Proc. ICASSP-91*, Toronto, CANADA, 14-17 May 1991, paper E1.3, pp. 3037-3040
2. K. A. Blanton and J. H. McClellan, "New Search Algorithm for Minimum Redundancy Linear Arrays," *Proc. ICASSP-91*, Toronto, CANADA, 14-17 May 1991, paper U3.5, pp. 1361-1364.

Journal Articles

1. 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.

Journal Articles (submitted or accepted)

1. L. B. Fertig and J. H. McClellan, "Dual Forms for Constrained Adaptive Filtering," *IEEE Trans. on Signal Processing*, (accepted subject to revisions).

Work Unit Five

TITLE:

Multiprocessor Systems and Tools for Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATORS:

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P. Gelabert, (Ph.D. Candidate)
C. P. Hong (Ph.D. Graduate)
B. Kim, (Ph.D. Graduate)
H. Kim, (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The objective of this research is to develop systematic techniques for the automatic generation of provably optimal multiprocessor implementations for a broad class of DSP algorithms and for a broad class of multiprocessor systems, and to develop high-level language tools for the design of DSP systems. The long term goal is to merge the capabilities inherent in fine-grained parallel systems with high-level algorithm design tools to provide a total environment for the design of DSP systems.

This research involves two different classes of compilers. The first class includes optimal fine-grained multiprocessor compilers for custom synchronous multiprocessors, for multiprocessors based on DSP microprocessors and for the automatic design of chips for specialized synchronous machines. A number of such compilers are currently being developed in this research unit. The second class involves the development of compilers for DSP machines in the style of C++, and the use of symbolic manipulation programs such as *Mathematica* to describe algorithms at a level that is compatible with the mathematical theory of signal processing. Ultimately, these systems will be used to generate programs that can run in the DSP machine environment.

RESEARCH ACCOMPLISHMENTS:

Work on multiprocessor architectures for DSP has been centered in five areas: optimal periodic scheduling theory for operations and communications; scheduling theory for parallel pipeline and clock-skewed architectures; a graph compiler for multiprocessors based on commercial DSP chips; a silicon compiler for optimal synchronous fine-grained implementations; and a general design procedure for exactly reconstructing analysis-synthesis systems based on filter banks.

In the tools area, the initial phase of the research work has concentrated on the implementation of a new set of signal processing packages within the symbolic environment of *Mathematica*.

These packages perform a variety of common signal processing operations: transform analysis, convolution, and reasoning about signal and system properties. Now they form the basis of new work on multidimensional filter structures.

The development of compilers for DSP chips is focusing on the definition of a general way of describing fixed-point arithmetic in any language and its implementation via objects in C++. The thrust of this work is to develop a compiler for fixed-point DSP machines using a syntax that is an extended form of the C language.

• *Optimal Multiprocessor Compiler for Clock Skewed Parallel Processing (CSPP) Systems*

The work in this research in this area has now been completed, and has resulted in a thesis by C. P. Hong [24]. This research topic is the extension of cyclic multiprocessor scheduling techniques, such as those used in the cyclo-static and generalized SSIMD compilers, to pipeline and parallel pipeline architectures. This new theory is based on a set of transformations which represent pipeline and parallel pipeline architectures as parallel MIMD systems [1]. These transformations represent individual pipeline processors (such as the AT&T DSP32 processor used in the OSCAR-32) as a number of *pseudo-processors* in a parallel structure. After the transformations, the result is a fully parallel architecture with no pipelined elements. Thus, parallel processor scheduling techniques can be applied directly to the transformed architectures to achieve optimal or near-optimal schedules. These multiprocessor realizations are then transformed back into their equivalent optimal or near optimal pipeline or parallel pipeline realizations.

At the beginning of this work period, an initial compiler had been written for finding the optimum pipelined implementation for a single pipelined processor in which the number of pipelined stages is equal to the processor bound of the graph [1]. Last year, the compiler was extended in three important ways.

First, a new class of parallel processing architectures, called *Clock-Skewed Parallel Processing* (CSPP) systems, was proposed. In these systems, a fixed skew is maintained between the instruction executions of different processors. These new systems have the property that, although they are fully parallel, they require essentially the same compiler as that previously developed for fully pipelined systems [1,2]. CSPP systems have the property that the optimal implementations generated by the compiler often exhibit better performance than the equivalent system without clock skew [2].

Second, a new interprocessor communication scheduling strategy and an associated multiprocessor compiler for the automatic generation of fine-grain DSP algorithms for CSPP systems [3] was developed. This strategy uses a multiple bus approach which takes maximum advantage of the TDM nature of CSPP systems to simplify the communications environment. The result is a relatively inexpensive class of multiprocessors and an associated optimal compiler which directly addresses the communications problem.

Third, the pipeline compiler and the CSPP compiler was combined to form an optimal compiler for parallel-pipelined machines [4]. A basic assumption in this compiler was that all operations had to flush their results before they could be used by another operation. This is a reasonable assumption for many machines, but the theory could not address machines with feedback paths in the pipeline.

This year, work in this area focused on parallel-pipelined machines with feedback paths in the pipelines. A new complete compiler was developed for two particular architectures: arith-

metic processors with feedback paths around the adder; and arithmetic processors with feedback paths around both the adder and the multiplier. These two architectures address the majority of DSP processors which have been proposed and built.

- *Optimal, Communications Inclusive Multiprocessor Compiler for Fully Specified Flow Graphs (FSFGs)*

Much of the previous research in synchronous multiprocessor implementations for DSP algorithms has assumed that all required communications paths would be available at run time. Although this is a valid assumption for many small and medium sized problems, it is not valid for many large problems. For these cases, often the communications scheduling and not the operation scheduling is the dominate constraint. Optimal synchronous multiprocessor compilers which include communications constraints have often been considered computationally untractable because they appear to concatenate two exponentially complex elements: the operations scheduler and the communications scheduler.

As part of this work unit, a new communication exclusive Cyclo-Static Compiler was developed and tested last year. This compiler was used in an extensive study of compiler effectiveness [7] for the class of algorithms that includes all time invariant and adaptive digital filters. The results of this study proved that optimal communications exclusive compilers of this type are completely practical for the class of common DSP algorithms, even though they may exhibit exponential complexity for pathological (and non-occurring) cases.

The current thrust of this area is to see if such practical, optimal compilers can be extended to include communications. The effectiveness of such compilers is based on two principles. First, not all possible graphs need be addressed, but rather only those graphs which represent useful DSP algorithms. Second, architecturally independent bounds can be computed for the graph (iteration period bound, delay bound and processor bound) which can be used to reduce the search space if only optimal solutions are sought. In this research, this concept has been extended to include a new *communications bound*. Like the previous bounds, this bound can be used to significantly reduce the complexity of optimal, communication inclusive compilers.

Thus far, these principles have been used to generate two new compilers. The first of these generates communications optimal multiprocessor schedules for systems based on multiple busses [26]. The second of these generates optimal and near optimal implementations for multirate systems from single rate schedules [27]. The current work, which should be completed next year, will develop and test a general optimal communications inclusive multiprocessor compiler.

- *Effective Multiprocessor Compiler for Systems Based on DSP Chips*

The research project in this area was completed during this year, and resulted in a Ph.D. thesis by B. M. Kim. While single chip DSP processors are approaching a significant level of maturity, they are not well designed to meet the needs of multiprocessing, particularly fine grain multiprocessing. Based on the WE DSP32 floating point DSP chip, a small multiprocessor, the OSCAR-32, has been implemented. The OSCAR-32 has several features that make it difficult to practically apply the (P)SSIMD or cyclo-static scheduling methodology. A practical graph based compiler for the OSCAR-32 and similar systems has now been developed. The compiler extends well known code generation techniques and combines them with extensions to list based

CPM scheduling. The main goal is to determine what the bottlenecks are in the architecture in terms of a realization and in terms of a practical compiler.

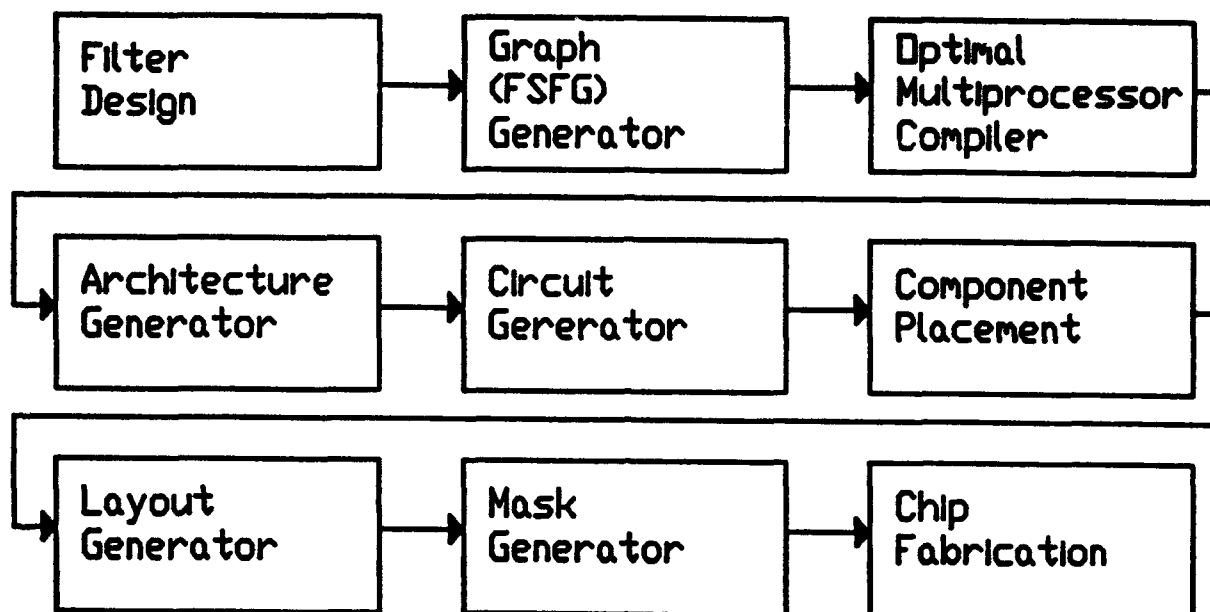
This research work can be divided into three parts. The first was the development of the practical multiprocessor compiler for DSP chips discussed above. This compiler was used to generate code for several current DSP multiprocessors, including the TI TMS320C30, the Motorola DSP96002 and the AT&T DSP32. The second part was the development of a "modification of optimal" compiler also for multiprocessors based on current DSP chips. This compiler will begin with an optimal implementation for an ideal processing element, and will systematically modify the solution so that it will fit the target processor. Finally, the last part was to systematically explore a set of architectural choices with the goal being a practical single chip DSP for fine grain multiprocessing with practical compiler/scheduling tools.

The completed compiler from this work unit has now attained a significant level of maturity [5,6,7]. The compiler can now design for AT&T DSP32, Motorola 56000 and 96000, and the TI TMS320C30 as well as for ideal processors. This can be done in a definable environment with a wide array of limited resources and limited communications architectures. In addition, the compiler can be easily configured to operate on many different multiprocessors.

• *An Optimal Silicon Compiler for Digital Filters Using LAGER*

Over the last decade, design tools for integrated circuits have reached a significant level of maturity. One of the most widely used is the *LAGER* system developed at the University of California at Berkeley. The *LAGER* system is very powerful, and allows the user many ways to approach the integrated circuit design problem. This includes an architectural approach, in which the chip design is performed completely from a circuit diagram using macrocells from a macrocell library. Using this approach, no low level circuit design is required and the process is essentially automatic.

Using the *LAGER* system, we are now in the process of developing a silicon compiler for optimal multiprocessor implementations of digital filters. A block diagram of the total system is shown below.



Like all of our compilers to date, the silicon compiler takes as input a *Fully Specified Flow Graph*. The FSFG is then scheduled using one of the existing optimal multiprocessor compilers from this research unit. The resulting schedule is then analyzed by the architecture generator to determine the exact amount of resources and the exact communications architecture required to support the optimal schedule. The resulting minimum architecture and the multiprocessor schedule is used by the circuit generator to create a complete circuit diagram, including all macrocell invocations and all control circuitry and microcode. This circuit diagram is then used as an input to LAGER, which does the component placement, layout generation, and mask generation for the chip fabrication.

The emphasis in this research is on the combination of the existing tools with a set of new tools to form a complete system. The new tools that have been developed as part of this research are the Architecture Generator and the Circuit Generator. Major components of both have already been developed and tested, and work on the both is continuing. It is expected that this research project will be completed next year.

• *General Design Procedure for Exactly Reconstructing Analysis-Synthesis Systems Based on Filter Banks*

Multirate analysis/synthesis systems based on filter banks are widely used for time-frequency decomposition (analysis) and reconstruction (synthesis) in many applications areas [15]. Adopting the most general view, these *analysis/synthesis* systems can be considered to be a class of generalized time-frequency transforms. The overall performance systems depends on the combination of many different factors associated with the individual filters in the filter banks, the characteristics of the overall filter banks, and the properties of the total analysis/synthesis sys-

tem. The important properties of the individual filters include: the passband sizes and ripples; the stopband sizes and ripples; the transition band sizes and shapes; the phase characteristics; the filter types and sizes (orders); and the filter structures. The important filter bank properties include: the number of frequency bands; the shape (bandwidths) of the frequency bands; the overall frequency coverage; and the overall filter bank efficiency. The important analysis/synthesis system properties include: the channel decimation rates; the reconstruction aliasing distortion; the reconstruction magnitude distortion; the reconstruction phase distortion; and the system delay. The design of effective analysis/synthesis systems for particular applications must address all of these separate properties simultaneously in a single design context.

Recently, FIR analysis/synthesis systems capable of exactly reconstructing the input without aliasing, spectral magnitude distortion or spectral phase distortion have received high visibility in the literature. Research in this area has focused on developing the reconstruction theory, identifying and classifying the various solutions, developing filter design procedures and algorithms, and the realization of efficient structures for implementation. Most of the theoretical developments and design procedures have been based on frequency domain analyses of the systems. In the frequency domain, the aliasing, magnitude and phase distortions can be separately identified and isolated. These distortions can then be minimized or completely eliminated by designing proper analysis and synthesis filters.

This research has adopted an alternative approach in which the analysis/synthesis system is primarily analyzed in the time domain. In this approach, the analysis filtering process is considered to be a linear operator whose output is a set of linear combinations of the present and (some) past input samples. In critically sampled systems, all of the redundant information is explicitly deleted by maximally decimating the outputs of the analysis filters. In the synthesis section, resulting information is used to extract and exactly reconstruct a specific time sample of the input sequence. This perspective leads to a set of necessary and sufficient conditions for exact reconstruction.

This research has developed a new formal description of the problem using a matrix notation, and then used the new, time domain formalism to derive the complete set of necessary and sufficient conditions for exact reconstruction. The power of these conditions derives from the fact that they include no notion of frequency selective filtering at all. They are simply a set of conditions for exact reconstruction based on a set of matrix operations. Thus, by using projection techniques, the time domain conditions can be combined separately with a set of frequency domain constraints using a cost function in an iterative design procedure.

The resulting design methodology is uniquely flexible and powerful. By imposing appropriate constraints, a very broad class of FIR (perfect and near perfect reconstructing) analysis/synthesis systems can be designed. These include filter banks with arbitrary numbers of bands, filter banks with linear phase filters, filter banks with highly efficient implementations, maximally decimated analysis/synthesis systems, exactly reconstructing analysis/synthesis systems, analysis/synthesis systems with minimum overall system delay, and many more. Nonuniform filter banks with different decimation rates in different frequency bands, can also be analyzed and designed under the same basic framework [9,10]. Most importantly, this design methodology provides a context in which many dissimilar system properties (decimation rate, aliasing distortion, filter performance, system delay, filter structure, etc.) can be simultaneously optimized using a single design procedure [9-18].

• *Signal Processing Design in Mathematica*

Our previous work resulted in a significant extension [28] of the *Mathematica*² environment [24], at least for signal processing applications. We have added Fourier transform, z-transform, Laplace transform, and convolution packages to *Mathematica*. In addition, we have been developing a set of *Mathematica* notebooks to encapsulate information about various design methodologies. These notebooks are modules that contain text, graphs and *Mathematica* programs to explain techniques used in designing DSP systems, e.g., filter design. A notebook is an interactive document in the sense that the code can be modified if the user wants to experiment with different parameters. Engineers can use this notebook format to document the basic approach to a design problem [23], as well as any subtle tricks needed to optimize the design.

Our packages and notebooks have been distributed to over 100 researchers in universities and labs around the world. We have devoted time and energy to revising this software and keeping the updates current. This has resulted in a set of packages that are well-tested and well-documented, since they have undergone debugging in many different situations.

Our extensions to *Mathematica* provide many of the common operations needed for the analysis and design of linear systems. Much of this knowledge is based on mathematics that is applicable to one-dimensional systems. For our present and future work, however, an important aspect of these packages is that they were built for multidimensional systems from the start. All of the transform packages can perform multidimensional forward and inverse transforms. In fact, several researchers here at Georgia Tech are using these packages as an analysis tool for different problems related to multidimensional systems.

The multidimensional capability of the *Mathematica* signal processing packages is now the primary focus of our research. To this end, we are developing rule bases for the manipulation of multidimensional filter bank structures. A central part of this development is the implementation of rules covering the operation of multidimensional sampling. The result will be that *Mathematica* can simplify, rewrite, and rearrange algebraic formulas that describe multidimensional filter banks. These rule bases for simplifying and rewriting signal processing structures can be combined with efficient search techniques in order to find optimal implementations of a symbolic signal processing expression. This will be an extension of earlier work [20,22] to multidimensions. Furthermore, since the signal processing packages can already generate C programs, a future phase of this research will focus on generating code for DSP architectures in order to enable fast prototyping and optimal implementation of DSP algorithms.

The proposed environment will provide numerous linear multidimensional operators. Memoryless operators (e.g., adders, modulators, and scalers) extend naturally to higher dimensions. Delays are now specified by a vector containing one delay value per dimension. Other linear shift-invariant operators, like recursive filters, are more difficult to extend because causality is not well-defined in multidimensions [29].

In multidimensions, sampling occurs on a grid of points called a *lattice* [29]. Sampling can be specified by a set of basis vectors which form the columns of the sampling matrix. Only the points in the original grid that are integral combinations of the columns of the downsampling matrix are kept. Downsampling decreases the sampling density by a factor equal to the determinant of this matrix. Once multidimensional data has been discretized, its sampling rate can be changed digitally using filters, upsamplers, and downsamplers. Upsamplers and down-

² *Mathematica* is a trademark of Wolfram Research, Inc.

samplers are specified by integer matrices instead of by integer resampling factors. Likewise, multidimensional rate-changing is defined by a rational matrix instead of a rational sampling rate. In multidimensions, upsamplers and downsamplers resample entire grids of points instead of inserting and deleting samples in a block. For rectangular sampling, the sampling matrix is diagonal and the diagonal elements correspond to the sampling rates in each dimension. When the sampling is not rectangular, e.g. hexagonal, the sampling matrix can be decomposed in terms of a shuffling operation, separable sampling, and another shuffling operation. This structured decomposition is a direct result of factoring the sampling matrix into its Smith-McMillan form [30,31].

Automatic rearrangement of multidimensional multirate structures is an important goal of a design environment. The ability to generate novel implementations of multirate structures depends on having a comprehensive set of rules that describe the mathematics underlying linear multidimensional multirate systems [29,30]. The process of multidimensional sampling or resampling can be decomposed into the cascade of a shuffling operation, separable resampling, and then another shuffling operation. This decomposition is a direct result of factoring the resampling matrix into its Smith form [32,33]. This decoupling leads to many simplification and rearrangement rules for up/downsamplers. The signal processing packages are being extended to implement these concepts [30,31].

The simplification and rearrangement rules for the building blocks of linear multidimensional multirate systems are much more complicated, especially when many non-separable multidimensional operations are involved. System properties extend naturally from one to higher dimensions, although now it is crucial to keep track of the domain of the input signals. Signal properties are much more difficult to extend because a multidimensional signal or its transform may not have rectangular support. It is the shape of the support that generates many of the interesting research questions and many of the new structures in the multidimensional case. Furthermore, properties like symmetry and linear phase are more complicated in multidimensions.

• *Compilers for Fixed-Point DSP Machines*

Over the past year, this thesis work has resulted in the final specification [35] of the *Scaled-Fractional Data Type*. This data type is needed to completely describe fixed-point arithmetic for a compiler. It has been emulated in a C++ class and included in the current release of the GNU C++ standard library `libg++` [36].

A major goal of this research is the development of a compiler for all fixed-point programmable DSP chips (PDSPs). This class of machines presents a different architecture where high-speed numerical units are desired, but low cost or chip area is a factor. Fixed-point arithmetic is simpler in hardware, but it is rather difficult to work with, because overflow and quantization errors necessitate extensive simulation and careful algorithm design. Usually, a fixed-point algorithm has to be programmed in assembly language, instead of a high-level language like C. An effective High-Level Language (HLL) compiler must generate efficient code for fixed-point arithmetic, so that the algorithm will run almost as fast as a hand-coded assembly language version. Other HLLs, such as Ada, do provide (unimplemented) fixed-point language features, but these are not tailored to DSP applications and do not provide a useful data abstraction for the PDSP programmer.

In the scaled fractional data type, a fixed-point number is represented as the product of a

left-justified integral value and a constant scale factor. Including the scale factor is important for algorithms where internal scaling must be optimized via simulation to get acceptable performance. Different types of scaling can be expressed in the same general form. An important aspect of this data type is that it standardizes the methodology used to deal with problems of overflow versus roundoff/truncation, and wordlength versus processing speed. Simulations can be derived automatically from the HLL specification of the fixed-point algorithm.

This scaled-fractional data type has been incorporated into an extended C compiler for the Motorola 56000 PDSP, by extending the GNU C compiler gcc. This implementation is being used to investigate machine code generation issues, especially optimization within the compiler. The structure of the extended GCC compiler is such that it can be retargeted to other PDSPs, while maintaining the same data abstraction. Several papers describing this data type and its use for DSP implementations are in preparation.

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Work Unit Six

TITLE:

Linear and Nonlinear Image Processing

SENIOR PRINCIPAL INVESTIGATOR:

W. T. Rhodes, Professor

SCIENTIFIC PERSONNEL:

David N. Sitter, (Ph.D. Graduate)

Joseph van der Gracht, (Ph.D. Graduate)

SCIENTIFIC OBJECTIVE:

The long-term scientific objective of this research has been to advance understanding and extend state-of-the-art capabilities in real-time nonlinear processing of 2-D images and high-speed linear processing of 3-D images.

RESEARCH ACCOMPLISHMENTS:

The research effort saw the completion of research in two project areas: (1) three-dimensional image processing, and (2) nonlinear image processing using partially coherent optical imaging systems. In addition, invited presentations were made on previously completed work in the areas of (3) nonlinear image processing via threshold decomposition and (4) exploiting coupled magnitude-phase spatial light modulators.

• *Three-Dimensional Image Processing*

The goals of this project, now completed, were (1) to understand better the conditions under which 3-D imaging can be characterized as shift-invariant in three dimensions, (2) to develop coordinate-transformation methods that convert shift-invariant 3-D imaging models to shift-invariant models, and (3) to apply this modeling technique to the restoration of 3-D imagery obtained with a shift-variant 3-D imaging system.

All goals were achieved during previous report periods. During the current report period a doctoral dissertation on the subject was completed [1].

The core of this research, a model for 3-D imaging that allows a shift-variant imaging operation to be viewed in terms of a modified shift-variant system, has been described in an article published in the scientific literature [2]. The practical importance of this publication for the 3-D image restoration research community lies in the observations that (a) almost all 3-D imaging systems must be treated as (often strongly) shift-variant systems, and (b) through the use of appropriate coordinate transformations in the modeling of the systems it is still possible to use FFT-based methods in the restoration operations. Additional work, presented in the above-mentioned doctoral dissertation, has assessed the importance of aberrations in the 3-D shift

variance and shown how, in some cases, they can be accommodated in the shift-invariant model. The basic model was also extended from the realm of incoherent imaging to that of partially coherent imaging.

- *Partially Coherent Image Processing*

Goals of this project, now completed, included (1) development of the theory of partially coherent image "filtering" using complementary source-pupil distributions and (2) the development and demonstration of partially coherent image enhancement operations using the complementary source-pupil image filtering technique.

The theory of partially coherent image processing is complicated by the nonlinear nature of partially coherent imaging. Except in the fully coherent and incoherent limits, where convolution integrals apply, partially coherent imaging cannot be described by simple linear relationships. Nonetheless, significant progress toward the achievement of goal (1) has been made through the application of bilinear transfer function analysis methods. Use of these methods has led to the introduction of design procedures for analyzing the effect of complementary source and pupil-plane masks in imaging operations. With such masks the bias term of the object amplitude transmittance is prevented from reaching the image plane, yielding an enhancement in contrast of the image. Random binary amplitude masks for complementary source-pupil filtering have been developed that provide independent control of the image spatial frequency cutoff and of the width of a low spatial frequency stop band. Work was completed on a useful analytical model that represents, in approximate form, a random-amplitude complementary source-pupil filtering system in terms of a cascade of a coherent darkground imaging system followed by an incoherent imaging system whose optical transfer function is determined by the random pupil function.

Goal (2) was achieved through the development of a new class of partially coherent image processing systems capable of notching out undesired periodic structures present in the input image. Two systems were designed and tested, numerically and on the optical bench. One was a fixed-pupil system capable of notching wave amplitude transmittance sinusoids of arbitrary spatial frequency by source modification. The other was a system capable of blocking more general periodic structures in the input while passing non-periodic image information.

A doctoral dissertation on the work in this project area was completed during the current report period [3].

- *Nonlinear Image Processing via Treshold Decomposition*

The goals of this project, now completed, were (1) to demonstrate the application of parallel optical convolution and thresholding combined with hardlimiting to morphological-transformations-based image processing, and (2) to initiate investigations into the effects of device limitations on the operations.

These two goals were largely achieved during previous report periods and have been documented in a journal publication [4] and in a doctoral dissertation [5]. While on leave from Georgia Tech the principal investigator continued investigations into the inherent noise immunity of the threshold-decomposition/morphological transformations-based image processing scheme. Results of that study indicate that these nonlinear image processing methods can be implemented

in parallel with low-accuracy analog optoelectronic devices in a high-accuracy digital host with no overall loss of accuracy. A preliminary invited presentation on the subject was given at a conference during the report period [6].

- *Exploiting Coupled Magnitude-Phase Spatial Light Modulators*

This project, now completed, was directed toward understanding how spatial light modulators characterized by coupled magnitude and phase transfer characteristics can be used in optical correlator-based pattern recognition systems. Goals of the research included (1) determination of the optimum form of the magnitude-phase coupling for the realization of optical correlator filter transparencies, and (2) further development of the role that filter magnitude plays in determining the performance of an optical correlator. A doctoral dissertation on the subject was published in 1990 [7]. During the current report period, the principal investigator gave an invited conference presentation that reviewed the basic principles and successes of the method [8].

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- [4] James M. Hereford and William T. Rhodes, "Optical Asymmetrical Median Filtering Using Gray-Scale Convolution Kernels," *Optics Letters*, vol. 15, no. 12 (15 June 1990), pp. 697-699.
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- [7] Mary A. Kaura, *Phase-With-Constrained-Magnitude Complex Spatial Filters in Optical Pattern Recognition*, Ph.D. Thesis, Georgia Institute of Technology, June 1990.
- [8] W. T. Rhodes, "Use of nonlinearities in optical correlators," presented at *SPIE Optcon 1991*, San Jose, November 1991, written version to be published in the proceedings of that meeting.

PUBLICATIONS:

Theses

1. David N. Sitter, *Space Invariant Modeling in Three-Dimensional Optical Image Formation*, Ph.D. Thesis, Georgia Institute of Technology, June 1991.
2. Joseph van der Gracht, *Partially Coherent Image Enhancement by Source Modification*, Ph.D. Thesis, Georgia Institute of Technology, June 1991.

Conference Presentations

1. J. van der Gracht, "Noise performance of a partially coherent sinusoid notching system," *1991 Annual Meeting of the Optical Society of America*, Technical Digest, p. 180, San Jose, November 1991.
2. W. T. Rhodes, "Threshold-decomposition optical image processing," *IEEE Lasers and Electro-Optics Society 1991 Annual meeting*, Technical Digest, p. 73, San Jose, November 1991.
3. W. T. Rhodes, "Use of nonlinearities in optical correlators," *SPIE Optcon 1991*, San Jose, November 1991. Written version to appear in the published proceedings of that meeting.

Work Unit Seven

TITLE:

Two-Dimensional Optical Storage and Processing

SENIOR PRINCIPAL INVESTIGATORS:

Thomas K. Gaylord
Elias N. Glytsis

SCIENTIFIC PERSONNEL:

Nile F. Hartman
Timothy J. Drabik
Gregory N. Henderson (Ph.D. Candidate)
Daniel W. Wilson (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The long-term scientific objective of this research is to develop broadly-based, theoretical and experimental knowledge of two-dimensional parallel hybrid optical/electronic information processing including devices, algorithms, architectures, and systems. This would bring together a range of concepts from grating diffraction and microelectronics through number representation and truth-table reduction. Parallel processing systems based on content-addressable memory processing and associative processing would be analyzed starting from basic physical principles and extending through experimental systems demonstration.

• *Antireflection Grating Surfaces on Lossless and Lossy Materials* [1-3]

Rectangular-groove surface-relief gratings on the surfaces of lossless and lossy materials are capable of exhibiting zero reflectivity (antireflection behavior). This can occur in dielectrics (lossless and low loss), semiconductors (lossy), metals (highly lossy), and plasmas (highly lossy) for a given wavelength, angle of incidence, and for either $E \perp K$ (TE) or $H \perp K$ (TM) polarization. In all cases, the grating acts as an impedance matching layer to the incident wave so that there is no reflection in the zero-order backward-diffracted (reflected) wave. If the grating period is suitably small, all diffracted orders other than the zeroth will be evanescent and the grating will then be totally transmitting (lossless material) or totally absorbing (lossy material). These gratings have applications as antireflectors, wave plates, stable color filters, photodetectors, solar cells, polarization-selective mirrors, spatial light modulators, x-ray generators, and other devices.

The design of antireflecting gratings in the small-period limit were described for the case of lossless and lossy materials. A multiplicity of groove depths and filling factors were found for a given set of incident wave conditions and substrate material. Examples for dielectrics and metals were given. Small-period results were verified using the exact rigorous coupled wave

analysis (RCWA). When the period increases to become comparable or larger than the incident wavelength, zero-reflectivity solutions are still possible. In this situation the small-period results can be used as a starting point and then RCWA employed to find zero-reflectivity solutions.

Experimental results for antireflecting gratings on gold surfaces were presented. The addition of dielectric overlayers produces the possibility of the grating being antireflecting for both $E \perp K$ and $H \perp K$ polarizations. Antireflecting gratings have been used for generating x-rays. A plasma is formed by a high-energy laser pulse and the light is mostly absorbed by the plasma (in the shape of a grating) and large picosecond fluxes of x-rays are produced.

- *High Spatial-Frequency Binary and Multilevel Stairstep Gratings: Polarization-Selective Mirrors and Broadband Antireflection Surfaces* [4]

High spatial-frequency surface-relief binary gratings have been shown to have diffraction properties similar to homogeneous layers of equivalent refractive indices which depend on the grating characteristics, angle of incidence, and polarization. Thus, these gratings in the long-wavelength limit could be used as equivalent thin-film coatings. Due to their polarization discrimination these gratings can function like polarization selective-mirrors. A procedure for designing these gratings to be antireflective for one polarization (TE or TM) and to maximize their reflectivity for the orthogonal polarization (TM or TE) was presented. Multilevel stairstep gratings can similarly exhibit characteristics like those of multilayer antireflection coatings (quarter-wave impedance transformers) thus allowing a broader wavelength bandpass. A systematic procedure for designing multilevel stairstep gratings to operate like multilayer thin-film antireflection surfaces was presented. These design methods are valid for both TE and TM polarizations and for any angle of incidence. Example designs were presented and the rigorous coupled-wave diffraction analysis was used to evaluate the performance of these gratings as functions of the ratio of their period to the incident wavelength. Comparisons were included with homogeneous layers that are equivalent to the gratings in the long-wavelength limit.

- *Multilayer Waveguides: Efficient Numerical Analysis of General Structures* [5]

An efficient numerical method was presented for accurately determining the real and/or complex propagation constants of guided modes and leaky waves in general multilayer waveguides. The method is applicable to any lossless and/or lossy (dielectric, semiconductor, metallic) waveguide structure. The method, which is capable of extracting all of the zeros of any analytic function in the complex plane, was applied in the present work to solving the multilayer waveguide dispersion equation derived from the well-known thin-film transfer matrix theory. Excellent agreement was found with seven previously published results and with results from two limiting cases where the propagation constants can be obtained analytically.

- *Phase Stability Measurements of Ferroelectric Liquid Crystal Switches* [6]

The increasing importance of ferroelectric liquid crystal (FLC) devices in a variety of applications makes an understanding of the optical properties of FLC materials essential. In particular, thermal effects associated with switching and environmental conditions need to be understood to assess the potential of FLC devices in optical computing and optical processing and provide

design information. Towards these goals, a displaytech-fabricated transmission device consisting of a surface-stabilized cell filled with a smectic C^* FLC was optically characterized. The cell was designed with a $\delta/(2\Delta n)$ thickness where Δn is the birefringence of the uniaxial FLC. Using a specialized SLM interferometric characterization system, the relative phase birefringence as a function of temperature was determined. Phase shift data as a function of temperature were presented. These results were then compared with optical axis tilt angle data as a function of temperature. The latter data was generated by monitoring optical transmission between crossed polarizers. For comparison purposes, effects due to switching operations were also evaluated using similar techniques and found to be small.

• *Beam Diameter threshold for Photoinduced Polarization Conversion in $\text{LiNbO}_3\text{:Fe}$ [7]*

Photoinduced polarization conversion is a form of "optical damage" in LiNbO_3 waveguide devices. In an attempt to better understand this phenomenon, we have studied the effect in bulk $\text{LiNbO}_3\text{:Fe}$. In this work, we have observed nearly complete ordinary-to-extraordinary polarization conversion in $\text{LiNbO}_3\text{:Fe}$ for input ordinary beam diameters greater than $200\mu\text{m}$ and no polarization conversion for beam diameters less than $60\mu\text{m}$. The extraordinary light was scattered into a wide angular distribution in a plane perpendicular to the optic axis of the crystal. For small beam diameters, there is no scattered light, and no energy is lost from the ordinary beam. However, as the beam diameter is increased, there is steady-state energy transfer out of the ordinary beam into two broad extraordinary peaks. Using the photovoltaic model, we have derived coupled equations that describe the polarization conversion process as a function of scattering angle and beam diameter. This model describes the distribution of the scattered extraordinary light and predicts the beam diameter threshold behavior of the polarization conversion.

• *Light Propagation Characteristics for Arbitrary Wavevector Directions in Biaxial Media by a Simple Coordinate-Free Approach [8]*

The general case of light propagation in lossless anisotropic media occurs in crystals that are biaxial, either naturally so or by induced means (e.g., by electro-optic effect). In these crystals the optical properties, such as the refractive indices, change with propagation direction and are conveniently described by the two-sheeted wavevector surface. Each sheet represents the properties of one of the two allowed orthogonally polarized propagating waves. Most published work treats light propagation only in the principal planes of the crystal, where the wavevector surface reduces to a circle and an ellipse and the mathematics is simplified. Commonly, however, a biaxial bulk or waveguide device, especially an active device, will be oriented so that the light propagation is not in a principal plane. In general, the two allowed propagating waves are "extraordinary-like." Therefore, the ray (Poynting) vector direction for each wave differs from the wavevector direction. Quantifying the optical properties of each wave requires the mathematical separation of the two sheets. A complete and concise coordinate-free approach was presented for isolating each sheet, thereby providing a convenient means for calculating the directional optical properties of the two decoupled waves for arbitrary wavevector directions and birefringence levels. The versatility of this approach coupled with available graphics software was demonstrated by displaying numerous cross sections of the wavevector surfaces.

- *Characteristics of Hybrid Modes in Biaxial Planar Waveguides* [9]

Light propagation in biaxially anisotropic dielectric crystals may be conveniently described by the two-sheeted wavevector surface. Each sheet represents the properties of one of the two allowed orthogonally polarized propagating waves. In general, the two allowed propagating waves are "extraordinary-like" and the Poynting (ray) vector direction for each wave differs from the wavevector direction. Dielectric planar waveguides may be biaxial, either naturally or through the electro-optic effect (as is frequently the case with modulators). The electromagnetic fields in a biaxial waveguide consist of a weighted sum of four "extraordinary-like" plane waves which are coupled and, in general, their individual ray vectors are not in the plane of incidence as they are for uniaxial and isotropic waveguides. Using a complete and concise coordinate-free approach for isolating each sheet of the wavevector surface, the properties of the hybrid guided modes were determined as a function of orientation of the principal dielectric axes. These include the allowed ranges for the propagation constants, propagation constant calculations, and electromagnetic fields for they hybrid modes. Determining the allowed ranges of propagation constants leads to the classification scheme that uniquely identifies each guided mode.

- *Performance Analysis of Givens Rotation Integrated Optical Interdigitated-Electrode Cross-Channel Bragg Diffraction Devices: Extrinsic and Inherent Errors* [10]

The effects of extrinsic and inherent errors were analyzed for the integrated optical Givens rotation device. The extrinsic errors, due to inaccurate voltage applied to the grating and inaccurate detection were found to be important. The inherent errors due to the propagation of these inaccuracies was detailed in algorithms for analog norm computation and in the QR -algorithm for numerical linear algebra. A calibration procedure is developed to eliminate most of the errors.

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PUBLICATIONS:

Journal Papers Published

1. 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.

Journal Papers Submitted or Accepted

1. E. Anemogiannis, E. N. Glytsis, and T. K. Gaylord, "Multilayer waveguides: Efficient numerical analysis of general structures," *Journal of Lightwave Technology*, vol. 10, pp. xxx-xxx, 1992.
2. E. I. Verriest, T. K. Gaylord, and E. N. Glytsis, "Performance analysis of Givens rotation integrated optical interdigitated-electrode cross-channel Bragg diffraction devices: Extrinsic and inherent errors," *Applied Optics*, vol. 31, pp. xxx-xxx, March 10, 1992.
3. E. N. Glytsis and T. K. Gaylord, "High spatial-frequency binary and multilevel stairstep gratings: Polarization-selective mirrors and broadband antireflection surfaces," *Applied Optics*, vol. 26, pp. xxx-xxx, 1992.

Conference Papers

1. T. A. Maldonado and T. K. Gaylord, "Cutoff conditions for hybrid modes in integrated-optical anisotropic (biaxial) waveguides," (Abstract) *Optical Society of America Annual Meeting Technical Digest Series*, vol. 17, pg. 87, November 1991.
2. M. G. Moharam and T. K. Gaylord, "Analysis techniques of diffractive optical elements," (Abstract) *Optical Society of America Annual Meeting Technical Digest Series*, vol. 17, pg. 69, November 1991.
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5. T. K. Gaylord, E. N. Glytsis, N. F. Hartman, M. G. Moharam, M. M. Murnane, H. C. Kapteyn, R. W. Falcone, and W. E. Baird, "Antireflection grating surfaces on lossless and lossy materials," *Mini-Symposium on Micro-Relief Structures in Opto-Electronics*, May 1991.

Patents

1. 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, issued April 16, 1991.

Work Unit Eight

TITLE:

Semiconductor Quantum Wave Devices

SENIOR PRINCIPAL INVESTIGATOR:

T. K. Gaylord, Regents' Professor
K. F. Brennan, Associate Professor
E. N. Glytsis, Assistant Professor

SCIENTIFIC OBJECTIVE:

The long-term scientific objective of this research is to generate the necessary knowledge of nanometer-scale semiconductor quantum wave devices that will allow the practical development and use of these structures. Utilization of these quantum devices would be both for ultra-small high-speed versions of present-day devices and for future guided electron wave integrated circuits. This activity would bring together understanding of the underlying physics, device modeling, development of software tools, device design methodology, evaluation of existing quantum interference experiments, crystal growth, device fabrication, and device testing.

RESEARCH ACCOMPLISHMENTS:

- *Ballistic Electron Transport in Semiconductor Heterostructures and its Analogies in Electromagnetic Propagation in General Dielectrics* [1]

A comprehensive set of analogies was established between electromagnetic propagation in general isotropic dielectrics (differing permeability and permittivity) and electron wave propagation in semiconductors. First, the electromagnetic results for propagation in non-magnetic dielectrics were generalized to describe propagation, reflection, and refraction in general dielectrics through the definition of separate phase and amplitude refractive indices. Through the analogous definition of electron wave phase and amplitude refractive indices, the expressions for electron wave propagation, reflection, and refraction were shown to have the same functional form as the electromagnetic results. Using these results the reflectivity characteristics such as total internal reflection (critical angle) and zero reflectivity (Brewster angle) were analyzed as a function of material parameters for both general dielectrics and semiconductor materials. The critical angle and Brewster angle results were then applied to electron wave propagation in the $\text{Ga}_{1-x}\text{Al}_x\text{As}$ material system, where it is shown that all interfaces in this material will have both a critical angle and a Brewster angle. This was the first prediction of an electron wave Brewster angle in semiconductors.

- *Ballistic Current-Voltage Characteristics of Semiconductor Superlattice Electron-Wave Quantum-Interference Filter/Emitter Negative Differential Resistance Devices* [2]

The transmission and current-voltage characteristics of semiconductor superlattice electron-wave quantum-interference filter/emitter negative differential resistance devices were analyzed with and without the self-consistency requirement. For the non-self-consistent calculation the single-band effective-mass time-independent Schroedinger equation was solved. For the self-consistent calculation, Schroedinger and Poisson equations were solved iteratively until a self-consistent electron potential energy and electron density were obtained. It was shown that suitably designed electron-wave quantum-interference filter/emitters can exhibit strong negative differential resistance in the current-voltage characteristics, similar to those of resonant tunneling diodes. For low to moderate (2-30 meV) Fermi energies in the conduction band of $\text{Ga}_{1-x}\text{Al}_x\text{As}$ (doping concentration less or equal to $2 \times 10^{18} \text{cm}^{-3}$), and temperatures near 30 K (in the ballistic transport regime), it was shown that the space-charge effect is relatively small and results in a shift of the current-voltage and transmission characteristics toward higher bias voltages. In a fashion similar to that occurring in resonant tunneling diodes, the self-consistent field in electron-wave filter/emitter negative differential resistance devices effectively acts to screen the positive applied bias. Designs of $\text{Ga}_{1-x}\text{Al}_x\text{As}$ devices were presented. Resonant devices with current peak-to-valley ratios of 50 as well as nonresonant (not exhibiting negative differential resistance) devices were analyzed. The corresponding electron charge density distributions were also presented. Superlattice electron-wave filter/emitter negative differential resistance devices can be used as high-speed switches and oscillators and as monoenergetic emitters in electroluminescent devices and photodetectors.

- *Quantum Interference Effects in Semiconductors: A Bibliography* [3]

Refinements in growth techniques such as molecular beam epitaxy (MBE) have produced materials with ballistic (collisionless) electron transport lengths of over a micron. Coupled with nanolithography it is now possible to fabricate structures with both lateral and vertical dimensions on the order of the deBroglie wavelength of a ballistic electron. In these structures quantum interference effects can dominate the electronic behavior. In view of the rapidly expanding interest and activity in this area, the following bibliography has been compiled as an introduction and study guide to this field. The papers listed describe the extensive theoretical and experimental results that have been obtained on quantum interference effects as well as discuss possible application areas. Works of a fundamental nature concerning phenomena that are basic to all semiconductor behavior have not been included. Articles on the properties and band structure of semiconductors, which are essential to a complete understanding of quantum interference effects, have not been included. Conference papers, though frequently very important, have not been included to conserve space. The papers are listed alphabetically according to the first author's surname. As in the compilation of any bibliography, numerous valuable and pertinent articles have probably been inadvertently omitted.

- *Electron Waveguiding in Quantum Wells, Voltage-Induced Quantum Wells, and Quantum Barriers* [4,5]

Recent experiments have produced ballistic electron transport over micron lengths in semiconductor two-dimensional electron gas (2DEG) systems. This has made possible the demonstration of electron devices that exhibit impressive optical-like behavior. In these devices, the quantum well at the 2DEG interface acts as a slab waveguide for ballistic electron waves. In this work, we showed how finite-potential heterostructure wells, homostructure voltage-induced wells, and heterostructure barriers can act as electron slab waveguides. We found that the waveguiding in all of these structures is described by a single dispersion relation and can occur at energies above all band edges. The guided mode cutoffs, electron velocity, effective mass, density of states, and ballistic current density were determined. A multiple layer theory was developed to analyze wells and barriers with arbitrary potential energy profiles. The maximum ballistic guided current flowing in a given direction for a 10 monolayer $\text{Ga}_{0.75}\text{Al}_{0.25}\text{As}/\text{GaAs}/-\text{Ga}_{0.9}\text{Al}_{0.1}\text{As}$ waveguide was found to be 2.3 mA per micron of waveguide width. This relatively large value suggests that interconnecting multiple ballistic electron devices through a single slab waveguide may be feasible.

- *Ballistic Electron Diffraction by Semiconductor Gratings: Analysis, Design, and Analogies to Electromagnetic Diffraction* [6-8]

Due to recent advances in the growth and fabrication of nanostructure electronic devices, it has been demonstrated that ballistic electron waves can be reflected, refracted, interfered, waveguided, and diffracted in a manner analogous to electromagnetic optics. This has provided a surge of interest in the new field of semiconductor electron wave optics. In this paper, ballistic electron grating diffraction by a grating with an arbitrary effective mass and/or potential energy profile was analyzed using a rigorous coupled-wave analysis (RCWA). These results are related to electromagnetic diffraction by a permittivity grating. It was shown that electron diffraction by a kinetic energy grating was exactly analogous to TE electromagnetic diffraction and that electron diffraction by an effective mass grating was exactly analogous to TM electromagnetic diffraction. Approximate solutions to the RCWA equations were derived that are equivalent to Bragg regime and Raman-Nath diffraction. Using these results, sample electron wave diffractive switches and multiplexers were designed using achievable device configurations. The angular and energy selectivity of these devices were examined.

- *Testing Multilayer Semiconductor Electron Wave Devices Using Ballistic Electron Emission Microscopy* [9,10]

Ballistic electron emission microscopy (BEEM) has recently been developed to study the electrical properties of buried interfaces where ballistic electrons are injected into a sample using a scanning tunneling microscope (STM). In this paper, a method was proposed that uses the BEEM technique to observe electron wave optical properties of ballistic transport in semiconductors. This method provides a three-terminal configuration for characterizing electron wave devices that overcomes many of the problems encountered in traditional two- and three-terminal techniques. Specifically, the method provides a highly collimated beam of ballistic carriers with a precisely controlled energy distribution. These carriers probe the quantum transmittance of a voltage-tunable electron wave interference device with minimal impurity scattering. A general procedure was presented for analyzing this experimental configuration based on a combination of the models used to describe BEEM and ballistic electron transport in semiconductors.

Using this procedure, a BEEM analysis of an electron wave energy filter was modeled, showing clear electron wave interference effects. This BEEM configuration allows for the precise characterization of a wide range of ballistic electron transport effects, such as quantum reflections from interfaces and electron wave interference effects, that are currently of wide interest.

- *Time-Dependent Characteristics of Semiconductor Resonant Structures* [11]

Double-barrier tunneling structures operate based on quantum mechanical tunneling through two barriers. Quantum electron wave structures operate based on traveling-wave propagation above all conduction band edges. These are the fundamental structures proposed to realize ballistic electron transport devices in semiconductors. The time-dependent behavior of resonant tunneling structures has been discussed extensively in the literature, but no such analysis has been performed on quantum wave structures. A numerical solution of the time-dependent effective mass equation was used to calculate the traversal time of a Gaussian packet and the percentage of the packet transmitted for resonant tunneling and quantum wave structures.

- *Electromagnetic Analogies to General-Hamiltonian Single-Band Effective-Mass Electron Wave Propagation in Semiconductors with Spatially Varying Effective Mass and Potential Energy* [12]

It was shown that exact, quantitative electromagnetic analogies exist for *all* forms of the general Hamiltonian of Morrow and Brownstein [*Phys. Rev. B* **30**, 678 (1984)] which applies to single-band effective-mass electron wave propagation in semiconductors. It was further shown that these analogies are valid for propagation in the bulk, propagation past abrupt interfaces between materials, and propagation within two-dimensionally inhomogeneous materials. These results indicate that the correct form of the single-band effective-mass Hamiltonian can be determined through appropriate wavefunction-amplitude-sensitive experiments. Wavefunction-phase-sensitive experiments (such as the measurement of electron wave refraction directions) are not adequate to specify completely the Hamiltonian.

- *Solid State Quantum Mechanical Electron and Hole Wave Devices (U.S. Patent No. 4,985,737) [13] and Semiconductor Biased Superlattice Tunable Interference Filter/Emitter (U.S. Patent No. 4,987,458) [14]*

Solid state quantum mechanical electron or hole wave devices which are analogous to optical thin-film devices provide among other things, energy selectivity for substantially ballistic electron or hole wave propagation in superlattice structures at energies above the superlattice potential energy barriers. Further, in accordance with the inventive method, the inventive devices may be designed by transforming existing optical thin-film design methods and existing optical interference filter designs into inventive semiconductor devices. This transformation from existing optical design methods and existing optical interference filter designs into semiconductor devices is performed for electron devices by mapping the optical phase index of refraction into a first solid state index of refraction for phase quantities which is proportional to the square root of the product of the electron kinetic energy and the electron effective mass and by mapping the optical amplitude index of refraction into a second solid state index of refraction for amplitude quantities which is proportional to the square root of the electron kinetic energy divided by the electron effective mass.

The present invention pertains to solid state quantum mechanical electron and hole wave devices and method for fabricating them and, in particular, to solid state quantum mechanical electron and hole wave devices such as, without limitation, low pass filters, high pass filters, narrow band and wide band notch filters, narrow band and wide band bandpass filters, impedance transformers, resonant electron and hole emitters, and so forth and methods for fabricating them.

Recent progress in semiconductor growth technologies, particularly in molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD), enable those of ordinary skill in the art to grow multilayered superlattice structures with precise monolayer compositional control. For example, successively grown layers of narrow and wide band gap semiconductor materials such as GaAs and $\text{Ga}_{1-x}\text{Al}_x\text{As}$ have been produced and widely used to provide multiple quantum well structures. In fact, there are many references in the prior art which are concerned with the use of these superlattice structures in resonant tunneling superlattice/multiple quantum well devices. Specifically, in such devices, a superlattice is formed by growing successive layers of narrow and wide band gap semiconductor material epitaxially and the materials and the widths of the layers in these devices are chosen so that quantum states which arise from spatial quantization effects in adjacent wells become coupled. Further, in such devices, the interaction of these coupled states leads to the formation of minibands of allowed energies through which carriers can tunnel.

Most of the above-described resonant tunneling superlattice devices disclosed in the prior art comprise a single quantum well, two barrier structure and such devices are of great interest as high frequency microwave oscillators. Recently, however, resonant tunneling through a multiple layer structure consisting of three wells and four barriers has been demonstrated in the GaAs/GaAlAs material system. Further, these structures have potential use as high energy injectors for electroluminescent devices, photodetectors, and fast ballistic transistors.

In addition to the above, there are prior art references which disclose the use of superlattices to provide miniband and forbidden energy bands at carrier energies above the barrier heights in order to produce negative differential resistance effects or to act as low-transmissivity blocking

contacts.

In further addition to the above, there is presently great interest in the art in providing devices which exhibit high speed orientation. Specifically, a major factor affecting the speed of semiconductor devices is the transit times of electrons from the input to the output terminals. If one can provide electrons which pass through the semiconductor without any scattering events, namely by "ballistic" or "collisionless" motion, then the transit time will be minimized and the potential speed of the devices will be maximized. The possibility of ballistic motion in semiconductor materials has recently been provided by experimental results in GaAs. As such, it is expected that when the length of the region to be traversed is on the same order as the electron mean free path (mfp), a sizable fraction of the electrons will traverse it ballistically. For example, although the mfp in silicon is on the order of 10 nanometers, the mfp for electrons in GaAs is approximately 10 times greater.

In the interest of investigating the efficacy of fabricating such ballistic electron devices, experiments have been described in the prior art in which a GaAs layer is sandwiched between two layers of an alloy of GaAlAs. They report that GaAlAs is a suitable material for use therein because it has the same lattice constant as GaAs and, as a result, it can be grown epitaxially thereon. In addition, further reported experiments have shown that ballistic hole motion also occurs in GaAs, albeit at a lower fraction than that which occurs for electron motion due to the peculiar band structure of the valence band of GaAs.

As a consequence of the recent references available in the prior art, there exists a need for electron and/or hole filter devices, such as low pass, high pass, notch and bandpass filters which can be used to fabricate solid state devices requiring energy selectivity such as electroluminescent devices, photodetectors, ballistic transistors and so forth.

Embodiments of the present invention solve the above-identified need in the art by providing solid state quantum mechanical electron and hole wave devices which can provide, among other things, energy selectivity. In preferred embodiments of the present invention, energy selectivity is provided for substantially ballistic electron wave propagation in superlattices at energies above the superlattice potential barriers. Further, in accordance with the inventive method set forth below, the inventive devices may be designed by transforming existing optical thin-film design methods and existing optical interference filter designs into inventive semiconductor devices.

Specifically, embodiments of the present invention comprise solid state: low pass filters; high pass filters; narrow band and wide band notch filters; narrow band and wide band bandpass filters; impedance transformers which are analogous to optical antireflection coatings; and high reflectance devices which are analogous to mirrors. Further specifically, these inventive solid state devices may be designed in accordance with the inventive method by transforming existing optical thin-film design methods and existing optical interference filter designs into inventive semiconductor devices. This transformation from existing optical design methods and existing optical interference filter designs into semiconductor devices is performed for electron devices by mapping the optical phase index of refraction into a first solid state index of refraction for phase quantities which is proportional to the square root of the product of the electron kinetic energy and the electron effective mass and by mapping the optical amplitude index of refraction into a second solid state index of refraction for amplitude quantities which is proportional to the square root of the electron kinetic energy divided by the electron effective mass. That is, the mapping which makes an exact analogy between the quantum mechanical electron wave and the electromagnetic optical wave comprises using the following electron wavevector:

$$k = [2m^*(E - V)]^{1/2} / \hbar \quad (13)$$

for the optical wavevector and using the following electron wave amplitude refractive index:

$$n_e(\text{amplitude}) = [(E - V)/m^*]^{1/2} \quad (14)$$

in expressions for reflectivity and transmissivity at a boundary, which expressions are well-known to those of ordinary skill in the art from electromagnetic design.

As a result, the use of these mappings between optical quantities and solid state quantities, enables one to use well known optical designs to provide analogous solid state filter devices which have Butterworth, Chebyshev, elliptic function, or other well-known filter characteristics. In addition, the inventive solid state filter devices can be incorporated monolithically into transistor structures in order to increase their speed.

As will be described in the Detailed Description section of the patent, the efficacy of the mapping between the electromagnetic optical waves and quantum mechanical electron waves depends on the utilization of ballistic electron transport in the solid state materials, i.e., the condition where electrons travel through the solid state materials without being scattered by deviations from crystalline perfection. The ballistic electrons have energies above the potential barriers in the solid state materials and exhibit quantum mechanical plane wave behavior. Further, since these plane waves maintain their phase through the device, there coherent waves will refract, reflect, interfere, and diffract in a manner which is analogous to the behavior of electromagnetic waves traveling through dielectrics.

Doping of semiconductors is not important for the embodiments of the present invention, however, it is preferred to exclude doping in order to avoid scattering within the materials. This provides a further advantage for the inventive devices because the absence of doping makes them easier to fabricate.

Present developments in the field of providing solid state materials, such as, for example, materials grown by MBE and/or by MOCVD have produced improved products which provide for substantially ballistic electron transport. Thus, the use of multilayer superlattices comprised of materials which substantially support ballistic electron transport are used to form embodiments of the present invention in which electrons are injected into superlattice structures at energies above the corresponding potential energy barriers to provide electron interference effects which are exactly analogous to those which occur in electromagnetic wave propagation in dielectric films. As a result, the quantitative mapping between quantum mechanical electron wave propagation in semiconductors and electromagnetic optical wave propagation in dielectrics can be used to translate thin-film optical device designs into semiconductor superlattice designs.

Although we have discovered that electron wave propagation at energies above the potential barriers can be mathematically described by a mapping between quantum mechanical electron waves in semiconductors and electromagnetic optical waves in dielectrics, semiconductor superlattice interference filter designs, for example, cannot merely be copies of thin-film optical filter designs. This is because, although optical designs which may be realized in nature are constrained by the available material indices of refraction, the design of the analogous semiconductor devices such as superlattice interference filters will be constrained by the fact that the thicknesses of layers in the superlattices are restricted to be integer multiples of monolayer thicknesses and by the fact that the requirement of substantially collisionless transport for the

carriers limits the usable composition ranges of the materials. This occurs because the requirement of collisionless transport often precludes using material compositions which have indirect band gaps. Nevertheless, as should be clear to those of ordinary skill in the art, one may use a trial and error method of determining which designs are physically realizable. However, in a preferred embodiment of the inventive method, which is described in the Detailed Description section of the patent, comprises a systematic method for determining superlattice designs which meet the appropriate physical constraints.

First embodiments of the inventive solid state electron wave devices comprise solid state analogs of Fabry-Perot optical interference filters which are fabricated from alloys of GaAlAs and GaAs.

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Work Unit Nine

TITLE:

Electromagnetic Measurements in the Time and Frequency Domains

SENIOR PRINCIPAL INVESTIGATOR:

G.S. Smith, Regents' Professor

SCIENTIFIC PERSONNEL:

J. Bourgeois, Graduate Research Assistant (Ph.D. Candidate)

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SCIENTIFIC OBJECTIVE:

Electromagnetic measurements play an important role in the advancement of electromagnetic technology. Measurements are used to verify new theoretical results and, ultimately, to test all new devices and systems. New measurement techniques are needed to support the current interest in miniaturization (integrated circuits), increases in operating frequency and bandwidth (millimeter waves), and the introduction of new materials.

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 techniques.

RESEARCH ACCOMPLISHMENTS:

• *Pulse Excited Antennas*

Radars that use base-band pulses, such as ground penetrating radars, require antennas that can radiate and receive temporally short, wide bandwidth pulses. These antennas have traditionally been analyzed using approximate methods, such as transmission line models or assumed current and aperture distributions. The antennas are generally electrically large (many wavelengths long) at the highest frequencies contained in the pulse. Thus, conventional frequency-domain numerical techniques, such as the method of moments, coupled with a fast Fourier transform are not efficient for analyzing these antennas.

The finite-difference time-domain method (FD-TD) is a numerical procedure used to solve Maxwell's equations directly in the time domain. While this technique has been used for several years, only recently has it become practical for solving three-dimensional structures due to the increases in the speed and storage of digital computers.

This technique (FD-TD) is being used to study antennas for radiating wide bandwidth pulses. The objectives are to obtain a better understanding of how pulses are radiated from such structures and to apply this knowledge to improve the performance of these antennas (lower internal reflections, reduce dispersion in the radiated pulse, etc.). All theoretical predictions will be verified with accurate experimental measurements.

As a beginning a few simple antennas were investigated – the cylindrical monopole and the conical monopole. These are rotationally symmetric antennas and therefore require only a two-dimensional analysis. Theoretical models formulated for these antennas are very good representations of the experimental models used for laboratory measurements. The FD-TD method was used to determine the response of these antennas to a Gaussian pulse, and the results were compared with experimental measurements to determine the accuracy of the FD-TD method. In all cases tested, the theoretical and experimental results were in excellent agreement, giving confidence in the methods used for modeling these antennas and the application of the FD-TD approach [1].

Antennas used to radiate pulses often contain resistive elements, which tend to reduce reflections (ringing) within the structure. Thus, for accurate modeling of these antenna, an efficient method is needed for incorporating resistive materials into the FD-TD method.

In practical applications, components constructed from resistive materials often have dimensions that are small compared to the penetration depth (skin depth) in the material. When the penetration depths are also small compared to the free space wavelengths involved, it is impractical to use a grid of uniform spatial increment in both the resistive material and free space. In this instance, an efficient computation can be obtained by replacing the resistive material by a surface impedance boundary condition (SBIC) and setting the spatial increment according to the free space wavelength. An efficient algorithm has been developed for implementing the SIBC in the FD-TD method, and this has been reported in the literature [2].

Another limiting case can occur when resistive materials are used in practical applications: the resistive material is a thin sheet whose thickness is small compared to the penetration depth (skin depth). In this case it is impractical to use a grid of uniform spatial increment, whose size is less than or equal to the sheet's thickness, in both the resistive material and in free space. An efficient algorithm has been developed for incorporating thin material sheets (both resistive and dielectric) in the FD-TD method. The spatial increment is set by the free space wavelength, not by the thickness of the sheet. For the purpose of verification, this algorithm was used in the FD-TD analysis of problems that have exact solutions. In all cases the FD-TD results were in good agreement with the exact results. An experimental verification of the algorithm was also accomplished: a monopole antenna was constructed from a thin resistive tube and the reflected signal at the terminals of the antenna compared with measurement [3],[4].

The new algorithms described above are now being used to study the role of resistance in designing broadband, pulse-distortionless antennas. Initial investigations involved a simple open-ended parallel plate waveguide with resistive walls over a portion of its length.

The resistance of the walls was varied with position so as to optimize the performance of the antenna for pulse radiation [5],[6]. A conical radiator formed from a thin resistive sheet whose resistance varies with position is now under investigation. The FD-TD method together with computer generated graphical displays of the near field are being used to optimize this antenna for pulse radiation. Model antennas are being fabricated, and measurements made with these antennas will be used to verify the theory [7].

• *Millimeter Wave Substrate Mounted Antennas*

In some microwave and millimeter-wave systems, the simplicity of the design and the economy of the production can be greatly enhanced by constructing antennas on the same substrate as the integrated circuitry. An example at microwave frequencies is the microstrip patch antenna. As the frequency is increased, however, guided modes in the substrate start to make the microstrip patch antenna less efficient. Quasi-optical devices, such as a spherical lens on the backside of the substrate, can be used to overcome this difficulty. In the millimeter-wave region, such quasi-optical devices are practical because they do not consume an unreasonable amount of space on the integrated circuit substrate, even though these devices are large compared to a wavelength.

The initial investigations in this program were for strip-dipole antennas mounted on substrates of finite thickness. Measurements were made on these structures at the frequency 230 GHz ($\delta_o = 1.33\text{mm}$) for comparison with the results from simple theories. The good agreement obtained gave confidence in both the measurement techniques and the theoretical arguments [8],[9].

A new type of millimeter-wave integrated-circuit antenna was developed [10]-[12]. The antenna is based on a quasi-optical design, with a Fresnel zone plate on one side of a dielectric substrate and a resonant strip dipole antenna at the focus of the zone plate on the opposite side of the substrate. The unique feature of this design is that all of the components are made using simple IC fabrication techniques: simple metal depositions on dielectric layers. Another unique feature of this design is the short focal length of the zone plate; the f/d of the zone plate ranges from 0.1 to 0.5.

A simple theoretical model was developed for this antenna based on the physical optics approximation. Several antennas were fabricated and measured at the frequency 230 GHz for comparison with the theory. Good agreement was obtained.

• *Circular Half-Loop with Coaxial Feed*

The thin-wire circular-loop antenna is one of the basic radiating structures. An analysis for this antenna in free space, based on a Fourier series for the current, has been available for a number of years. The Fourier series analysis has been extended to cover bare and insulated loops in dissipative media, ferrite loaded loops, etc.

The conventional Fourier series analysis for the transmitting loop, or its image equivalent the half loop, uses a Dirac delta-function generator for excitation. This method of excitation introduces two problems: it does not correspond to any realizable method of feeding the antenna so an accurate comparison with measurement is not possible, and it produces a divergent series for the input susceptance. To overcome these problems, a new theoretical model has been developed for this antenna: a half loop driven through an image plane by a coaxial transmission line, with a TEM mode assumed in the aperture of the coaxial line. This model is solved in a manner that preserves the simplicity of the original Fourier series analysis; all coefficients are obtained as closed form expressions. Input admittances calculated from this new theoretical model are in excellent agreement with accurate measurements [13].

The new model has been applied to multiturn half-loop arrays [14]. These antennas consist of several parallel half loops mounted on an image plane, with the individual antennas inter-

connected by coaxial lines under the image plane. The size and spacing of the loops and the lengths of the coaxial lines are adjusted to obtain the desired radiation pattern. Such antennas are applicable on structures with metal surfaces such as airplanes, ships and land vehicles. The radiation patterns predicted by the theory are in good agreement with measurements.

- *Electrical Properties of Materials*

Knowledge of the electrical properties of materials over a wide bandwidth of frequencies is necessary when designing systems that utilize signals that are narrow pulses. One such system is the ground penetrating radar, where a knowledge of the electrical properties of soil are required. The electrical properties of soil are dependent upon several factors: type of soil, moisture content, salinity of water, etc.

In this study the electrical parameters (permittivity and conductivity) of a particular soil, "Georgia red clay," were measured as a function of frequency (50 MHz to 1.25 GHz) and water content ($\approx 0\%$ to 30% by dry weight) [15]. These measurements made use of an open-circuited coaxial line sample cell previously developed on this program [16].

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Work Unit Ten

TITLE:

Automated Radiation Measurements for Near- and Far-Field Transformations

SENIOR PRINCIPAL INVESTIGATOR:

Edward B. Joy, Professor

SCIENTIFIC PERSONNEL:

Donald N. Black, (Ph.D. Candidate)

Michael G. Guler, (Ph.D. 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 the determination of the limits of accuracy in the measurements for known geometrical or electromagnetic anomalies.

Three application areas are pursued: a) antenna measurements, where the effects of scatterers are suppressed or compensated, b) scattering measurements, where the effects of scatterers are enhanced, and c) radome measurements, where the effects of the scatterer (the radome) are of equal importance to the antenna measurement.

RESEARCH ACCOMPLISHMENTS:

Three developments are worthy of mention. Detailed descriptions of these research results are contained in the four references published during this contract. Also several unusual citations of the flower petal edged reflector developed under JSEP sponsorship are listed. Several theories and resulting measurement techniques have been transferred to the DoD and DoD related industries. There are summarized below:

• *Spherical Microwave Holography Demonstrated*

Significant progress has been made toward the development of the theory and associated technique of spherical back transformation of spherical surface near field antenna measurements. The tangential components of the electromagnetic field on the surface of a sphere enclosing an antenna or antenna/radome combination are measured. The measured fields are expanded in a finite set of spherical modes and the interaction between the spherical surface field and the range antenna is carried out using the spherical mode expansion of the range antenna fields. This system of spherical mode coupling equations are solved for the spherical mode set for the antenna under test.

The spherical back transformation involves evaluating each of the spherical nodes on surfaces between the antenna under test and the near field measurement sphere. This surface can include

surfaces just outside the antenna under test. The high order spherical modes become evanescent as the radius of evaluation becomes small. This research is attempting to understand this evanescent behavior in light of the limited dynamic range of field measurement receivers.

Spherical microwave holography measurements were performed for a radome with various sizes of additional dielectric material placed on the radome surface. The increased insertion phase for the thicknesses of materials used ranged from 10 degrees to 90 degrees. The location, size, shape and thickness of these materials was accurately determined to a surface resolution of approximately one half wavelength and to a phase accuracy of approximately two degrees. One measurement was made of dielectric tape, one half wavelength wide, in the shape of the capital letters GT taped to the radome. The letters were clearly visible in a phase comparison diagram, where the phase of the surface fields are compared with and without tape.

The ability to accurately determine antenna and radome surface fields should allow the manufacture of higher accuracy antennas and radomes. Manufactured antennas and radomes would be measured and surface fields determined. Errors in the surface fields show where and by how much the antenna and/or radome needs to be adjusted. Based on current manufacturing techniques for radomes, a ten-fold increase in radome performance can be easily attained using this technique.

• *Spherical Surface Range Evaluation Demonstrated*

Several techniques are currently used for evaluating the quality of far-field, anechoic chamber and compact antenna and radar cross-section measurement ranges. The most accurate techniques require linear or planar scanners to measure the range field in the test zone region. A technique has been developed and demonstrated to measure range test zone fields using the range, spherical positioners. A range probe antenna is mounted on a boom with length equal to the radius of the test zone volume. The range spherical positioners are used to probe the range field over the surface of the test zone spherical volume. The measured field is decomposed into spherical modes and used to construct a plane wave representation of the test zone field to determine the quality of the range under test.

This technique was demonstrated by the measurement of the test zone field over a 14 wavelength diameter sphere of the School of Electrical Engineering Anechoic Chamber at a frequency of 11.75 GHz. The plane wave spectral display of this field showed the reflectivity level of the chamber as a function of angle as viewed from the test zone. This measurement technique can be used to identify the angular location and strength of range reflections and leakage. This technique reduces antenna measurement range testing time by several orders of magnitude, while providing several orders of magnitude more information about the range.

• *New Reflector Antenna Configuration*

Research is currently underway and promising results have been presented on a new type of reflector antenna. Through the use of "flower petal" shaped edge serrations any type of reflector antenna's (paraboloidal, corner, flat plate, shaped, spherical, etc.) performance can be improved. Specifically, sidelobe levels can be reduced while retaining gain. The edge serrations give the reflector antenna designer an additional degree of freedom. This work is an outgrowth of the new type of edge treatment for compact range reflectors that was implemented at the U.S.

Army Fort Huachuca Electronic Proving Ground. One paraboloidal reflector antenna, using the flower petal shaped edge serrations, has been designed, constructed, and tested. It is thought that this antenna type will find applications in radar antennas, satellite antennas, compact range antennas and point-to-point communications antennas.

TECHNOLOGY TRANSFER:

1. In process of transferring spherical backward transform to Texas Instruments, McKinney, Texas.
 2. In process of transferring several JSEP techniques to U.S. Navy, NWSCC, Crane, Indiana, proposed planar near-field antenna measurement facility.
 3. Jet Propulsion Laboratory, Pasadena, CA, is incorporating several JSEP Techniques in the design and construction of a new cylindrical near-field range.
 4. See unusual citations concerning the new JSEP developed reflector antenna.
- *Unusual Citations of "Flower Petal" Edged Reflector Invention*
1. *Defense News*, November 4, 1991, "Sunflower Inspires Radar Dish," article.
 2. *Business Week Magazine*, November 11, 1991, "Better-Looking Radar Dishes May Work Better, Too," article and drawing.
 3. *Associated Press*, Nationwide, November 28, 1991, "Prof Puts Petal to the Metal," article and photo.
 4. *Design News*, December 1, 1991, "Flower Petal Edge Enhances Satellite Dishes," article.
 5. *Chicago Tribune*, December 1, 1991, "Better Satellite Dishes Have Flowery Edge," article and photo.
 6. *National Public Radio*, December 5, 1991, Fort Huachuca, Flower Petal Edge Reflector Compact Range.
 7. *CNN Headline News*, December 5, 1991, Fort Huachuca, Flower Petal Edge Reflector Compact Range.
 8. *Wall Street Journal*, December 16, 1991, "Cutting Edge Sharpens Antenna Performance," article and photo.
 9. *Johnny Carson Monologue*, December 19, 1991, "An electrical engineer in Atlanta, Georgia says that you can improve the performance of your satellite dish by shaping the edge of it like the petals of a flower. The problem is that your dish is then attacked by these enormous bees."
 10. *New York Times*, January 19, 1992, "Dish with a Difference," article and photo.
 11. *Poetry of Facts*, vol. 7, Arno Reinfrank, to be published in 1993, "Radar-Blumen," a poem in German about a flower-like radar antenna.

PUBLICATIONS:

Conference Proceedings

1. Michael G. Guler, Edward B. Joy, Chester F. Boncek, Donald N. Black, and Richard E. Wilson, "Measurement and Calculation of Fields on the Outer Surface of Radomes," *Proceedings of the 4th DoD Electromagnetic Windows Symposium*, Monterey, CA, November 19-21, 1991, pp. 130-137.
2. R. E. Wilson, D. N. Black, E. B. Joy, M. G. Guler, and G. Eder, "Spherical Probing Demonstrated on a Far-Field Range," *Proceedings of the 1991 Antenna Measurement Techniques Association*, Boulder, CO, October 7-11, 1991, pp. 10A, 15-21.
3. D. N. Black, E. B. Joy, M. G. Guler, and R. E. Wilson, "Range Field Compensation," *Proceedings of the 1991 Antenna Measurement Techniques Association*, Boulder, CO, October 7-11, 1991, pp. 3B, 19-24.
4. Michael G. Guler, Edward B. Joy, Donald N. Black, and Richard E. Wilson, "Resolution in Spherical Near-Field Microwave Holography," *Proceedings of the 1991 Antenna Measurement Techniques Association*, Boulder, CO, October 7-11, 1991, pp. 5, 9-15.