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# MATHEMATICAL SCIENCES DIVISION

## 1992 Programs



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OFFICE OF NAVAL RESEARCH  
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ARLINGTON, VA 22217-5660

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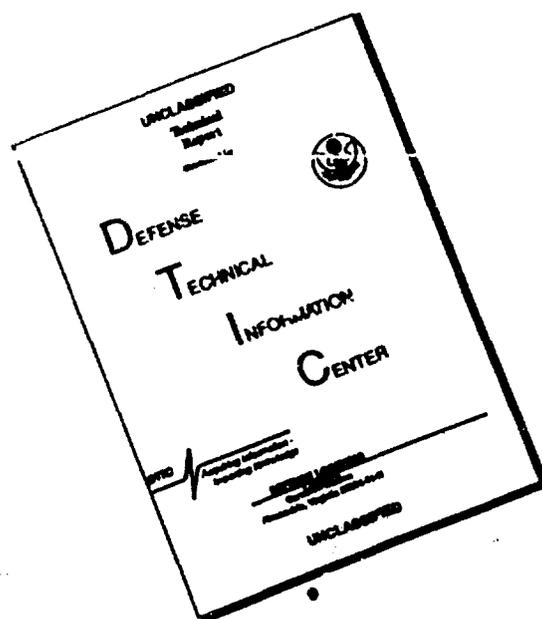
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# **MATHEMATICAL SCIENCES DIVISION**

## **1992 Programs**



**OFFICE OF NAVAL RESEARCH  
800 NORTH QUINCY STREET  
ARLINGTON, VA 22217-5660**

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FOREWORD

This book describes research projects carried out under sponsorship of the Mathematical Sciences Division of the Office of Naval Research (ONR) during fiscal year 1992. The Division's research is organized in six programs:

- Applied Analysis
- Discrete Mathematics
- Numerical Analysis
- Operations Research
- Probability and Statistics
- Signal Analysis

These programs are described in the Introduction. The individual research projects supported by each are described in the chapters that follow.

This book is but one of several means by which we communicate our interests to the scientific community. If you wish further information, please do not hesitate to contact us; our names and phone numbers are listed in the Introduction. We welcome your interest in our programs.

Neil L. Gerr  
Director  
Mathematical Sciences Division

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CONTENTS

FOREWORD . . . . .	i
INTRODUCTION . . . . .	iii
APPLIED ANALYSIS . . . . .	1
DISCRETE MATHEMATICS . . . . .	33
NUMERICAL ANALYSIS . . . . .	69
OPERATIONS RESEARCH . . . . .	97
PROBABILITY AND STATISTICS . . . . .	123
SIGNAL ANALYSIS . . . . .	165
DIVISION PROJECTS . . . . .	201
INDEX . . . . .	209

## INTRODUCTION

The Mathematical Sciences Division supports basic research that is carried out under grants and contracts that are awarded on a competitive basis. Proposals received in response to the ONR Broad Agency Announcement published in the Commerce Business Daily are evaluated according to the following criteria:

1. Scientific Merit.
2. Navy Relevance.
3. Potential for success.
4. Cost.

In general, proposals are evaluated in-house by the appropriate Scientific Officer. All of the Division Scientific Officers have Ph.D.s and are well versed in current Navy needs.

As noted in the Foreword, the Mathematical Sciences Division is organized in six programs. These are described below and the responsible Scientific Officer is indicated. Dr. Neil L. Gerr is the Director of the Mathematical Sciences Division. Dr. Bobby R. Junker is the Director of the Mathematical and Physical Sciences Directorate, of which the Mathematical Sciences Division is a part.

### I. Applied Analysis

Scientific Officer: Dr. Reza Malek-Madani (Acting)  
(703) 696-4314

The program develops and exploits methods in modern and classical mathematical analysis, with emphasis on mathematical models of physical phenomena. Naval interest in waves and flows motivates research in convection-diffusion, with emphasis in the areas of shock capturing, inertial manifolds, vortex-free surface interaction, and control of fluids. Acoustics, electromagnetics, modeling the ocean bottom and the ocean medium, and nondestructive evaluation motivate research in inverse scattering and mathematical inverse theory.

### II. Discrete Mathematics

Scientific Officer: Dr. Marc J. Lipman  
(703) 696-4310

The goal is to develop areas of discrete mathematics which have application to engineering and information sciences. This includes specific structural parameters and invariants for combinatorial configurations such as graphs, networks, sequences, and partially ordered sets. The use of discrete structures for modeling, consensus formation, and classification is of particular interest.

### III. Numerical Analysis

Scientific Officer: Dr. Richard L. Lau  
(703) 696-4316

Research is conducted on the numerical solution of partial differential equations. Areas of particular interest at present include the problems of engineering design, acoustic propagation, geophysical fluid mechanics, and electromagnetic scattering. Emphasis is placed on methods to estimate, control, and reduce computational error, and on the analysis of error induced by mathematical approximations, such as dimensional reduction, and by data errors.

### IV. Operations Research

Scientific Officer: Dr. Donald K. Wagner  
(703) 696-4313

The program focuses on mathematical programming and its application to problems in the areas of logistics, resource allocation, production, and command and control. This includes research in linear, nonlinear, integer and combinatorial optimization, and in sequencing and scheduling. Theoretical development, algorithm design and analysis, computational techniques for large-scale problems, and innovative and relevant applications are all of interest. Interior-point methods and related algebraic and geometric concepts are an area of particular emphasis.

### V. Probability and Statistics

Scientific Officer: Dr. Julia Abrahams  
(703) 696-4320

The focus is on probabilistic analysis and statistical inference for random fields and spatial processes which model the temporal and spatial evolution of physical phenomena, with particular emphasis on oceanographic applications. Stochastic geometry and geometric probability in conjunction with image analysis and the modeling of shape are of interest. Several efforts developing stochastic models for the neural sciences are also supported.

### VI. Signal Analysis

Scientific Officer: Dr. Neil L. Gerr (Acting)  
(703) 696-4321

This program aims to develop the mathematical and statistical theory that underlies modern signal analysis. There is a strong emphasis on stochastic processes and time series, particularly those which provide realistic models for random signals and noise, and their characterization in the spectral domain. A primary goal is to develop new techniques for detecting and classifying broadband and transient acoustic signals received in noise.

**Applied Analysis**

**TITLE:** Fast Algorithms for Three-Dimensional Inverse Scattering Problems

**PI:** Andrew E. Yagle  
University of Michigan  
Department of EECS  
(313) 763-9810

**FUNDING AGENCY:** University Research Initiative

**R&T PROJECT CODE:** 400x068yip03

**CONTRACT NO:** N0001490J1897

**CURRENT END DATE:** 31 AUG 1993

**SCIENTIFIC OFFICER:** Reza Malek-Madani

**Technical Objective:**

Layer-stripping algorithms that reconstruct the scattering potential at a wavefront in a three-dimensional medium and use the information obtained to recursively propagate the wavefield further into the medium will be developed. The algorithms to be developed will be fast on serial computers and will be parallelizable.

**Approach:**

The scattering problems will be expressed by the Schroedinger wave equation with time-invariant potential and by acoustic wave equations with variable velocity and density. Three-dimensional one-dimensional layer-stripping algorithms developed by the proposer and others. Computations will be carried out to verify the theoretical results.

**Progress:**

Recent work addressed the problem of inverting spherical means, the goal being to recover a function from its averages over all spheres passing through the origin. Geometric inversion was used to transform the problem into an inverse Radon transform problem. By reflecting functions about the sphere marking the outer limit of known data, averages over spheres are transformed into averages over planes. In addition, it was shown that measurements at a single sensor are sufficient to reconstruct the scattering potential in either the Born or Rytov approximations provided either 1) wideband data are available, or 2) the average value of the potential is known.

TITLE: Acoustics, Waves and Flows

PI: Joseph B. Keller  
Leland Stanford Junior University  
Department of Mathematics  
(415) 723-0851

FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112549---07

CONTRACT NO: N0001491J1121

CURRENT END DATE: 30 SEP 1993

SCIENTIFIC OFFICER: Reza Malek-Madani

Technical Objective:

The first objective is to treat the two-dimensional case of an infinitely long straight vortex parallel to the surface and obtain a complete description of the motion of the surface and the vortex. Extension will then be made to the three-dimensional linear case and the two-dimensional nonlinear case. Finally, the three-dimensional nonlinear case will be addressed. Both short and long-time solutions will be derived.

Approach:

The surface will be represented by a Green's function integral or some equivalent expression. To evaluate the integral, asymptotic methods will be used. Nonlinearity will be taken care of by perturbation expansions and numerical methods. These methods depend on the use of complex variables and identification of all of the singularities of the flow. A hybrid Galerkin-perturbation method, an adaption of the perturbation-expansion method that is expected to be more powerful for the cases under consideration, will also be used.

Progress:

Simplified equations governing the potential flow and shape of slender jets and thin sheets of liquid were derived, taking account of surface tension. Families of similarity solutions of these equations were introduced. For jets and symmetrical sheets they satisfy ordinary differential equations. The properties of these similarity solutions were examined analytically and numerically. They can be used to describe the motion of a liquid sheet on a solid, the thickening and flow following the breaking of jets, and the merging of two jets.

**TITLE:** Inverse and Optimization Problems for Low Frequency  
Data and Low Frequency Electromagnetic Inverse Problems

**PI:** Joyce R. McLaughlin and Margaret Cheney  
Rensselaer Polytechnic Institute  
Department of Mathematical Sciences  
(518) 276-6349

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4112621---08

**CONTRACT NO:** N0001491J1166

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Reza Malek-Madani

**Technical Objective:**

The wave speed in a medium of finite extent will be determined from the interior eigenvalues and scattered field data at frequencies that are not eigenvalues. The information content of each eigenvalue will be determined and stability of the algorithm will be shown. Under the expansion task, improved techniques for electromagnetic inverse problems will be developed.

**Approach:**

The theory of Riesz bases and non-self-adjoint operators will be used. Algorithms will be based on spectral methods. Research on determining wave speed will be carried out first for the spherically symmetric problem and then for fully multi-dimensional problems. For electromagnetic inversion, multidimensional layer-stripping methods will be developed.

**Progress:**

A connection between inverse scattering and inverse spectral theory was established in the context of spherically symmetric three dimensional inverse acoustic scattering. It was shown that averages of the scattering amplitude determine the eigenvalues for an eigenvalue problem. Using techniques of inverse eigenvalue problems, a uniqueness theorem to determine the sound speed was obtained. New properties of this nonlinear inverse problem are 1) the "size" of inhomogeneities in the sound speed can be determined by the largest eigenvalues, 2) the sound speed is uniquely determined by the eigenvalues if the "size" is small, and 3) no linear approximation is required.

**Title:** Energy Stability and Bifurcations in  
Langmuir Circulation

**PI:** Isom H. Herron  
Howard University  
Mathematics Department  
(202) 806-6830

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4112632---06

**CONTRACT NO:** N0001490J1290

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Reza Malek-Madani

**Technical Objective:**

The work aims to develop for flows on unbounded domains the relationship between spectral theory on one hand and weakly nonlinear stability and bifurcation theory on the other. Flows in boundary layers, jets and shear layers will be addressed. The effect of curvature on the nonlinear stability of various flows will be derived. Incompressible flows in two and three dimensions will be considered.

**Approach:**

Weighted inner-product spaces and computational experiments will be used to establish the relationship between spectral theory and nonlinear stability theory and bifurcation theory. Nonlinear stability of flows with curvature will be investigated by the method of energy, which has proven to be effective in explaining Taylor-Couette flow between rotating cylinders.

**Progress:**

The linearized equations for the evolution of disturbances to four wall bounded flows were treated. The flows are plane Couette flow and plane Poiseuille flow, Hagen-Poiseuille pipe flow, and the asymptotic suction profile. By looking at the vorticity it was proved that plane Couette and Hagen-Poiseuille flow are linearly stable.

**Title:** Mathematical Analysis of Strong Fluid  
Mechanical Effects in Turbulence and  
Detonation Physics

**PI:** Andrew J. Majda  
Princeton University  
Department of Mathematics  
(609) 258-5114

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4112633---07

**CONTRACT NO:** N0001489J1044

**CURRENT END DATE:** 30 SEP 1994

**SCIENTIFIC OFFICER:** Reza Malek-Madani

**Technical Objective:**

Fully developed turbulence involves velocity fields which have a continuous range of excited space and time scales. These induce substantial additional dissipation at high Reynolds numbers due to the development of energetic small scales. A primary goal here is to assess the effect of the motion at arbitrarily small length scales on the large length scales without resolving the small scales in detail.

**Approach:**

Classes of model problems that retain some of the subtle features of turbulent transport and for which renormalization theory can be solved with mathematical rigor will be developed for turbulent advection-diffusion. These will provide an unambiguous check on the variety of ad hoc methods for renormalizing turbulent transport. In addition, behaviors observed for various regimes of velocity statistics will suggest improved theories for eddy diffusivity in more general contexts.

**Progress:**

Developed a rigorous renormalization theory for a model problem of advection-diffusion of a passive scalar by an incompressible velocity field. In particular, explicit formulas for the renormalized anomalous time scaling as well as both the explicit Green's function for the eddy diffusivity equation and higher order statistics were derived.

**Title:** Wave Propagation and Inverse Problems in  
Heterogeneous Elastic and Anelastic  
Layered Media

**PI:** William W. Symes  
Rice University  
Department of Mathematical Sciences  
(713) 527-4805

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4112634---06

**CONTRACT NO:** N0001489J1115

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Reza Malek-Madani

**Technical Objective:**

The resolution of wave velocity from reflected waves, and its dependence on model completeness, will be quantified in the context of layered acoustic and elastic media. The resolution of the parameters of viscoelastic and poroelastic layered solids from pre- and post-critical reflected wave data will be quantified under realistic assumptions for interwell and shallow seismology and seabed sounding.

**Approach:**

Perturbation theory, high-frequency asymptotics, and energy estimates will be used to determine the sensitivity of reflection data to small perturbations in various classes of model parameters.

**Progress:**

A new formulation was introduced for the velocity inversion problem via reparameterization by travel-time. The new formulation requires the solution of a large scale optimization problem. The inversion is regularized (the optimization made non-pathological) by incorporating a penalty term that enforces the appropriate mathematical constraint. Initial results applying the approach to the problem of plane wave reconstruction are very encouraging.

Title: Rotational Inviscid Flows with Free Boundaries

PI: J. R. Ockendon  
Oxford University  
Mathematical Institute  
(0865) 448-6527

FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112644---10

CONTRACT NO: N0001491J1163

CURRENT END DATE: 30 SEP 1992

SCIENTIFIC OFFICER: Reza Malek-Madani

**Technical Objective:**

The objective in vortex/free surface interaction is to develop analysis explaining the bouncing phenomenon for line vortices beneath a free surface, the movement of curved vortices near a free surface and the singularities that occur when vortices are near a free surface. The objectives in marine meteorology are to determine the smoothness of the solution of a meteorological variational problem over a modern measure space and to use of properties of this solution to design practical numerical methods for weather fronts.

**Approach:**

The research on vortex/free surface interaction will be carried out using ordinary-differential-equation models, generalized-function representations of the vortices, asymptotic techniques, transform techniques, point-vortex methods, vortex-blob methods and ring-vortex methods. The research in meteorology will be carried out using geometrical and linear programming methods for solving problems in  $L_p$  spaces, generalized solutions of the Monge-Ampere equation that preserve local potential vorticity and numerical solution procedures.

**Progress:**

The mathematical theory of total internal reflection of light rays emanating from a real source above an interface between two homogeneous media was analyzed using the method of multiple scales. This allows geometrical optics to be applied away from the critical ray, and ray optics to be matched into this framework near the interface. Most recently, models for phase changes in isothermal superconductors were identified with vector versions of previously analyzed free boundary models of supercooled solidification. This may allow knowledge from solidification theory to be applied to superconductor design.

Title: Mathematical Stability Analyses of  
Benard Convection

PI: David J. Wollkind  
Washington State University  
Pure and Applied Mathematics Department  
(509) 332-2162

FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112656---07

CONTRACT NO: N0001491J1066

CURRENT END DATE: 30 SEP 1993

SCIENTIFIC OFFICER: Reza Malek-Madani

Technical Objective:

Linear stability of the conduction solution for aerosol one-layer Rayleigh-Benard models and weakly nonlinear stability of the conduction solution for a two-layer Benard-Marangoni system will be determined. The resulting theoretical predictions will be compared to experimental results on buoyancy-driven columnar instability in aerosol-air mixtures. The discrepancy between experimental results and currently available theoretical results will be at least partially resolved.

Approach:

Asymptotic methods will be used throughout. First, the analysis will be carried out in an unbounded region. Then a layer of finite depth will be considered. Normal-mode expansions will be used to create systems of ordinary differential equations, which will be solved by Galerkin and other numerical methods. In the research on two-layer cases, a certain interfacial condition will be assumed.

Progress:

The weak nonlinear stability of the pure conduction solution for an aerosol one-layer Rayleigh-Benard model of a Boussinesq particle-gas system in thermal equilibrium was addressed. A reduction of the threshold temperature gradient associated with the occurrence of the supercritically equilibrated state was predicted for a clean gas, that reduction increasing with decreasing layer depth.

Title: An Analytical Study of Some Problems in Partial  
Differential Equations with Applications to  
Fluid Dynamics and Wave Propagation

PI: George H. Knightly  
University of Massachusetts  
Department of Mathematics  
(413) 545-0823

FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112667---05

CONTRACT NO: N0001490J1031

CURRENT END DATE: 31 OCT 1992

SCIENTIFIC OFFICER: Reza Malek-Madani

Technical Objective:

Research will be performed on (a) stability and bifurcation for viscous, incompressible Couette flow under various driving forces; (b) well-posedness of the equations governing two-phase phenomena in the presence of convection and properties of the region separating the solid and liquid phases; (c) stability and accuracy of marching methods for predicting wave propagation in inhomogeneous media (Helmholtz equation of underwater acoustics).

Approach:

In area (a), methods developed recently by others for a class of differential equations in Banach space will be adapted. In area (b), methods of nonlinear functional analysis will be utilized. In area (c), the methods of stability analysis for numerical schemes will be utilized to estimate accuracy and computational stability.

Progress:

Periodic waves were shown to exist and their expansions derived for a variety of Couette-Poiseuille problems in the narrow gap limit of viscous flow between rotating sliding cylinders under applied axial and circumferential pressure gradients. For rotating Couette flow, a continuum of periodic waves bifurcating from the basic spiral flow was found. A connection between such spiral flows and Langmuir circulation in upper ocean mixing was established. Langmuir circulation in the form of periodic waves was generated for certain problems in which the Stokes drift is not aligned with the wind direction.

**Title:** The Application of Inverse Methods to  
the Ocean Environment

**PI:** Norman Bleistein  
Colorado School of Mines  
Department of Mathematical & Computer Sciences  
(303) 273-3255

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4112669---05

**CONTRACT NO:** N0001491J1267

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Reza Malek-Madani

**Technical Objective:**

An inverse-scattering theory for complex background structures and realistic (separated) source/receiver configurations will be developed. Inversion procedures for both isotropic and anisotropic elastic media will be created. Methods for separating signals and for correlation of reflector locations will be developed. Computer codes to implement these procedures will be written. Extension of both modeling and codes to three dimensions will be carried out. In addition, enhanced methods for direct propagation prediction will be developed.

**Approach:**

The Born approximation and backprojection are the basis of the analysis and the computational procedure. The backprojection method will be extended to allow for complex background structures and separated source/receiver configurations. Time windows will be used to separate signals. The postprocessing analysis for correlation of reflector locations will be based on processing with different travel time inversion operators. In addition, the ideas of wavefield splitting, invariant embedding, and phase space analysis will be used.

**Progress:**

Conventional seismic inversion methods for imaging structure inside the earth require reasonable background velocities. A new technique was introduced in which velocity analysis and imaging are performed at the same time. The medium is assumed to consist of constant-velocity layers separated by arbitrary smooth interfaces. The goal of the inversion is to determine layer velocities and interface depths. The approach is based on the fact that velocity error yields image distortion. The sensitivity to velocity error was derived for some special cases. The technique is now being tested on synthetic and experimental data.

Title: Uniqueness Theorems and Numerical Solution  
of 3-D Inverse Scattering Problems

PI: Alexander G. Ramm  
Kansas State University  
Department of Mathematics  
(913) 532-6750

FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112693---03

CONTRACT NO: N0001490J1192

CURRENT END DATE: 31 OCT 1992

SCIENTIFIC OFFICER: Reza Malek-Madani

Technical Objective:

New uniqueness theorems for three-dimensional electromagnetic inverse scattering problems will be proved. A constructive analytical method for inversion of the scattering data at a fixed frequency will be obtained. Stability of this method will be established. Convergence of the method for exact data will be proved. Error estimates as the error of the measurements tends to zero will be found.

Approach:

Techniques of functional analysis, including Sobolev space theory, will be used to establish inversion formulas and prove uniqueness. Techniques of numerical error analysis will be used to establish the properties of the computational method.

Progress:

Results were obtained in a number of areas:

- A method was developed for determining the stability of the exact inversion problem for 3D fixed-energy scattering. Error estimates for the inversion of noisy 3D fixed-energy scattering were derived.
- An algorithmically verifiable characterization of the class of scattering amplitudes corresponding to small local potentials was obtained.
- Necessary and sufficient conditions on the scattering data were found for the scatterer to be spherically symmetric.

Title: Mathematical Methods in Applied Wave Propagation

PI: Gregory A. Kriegsmann  
New Jersey Institute of Technology  
Department of Mathematics  
(201) 596-5785

FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112694---03

CONTRACT NO: N0001492J1261

CURRENT END DATE: 30 SEP 1993

SCIENTIFIC OFFICER: Reza Malek-Madani

**Technical Objective:**

The method of normal modes, which has been successfully applied to range-independent oceans, will be applied to range-dependent ocean environments. An "effective-medium" wave equation that describes scattering of acoustic waves by the ocean bottom will be developed. The acoustic fields both near and far from a target will be described. Computational experiments will be carried out.

**Approach:**

Analytical, numerical and computational methods will be used throughout the research. Slowly varying range dependence will be assumed. Asymptotic procedures will be used to determine reflected and transmitted-wave components at the ocean bottom.

**Progress:**

An algorithm was developed which uses phase information from the geometrical optics limit for acoustic object reconstruction. Essentially, the phase in the back scattered direction determines the tangent plane at the unknown specular point. This plane depends on the two spherical angles which describe the incident wave direction. The observation that the tangent plane envelopes the object as these angles are varied allows the derivation of an explicit formula for the surface in terms of the measured scattered phase.

**Title:** Stability, Bifurcation and Fracture in Ice Mechanics

**PI:** Reza Malek-Madani  
U.S. Naval Academy  
Department of Mathematics  
(301) 267-3603

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4112696---03

**CONTRACT NO:** N0001492WR24006

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

Global weak solutions for the nonlinear equations that model compressible, visco-plastic deformation of quasi-two-dimensional sheets of ice will be obtained. Localization of flow near coastal boundaries will be determined for circular regions. For single three-dimensional blocks of ice, the formation of wing cracks by primary-secondary bifurcation will be studied. The stability of wing cracks as equilibrium solutions of the governing equations will be proved.

**Approach:**

Recently developed functional-analytic results on minimization of nonlinear functionals will be used to prove existence of global weak solutions of the two-dimensional equations. Steady-state solutions for a circular domain will be used to quantify the localization of the flow near coastal boundaries. The ice block will be modelled as an anisotropic thermally conducting material with a nonlinear constitutive law. Solution of the nonlinear equation will be accomplished by the methods of functional analysis.

**Progress:**

Recent work addresses the system of partial differential equations that model simple shearing of a slab of thermo-plastic material. The class of constitutive laws that gives rise to a variational formulation was identified, and a phase-plane argument was used to construct time-independent solutions that may be interpreted as steady-state shear bands. Techniques from bifurcation theory were used to classify stable and unstable solutions in terms of the shape of the solution branch that arises when strain-rate is plotted against shearing force.

**Title:** Phenomenological Behavior of Multipolar Viscous Fluids

**PI:** Hamid Bellout  
Northern Illinois University  
Department of Mathematical Sciences  
(815) 753-6763

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4112699---02

**CONTRACT NO:** N0001491J1002

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Reza Malek-Madani

**Technical Objective:**

A new constitutive "multipolar" theory to describe the flow of viscous fluids will be formulated. This theory assumes nonlinear relations between the stress tensors and the higher spatial derivatives of the velocity. For various steady flows, the solutions of the new equations will be compared to the Prandtl boundary-layer solutions of the standard Navier-Stokes equations. Computations will be carried out for an isothermal, incompressible, dipolar fluid. Continuous dependence and existence results will be proved.

**Approach:**

The physics of fluid flow will be used to create the nonlinear constitutive relations. Existence and continuous dependence of the solutions of the new equations with the nonlinear constitutive relations will be established by methods of functional analysis (Sobolev spaces). The comparison of the new equations with the standard Navier-Stokes equations will be carried out using Prandtl boundary-layer theory and computations.

**Progress:**

Recent work addressed the existence, uniqueness, and stability of solutions to the full three-dimensional initial-boundary value problem for an isothermal, incompressible, dipolar viscous fluid. The boundary conditions considered were more general than those used previously in that they allow for time-dependent nonhomogeneous boundary data. This is equivalent to the case where fluid is flowing into and/or out of the region of interest, thus allowing more possible flows.

**Title:** Nonlinear Aspects of Multidimensional  
Inverse Scattering Problems

**PI:** Adrian I. Nachman  
University of Rochester  
Department of Mathematics  
(716) 275-4416

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4112700---02

**CONTRACT NO:** N0001491J1107

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Reza Malek-Madani

**Technical Objective:**

The d-bar method for multidimensional acoustic inverse scattering will be further developed to take into account practical limitations. The integral equations in several complex variables that arise in the d-bar method will be extended to allow for the presence of singularities. The exceptional points (singularities) that arise in the complex frequency range will be studied. A method to calculate the exceptional points from the scattering data and to use them in the inversion procedure will be developed.

**Approach:**

Functional-analytic methods will be used to extend the integral equations in several complex variables that arise in the d-bar method to allow for the presence of singularities. The singularities will be studied using the spectral theory of non-self-adjoint operators, weighted inner product spaces, harmonic analysis estimates, perturbation methods and numerical calculations.

**Progress:**

The problem of recovering the quantum mechanical two-body Hamiltonian  $-D+V$  in  $L^2(\mathbb{R}^n)$ ,  $n \geq 3$ , from knowledge of the corresponding scattering matrix at one energy was addressed. It was shown that if the potential  $V$  has compact support and is in  $L^{n/2}$  then it is uniquely determined by the scattering matrix; the proof gives a method to reconstruct the potential from the scattering matrix.

**Title:** Functional Regularity of Entropy  
Solutions to Nonlinear Conservation Laws

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4112701---02

**CONTRACT NO:** N0001491J1076

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Reza Malek-Madani

**Technical Objective:**

Functional analysis for calculating entropy solutions of nonlinear scalar conservation laws in several space dimensions will be developed. Regularity (that is, smoothness that is inherited or maintained as time passes) of the solution of a multidimensional scalar conservation law will be established. Stability and convergence of leading numerical methods for calculating the solutions of conservation laws will be determined in a Besov-space setting.

**Approach:**

To prove regularity for conservation laws, the theory of Besov spaces will be used. To characterize the solutions of conservation laws, a model based on phase averaging of the kinetic solutions of transport equations related to the conservation law will be used. The theory of nonlinear approximation of (discontinuous) functions in Besov spaces will be used to establish stability and convergence of numerical methods.

**Progress:**

Questions of the behavior of solutions to the heat equation in nonconvex regularity spaces were addressed. In particular, it was shown that convolution with the heat kernel is bounded on  $B(n,p)$ , the space of  $L_p$  functions that have  $n$  derivatives, if  $1/p - n < 1$ . In other work, stability, total variation, and error properties of spectral viscosity approximations were derived.

**Title:** Reduction of Partial Differential  
Equations to Ordinary Differential  
Equations

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4112702---02

**CONTRACT NO:** N0001491J1140

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Reza Malek-Madani

**Technical Objective:**

Algebraic procedures for the reduction of partial differential equations governing fluid flows, in particular, Navier-Stokes equations, to systems of ordinary differential equations will be developed. To this end, a family of analytical sets approximating the global attractors of the partial differential equation, a family that describes the interaction between small and large eddies, will be studied. The theory of a canonical normal form of these equations will be developed. This theory will be used to solve the Hopf bifurcation equation in turbulence theory.

**Approach:**

The partial differential equations will be treated as vector fields in infinite-dimensional phase spaces. The zeros of polynomial maps will be used to approximate the attractor of the equations. The flow on the attractor will be studied through the algebraic properties of the sets of zeros. When the attractor is a single fixed point, the normal form of the equation will be used to integrate explicitly the partial differential equation.

**Progress:**

In recent work it was proved that the nonlinear operator associated with the normal form of the Navier-Stokes equations with potential body forces is unique. A method for computing this operator in terms of a sequence of defining polynomials was derived. These polynomials can be used to compute the flow of the Navier-Stokes system. The approach is also applicable to other nonlinear parabolic equations.

Title: Regularity and Approximation for Hyperbolic Conservation Laws in Several Space Dimensions

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FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112703---02

CONTRACT NO: N0001491J1152

CURRENT END DATE: 30 SEP 1993

SCIENTIFIC OFFICER: Reza Malek-Madani

Technical Objective:

Two types of regularity for conservation laws will be established: 1) If the initial condition is in a certain Besov space, then the solution remains in that space at later times; and 2) If the initial condition is in a certain space rougher than the Besov space, the solution is at later times in the Besov space (that is, it gains regularity or smoothness). It will be shown that the solution of the phase average of the so-called kinetic approximation to the conservation law converges to the solution of the conservation law.

Approach:

Results from approximation theory and operator theory that characterize the multidimensional functions that can be well approximated by wavelet-type decompositions will be used to prove the regularity results. Fourier multiplier theory, wavelet decompositions and comparison theorems of Kuznetsov will be used to establish regularity and convergence of solutions of the kinetic equation.

Progress:

A mathematical theory for image compression based on nonlinear approximation theory was developed which describes of such operations as quantization, threshold coding, and clipping. The results show how to optimally use the wavelets for compression by minimizing the error, defined in terms of an  $L_p$  metric, between the original image and the compressed image. In particular, it was shown how to quantize in order to achieve optimal compression under a given metric. The issue of the choice of metric was also addressed, and it was demonstrated that the  $L_1$  metric, rather than the more commonly used  $L_2$  metric, leads to quantization which better matches the Threshold Sensitivity Curve used by psychologists to model the human visual system.

Title: Nonlinear Systems of Conservation Laws

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FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112705---02

CONTRACT NO: N0001491J1384

CURRENT END DATE: 30 SEP 1992

SCIENTIFIC OFFICER: Reza Malek-Madani

**Technical Objective:**

New, more efficient nonlinear methods of solving certain classes of multidimensional nonlinear conservation laws for compressible and incompressible flow will be formulated. A rigorous theoretical basis, including stability, convergence and error-estimate results, for these methods will be developed. The methods will be used in computations for more complicated classes of multidimensional conservation laws to guide further theoretical development.

**Approach:**

Nonlinear versions of various methods of functional analysis and numerical analysis will be used. These methods include compactness methods, estimate methods, asymptotic expansions, geometric-measure methods and topological methods. Well-posedness and qualitative behavior of solutions in measure spaces such as  $L^\infty$  and BV will be used as the basis for analyzing numerical methods and proposing improvements.

**Progress:**

The convergence of a pure second-order shock-capturing scheme for the system of isentropic gas dynamics with  $L^\infty$  initial data was established. The scheme is a version of the classical MUSCL (monotonic upstream scheme for conservation laws) modified in order that points near the vacuum not take negative density and to prevent the local entropy from dramatically increasing near shock waves. Convergence of the scheme for the piston problem, which is complicated by the reflection of shock waves at the rigid wall, was also addressed.

Title: Discontinuous Solutions for Multidimensional  
Conservation Laws

PI: Dening Li  
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FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112706---02

CONTRACT NO: N0001491J1291

CURRENT END DATE: 30 SEP 1992

SCIENTIFIC OFFICER: Reza Malek-Madani

Technical Objective:

The stability of a contact discontinuity for compressible flow will be determined. The Cauchy problem with discontinuous initial data containing shocks, rarefaction waves or vortex sheets will be addressed. A mathematical theory for the existence and stability of Mach node formation will be developed. The structure of the solution of the two-dimensional Euler equations with piecewise smooth initial data will be determined.

Approach:

Existence and stability of compressible-flow solutions will be determined using energy estimates and iterative techniques. The structure of solutions of the Cauchy problem will be derived using linearization and Nash-Moser iteration. Mach node formation will be examined using asymptotic analysis and techniques for free-boundary problems. The two-dimensional Euler equations will be addressed by explicit construction of piecewise smooth solutions. Computational experiments will be used occasionally to guide the analysis.

Progress:

For a one-dimensional two-phase degenerate Stefan problem, it was proved that the boundary and the solutions up to the boundary are  $C$ -infinity smooth. The proof is based on performing the hodographic transformation to fix the free boundary and establishing a nonlinear a priori estimate for the solution.

Title: Analysis, Approximation, and Computation  
of Flow Control Problems

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FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112710---02

CONTRACT NO: N0001491J1493

CURRENT END DATE: 30 SEP 1992

SCIENTIFIC OFFICER: Reza Malek-Madani

Technical Objective:

The goal is to solve optimal-control problems for incompressible fluid flows. Functional-analytical, numerical-analytical and computational research will be carried out on drag minimization, avoiding hot spots, maximization of mixing, minimization of mixing and achieving an a priori specified flow field. Control mechanisms to be used in the models will be physically implementable controls such as velocity at the boundary (injection, sucking), temperature at the boundary, body forces (magnetism) and shape of the boundary.

Approach:

The mathematical analysis of the models will be carried out using nonlinear functional analysis for Navier-Stokes equations in standard and novel Sobolev spaces and using Lagrange-multiplier techniques for the constraints. Discretization will be carried out by finite elements. Rigorous numerical analysis of the discrete problems will be carried out by extending finite-element analysis of discretizations of the uncontrolled Navier-Stokes equations. Computer codes for solving the discrete problems will be written.

Progress:

A number of results were extended from steady-state flows to time-dependent flows. In particular, necessary conditions from which optimal states and controls can be determined were given in the form of systems of partial differential equations. Analysis of these optimality systems shows that practical computational solutions can be derived.

Title: Control Theory of Nonlinear Partial  
Differential Equations with Applications  
to Fluid Mechanics

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FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112712---02

CONTRACT NO: N0001491J1494

CURRENT END DATE: 30 SEP 1992

SCIENTIFIC OFFICER: Reza Malek-Madani

Technical Objective:

The grantee will address optimal-control problems for incompressible fluid flows. Functional-analytic and numerical-analytic research will be carried out on stabilization, drag reduction, flutter reduction and boundary stress minimization for laminar and turbulent flows by boundary shape control, boundary velocity control and hybrid shape/velocity control.

Approach:

Throughout the research, the techniques of Lagrangian analysis of optimization problems will be applied. Generalizations of the notion of weak solution of inhomogeneous boundary-value problems will be used. In deriving and manipulating a maximum principle, boundary controls of bounded variation will be used. Estimates will be derived using the concept of monotonicity of solutions of elliptic equations. Invariant manifold theory will be used to prove the stabilization results. Discretization will be carried out by finite elements.

Progress:

Necessary conditions were derived for the existence of optimal controls for the boundary control problem associated with the stationary Navier-Stokes equations. The control is the velocity on part or all of the boundary of the flow domain. The use of the Lagrange multiplier rule was justified as a means to derive first order necessary conditions for optimality, which were expressed as a system of partial differential equations.

Title: Inverse Scattering and Nonlinear Waves

PI: Mark J. Ablowitz  
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FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112713---02

CONTRACT NO: N0001491J4037

CURRENT END DATE: 30 SEP 1993

SCIENTIFIC OFFICER: Reza Malek-Madani

Technical Objective:

1) The existence of optimal controls and the validity of the Pontryagin maximum principle will be proved. Suboptimal controls produced by discretizations will be derived. 2) The influence of currents, periodic waves and change of wind on Langmuir circulation (upper-ocean mixing) will be determined. 3) Wavelet based methods for capturing shocks and inverting the Radon transform will be developed. 4) Multidimensional inverse scattering methods will be developed.

Approach:

1) Dynamic programming, the Ekeland variational principle, invariant manifolds and viscosity solutions of Hamilton-Jacobi equations will be used to obtain results on control of fluids. 2) The system of partial differential equations governing Langmuir circulation will be rewritten as a singular evolution equation in an infinite-dimensional space and solved by techniques developed for singular Navier-Stokes equations. 3) Wavelets will be used to transform smoothing operators into sparse matrices to solve fluid-flow equations and the generalized Radon transform. 4) The DBAR method, which supplants the Riemann-Hilbert problem of one-dimensional inversion by a linear equation for the DBAR derivative of the eigenfunction whose coefficients are the scattering data, will be extended from continuous to discrete problems.

Progress:

New results were derived for optimal control for viscous fluids. In particular, the relationship between two notions of generalized solution for the Hamilton-Jacoby-Bellman equation was determined. A large class of viscous flow problems was then formulated in terms of infinite dimensional nonlinear control, with exterior hydrodynamic flow an example. An existence theorem for optimal control was produced.

**Title:** Mathematical Algorithms for Multidimensional Inverse Scattering Problems in Inhomogeneous Media

**PI:** Michael Klibanov  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4112714---01

**CONTRACT NO:** N0001492J1008

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Reza Malek-Madani

**Technical Objective:**

The technical objective is to develop improved mathematical algorithms for 3-D inverse scattering problems. Areas of specific interest include inversion at low frequencies, time-dependent data, convergence rates and numerical efficiency.

**Approach:**

Significant improvement in medium recovery is anticipated through the use of specially designed Newton-type iterative methods. Since these require a good initial approximation, alternating direction methods, which are less dependent on initialization, will also be considered. Hybrid methods will be developed, implemented, and evaluated numerically.

Title: Transport, Mixing, and Dispersion in Geophysical  
Flows: A Dynamical Systems Approach

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FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112715---01

CONTRACT NO: N0001489J3023

CURRENT END DATE: 14 JUN 1992

SCIENTIFIC OFFICER: Reza Malek-Madani

Technical Objective:

The theory of nonlinear dynamics will be developed and applied to problems of transport, mixing, and dispersion in geophysical flows. The strongly nonlinear deterministic problem of the motion of tracer particles under a specified velocity field is of particular interest.

Approach:

The mechanisms governing transport and mixing will be determined: 1) in coherent structures of modon type (i.e., elliptical regions of localized vorticity), and 2) for passive tracers and potential vorticity associated with Rossby waves in eastward and westward jets. A Hamiltonian formulation for the dynamics of an elliptical vortex in time-varying strain rate and vorticity fields will be used. The size and geometry of the mixing region will be correlated with those of the vortex distribution via invariant manifold theory. Melnikov theory will be used to quantify the geometry and size of the mixing region in terms of parameters such as circulation and strain rate.

Progress:

Recent work addressed the connection between chaos in dynamical systems and open shear flow turbulence. A simple dynamical model based on physical arguments relative to large and small eddy motions was developed for a broad class of flows. Using the Melnikov technique, it was shown that the system has chaotic solutions under deterministic forcing. The model exhibits many features of shear flow transition, including 1) there is an inherent cascade process, 2) the value of the control parameter (inverse Reynolds number) at onset of chaos is not unique but depends on the forcing (disturbance) amplitude, and 3) chaos persists as the control parameter tends to zero, the forcing amplitude required to induce chaos simultaneously tending to zero.

Title: Problems in Compressible Wave Motion

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FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112716---01

CONTRACT NO: N0001492J1245

CURRENT END DATE: 30 SEP 1994

SCIENTIFIC OFFICER: Reza Malek-Madani

Technical Objective:

The objective is to develop new understanding of the role of wave focusing in 2-D conservation laws, particularly in the context of radial motions of a 2-D ideal gas and nonlinear geometric optics. In addition, the method of viscous perturbation will be applied to the problem of shock capturing in mixing fluids. This involves the application of small viscous perturbations to nonconserved primitive variables, making the algorithm conservative to the order of numerical approximation.

Approach:

Small radial and compactly supported perturbations of the constant states for a 2-D ideal gas in the exterior of the unit disc will be modeled and analyzed. The radial solution to the Euler equation will be analyzed in the asymptotic regime of nonlinear geometric optics. Computations of mixing fluids using a nonconservative scheme on primitive variables will be used to generate shocks with oscillation-free interfaces.

Title: Analysis and Computation of Viscous  
Shock Layers and Related Problems

PI: Jonathan B. Goodman  
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FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112717---01

CONTRACT NO: N0001492J1267

CURRENT END DATE: 30 SEP 1994

SCIENTIFIC OFFICER: Reza Malek-Madani

Technical Objective:

The goal is to establish the multidimensional stability of viscous shock fronts for the equations of gas dynamics and to produce error estimates for adaptive finite elements when applied to flows with localized singularities. The error estimates will be obtained without restriction on the shape of the finite elements.

Approach:

The stability of a planar viscous shock profile will be established for the equations of gas dynamics with perturbations. Stability estimates will be derived via the Kreiss symmetrizer as applied to the linearized equations. Adaptive space-time finite elements will be applied to flows with shock fronts and to the problem of detonation ignition by the collision of two shocks in a combustible gas.

**Title:** Shock-Capturing in Conservation Laws and Applications of Dynamical Systems

**PI:** Chris Jones and Constantin Dafermos  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4112718---01

**CONTRACT NO:** N0001492J1481

**CURRENT END DATE:** 31 OCT 1994

**SCIENTIFIC OFFICER:** Reza Malek-Madani

**Technical Objective:**

The stability of viscous diffusion waves for systems of conservation laws will be established. Then, a systematic analysis of various fan admissibility criteria will be carried out for strictly and nonstrictly hyperbolic conservation laws. Finally, a class of Petrov-Galerkin type finite element methods will be developed and applied to multi-dimensional conservation laws.

**Approach:**

An eigenvalue tracking technique, a topological invariant, and singular perturbation will be used to obtain stable viscous diffusion waves. Generalized characteristics will be developed with the goal of understanding the global properties of solutions directly and without appealing to Glimm's random choice method. A class of Petrov-Galerkin finite elements will be combined with a class of total variation stable time discretization and the resulting algorithm will be applied to two-dimensional gas dynamics.

**Title:** Nonlinear Stability Analyses in Fluid Dynamics

**PI:** Yuriko Renardy  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4112719---01

**CONTRACT NO:** N0001492J1664

**CURRENT END DATE:** 30 SEP 1994

**SCIENTIFIC OFFICER:** Reza Malek-Madani

**Technical Objective:**

The goal is to characterize the stability properties of all eleven solutions of the system of partial differential equations that describe double-diffusive convection. Among these solutions are standing rolls, travelling rolls, and travelling patchwork quilts.

**Approach:**

Bifurcation analysis of double-diffusive convection will be performed by applying the theory of pattern selection introduced by Roberts, Swift, and Wagner. This approach has been used by the Principal Investigators in their previous analysis of the two-layer Benard problem. The Center Manifold Theorem plays a crucial role in establishing connections between the linear stability and spectral properties of such viscoelastic flows.

Title: Conference on Dynamical Systems and Applications

PI: I. E. Block  
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FUNDING AGENCY: Office of Naval Research

R&T PROJECT CODE: 4112720---01

CONTRACT NO: N0001492J1565

CURRENT END DATE: 31 DEC 1992

SCIENTIFIC OFFICER: Reza Malek-Madani

**Technical Objective:**

The conference will be held in Salt Lake City on October 15-19, 1992. The conference will bring mathematicians together with engineers, physicists and biologists. The conference program will include twelve invited speakers and thirty minisymposia. The topics of minisymposia range from computational complexity and chaos to low dimensional dynamics of partial differential equations.

**Approach:**

In each subtopic of nonlinear dynamical systems, speakers that are world leaders in their area are invited to deliver a lecture. The minisymposia will complement the concepts and ideas that are introduced in the invited lectures.

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**Discrete Mathematics**

**TITLE:** Studies in Traversability in Graphs

**PI:** Herbert S. Wilf  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111008---09

**CONTRACT NO:** N0001491J1022

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

A deeper understanding of the relationship between combinatorial identities and the rational functions which "prove" them will be sought. New lower bounds for maximum sizes of codes will be derived.

**Approach:**

The combinatorial identity associated with a particular rational function will be determined. This will yield new relationships between families of combinatorial identities. Computer-useful representations of hypergeometric series will be built. This will permit construction of a database for combinatorial identities. The spectrum of the distance graph of a code will be used to derive lower bounds on the independence number of that graph, and hence a lower bound on the maximum size of the code.

**Progress:**

The grantee has significantly extended his method whereby computers can quickly find proofs of hypergeometric summation identities in a single variable. This extension allows for automation of proofs of summation-integration identities that involve several summation variables or q-sums or multivariate q-sums. In particular, such sums always satisfy recurrences with polynomial coefficients, computers can find these recurrences, and that bounds for the orders of the recurrences can be given in advance. Using these results, the grantee produced computer-generated proofs of a number of important and famous identities.

**TITLE:** On-Line Algorithms and Polynomial Time Approximation

**PI:** Henry A. Kierstead  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111009---07

**CONTRACT NO.:** N0001490J1206

**CURRENT END DATE:** 30 NOV 1992

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

Three general areas will be investigated. The first involves on-line algorithms and dynamic storage allocation. The second concerns the problem of computing the chromatic index of a multigraph. In particular, it is unknown if this can be done in polynomial time. The third includes several classic problems in the dimension theory of partially ordered sets.

**Approach:**

Algorithms on partially ordered sets will be developed for finding important parameters and structures. The complexity of on-line algorithms will be studied. The chromatic index of multigraphs and various aspects of the dimension theory of partially ordered sets will provide important examples to test the approach.

**Progress:**

The grantee characterized those trees for which the first-fit on-line graph coloring algorithm has worst-case behavior that is bounded when restricted to acting on graphs which do not contain that tree as an induced subgraph. This means that first-fit yields a coloring requiring no more colors than a known function of the minimum number of colors necessary to color the graph. Some trees were identified for which first-fit fails to have this property.

**TITLE:** Matching and Covering in Graphs and Networks

**PI:** Michael D. Plummer  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111011---07

**CONTRACT NO:** N0001491J1142

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

Improved lower and upper bounds for the number of perfect matchings in a graph will be sought and a decomposition theory for bricks developed. Well-covered graphs having girth less than five will also be studied in the hopes of obtaining a complete characterization of all well-covered graphs.

**Approach:**

The approach to the structure of bricks and bicritical graphs involves the  $n$ -extendable graphs, i.e., graphs in which every matching of size  $n$  lies in a perfect matching. Previous methods will be generalized to characterize four and five regular well-covered graphs.

**Progress:**

Grantee produced a new degree sum condition and a new neighborhood union condition each of which guarantees that a graph is  $n$ -extendable for a suitable choice of  $n$ . In the particular case of  $n$  equal to 1, the graph is guaranteed to be bicritical as well as 1-extendable.

**TITLE:** Structure of Ordered Sets and Graphs

**PI:** Dwight Duffus  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111016---07

**CONTRACT NO:** N0001491J1150

**CURRENT END DATE:** 31 OCT 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The goal is to develop structural properties of graphs and ordered sets. Random orders will be studied as will a variety of other combinatorial problems involving familiar, highly structured objects such as Boolean lattices and subspace lattices of finite vector spaces.

**Approach:**

Fibres and cutsets in both determined and random ordered sets will be analyzed. Order preserving maps will be counted which will help determine which ordered sets can be sorted when comparisons are unreliable. A search will be made for a polynomial algorithm for the  $m$ -machine unit time preemptive scheduling problem. The topic of random maximal graphs for various properties will be explored.

**Progress:**

The grantees produced an example of a finite poset with no one-element maximal antichain and containing no fibre of size at most half the size of the poset. But they also showed that there is an absolute constant, at most two-thirds, so that every finite poset contains a fibre of size at most that constant times the size of the poset. In addition, they proved that the elements of an arbitrary poset can be partitioned into two sets so that every two-element maximal antichain spans both sets.

**TITLE:** Intersection Graphs and Geometric/Combinatorial Optimization

**PI:** Edward R. Scheinerman  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111020---07

**CONTRACT NO:** N0001491J1220

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

Three areas will be investigated: (i) random representations, leading to a general theory of random intersection graphs, (ii) containment representations of partially ordered sets, particularly circle and sphere containment orders, and (iii) generalized chromatic numbers on random graphs, leading to generalized perfect graphs.

**Approach:**

The theory of random interval graphs, invented by the contractor, will continue to be developed. Results will be used to investigate the dimension of random interval orders. Classes of partially ordered sets which arise as the containment orders of various geometric sets such as circles and angles will be studied. Random methods will be applied to fault tolerant analysis of non-arbitrary interconnections between processors, such as the hypercube architecture.

**Progress:**

Grantee proved that the vertex containment (edge containment, bounded-face containment) order of a 3-connected planar graph is a circle order. This has an important corollary about plane drawings of planar graphs. Grantee also proved that the vertex containment (edge containment) order of any graph is a sphere order. Grantee established global growth rates for the numbers of graphs with hereditary properties. Hereditary properties can have constant, polynomial, exponential, factorial, and superfactorial rates of growth as a function of the number of vertices in the graph.

**TITLE:** Tolerance Intersection Models

**PI:** Michael S. Jacobson  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111021---07

**CONTRACT NO:** N0001491J1098

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

Tolerance intersection graphs and posets will be constructed for a wide range of types of tolerance including minimum, maximum, and sum tolerance. Comparisons with classic intersection models will demonstrate the increased utility of these models.

**Approach:**

For a given tolerance condition, such as minimum tolerance, the tolerance interval graphs will be characterized. Then the question of unit intersection versus proper intersection will be extended to tolerance interval structures. Properties of special classes of tolerance structures will be found, such as tolerance competition graphs. Finally, the concept of asymmetry in tolerance will be developed, specifically tolerance intersection digraphs.

**Progress:**

The grantee made fundamental discoveries about sphere-of-influence graphs. Specifically, sphere-of-influence trees were characterized, and sufficient conditions determined for a triangle-free graph to be the sphere-of-influence graph of some set of points in the plane.

**TITLE:** Ordinal and Percentile Clustering

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111030---09

**CONTRACT NO:** N0001490J1008

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

A new technique of cluster analysis will be developed that combines the ordinal theory of clustering with the theory of probabilistic metric spaces. The goal is to improve classification in large data sets where there is variation within the objects to be clustered.

**Approach:**

Various aspects of ordinal clustering and the related lattice theory will be developed. Some of the machinery from the theory of probabilistic metric spaces, notably properties of t-norms and triangle functions, will be modified and extended to fit the applications at hand. Algorithms necessary to implement the new techniques will be developed and tested on the computer.

**Progress:**

Software PCluster was created and is available on disk. This set of programs performs standard clustering as well as grantee's own hierarchical method, percentile clustering, on PCs. Data can be in either attribute or dissimilarity form. PCluster computes dissimilarities, clusters, and displays dendrograms in either text or graphic mode. More than a dozen standard clustering algorithms are implemented. Grantee also characterized arbitrary quota rule consensus methods in a median semilattice. These methods allow for any fixed proportion of voters to control decisions.

**TITLE:** Distance and Extremal Subgraphs in Graphs and Digraphs

**PI:** Gary Chartrand  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111032---05

**CONTRACT NO:** N0001491J1060

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The primary objectives are to fully develop, in the context of graph theory, the concept of common substructures of a given family of structures, and construct families of metric structures in spaces of graphs.

**Approach:**

Several definitions of the greatest common subgraph and smallest common supergraph of a collection of graphs will be explored. New parameters involving generalized distance (e.g.,  $n$ -eccentricity,  $n$ -radius,  $n$ -center) will be compared. Metrics based on edge-slide distance, edge-rotation distance, and Steiner distances will be developed and investigated.

**Progress:**

Introduced two metrics defined on the subgraphs of a graph: One for induced subgraphs with the same number of vertices, one for edge-induced subgraphs with the same number of edges. Each is a generalization of the classic graph distance. Produced an efficient algorithm for computing the vertex subgraph metric. For any graph and specified order of subset, constructed a graph which models this distance, so that the subgraph distance in the original graph is the ordinary graph distance in the construct. Constructed two metrics in digraphs based on the usual digraph "distance," which is itself not a metric.

**TITLE:** Ordered Sets and Intervals

**PI:** Kenneth P. Bogart  
Dartmouth College  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111033---07

**CONTRACT NO:** N0001491J1019

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

New types of ordered sets and graphs, and algorithms defined on them, will be developed and applied in the context of scheduling problems. The notion of tolerance will be introduced to the study of interval orders and interval graphs.

**Approach:**

New representations of interval orders and interval graphs that employ tolerance will be used to model scheduling situations in which there is uncertainty concerning the actual timing of the events modeled. These representations give rise to "extended interval orders." The properties of these orders will be developed.

**Progress:**

Dowling lattices were characterized in terms of the existence of special bases and their weight functions. Dowling lattices give rise to a large class of non-representable matroids, and they are modularly complemented. These lattices are generalizations of the lattice of partitions of a set, and this characterization yields a new characterization of this lattice as an important corollary.

**TITLE:** Intersection Multigraphs and Related Constructs

**PI:** Terry A. McKee  
Wright State University  
Department of Mathematics and Statistics  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111034---05

**CONTRACT NO:** N0001491J1210

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

A new theory of intersection multigraphs will be developed as a generalization of the theory of intersection graphs.

**Approach:**

Characterization theorems for interval, intersection, and bi-intersection multigraphs will be proved and exploited. The extensive use of neighborhood union conditions will be integrated into the grantee's intersection multigraph theory. The properties of generalized complete bipartite graphs will be developed as the analogue of cliques in bi-intersection multigraphs.

**Progress:**

The grantee generalized the concept of boxicity to chordality in graphs. He showed that series-parallel graphs have chordality 2, planar graphs have chordality 3, and that chordality is bounded above by the tree width. He further showed how chordal graphs model decomposable loglinear model statistical contingency tables.

**TITLE:** Seventh International Research Conference on Graph Theory, Combinatorics, Algorithms and Applications

**PI:** Yousef Alavi  
Western Michigan University  
Mathematics and Statistics  
(616) 387-4510

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111037---03

**CONTRACT NO:** N0001492J1566

**CURRENT END DATE:** 31 MAR 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The technical objective is to advance the state-of-the-art in the many areas of graph theory, combinatorics, algorithms, and applications of these fields.

**Approach:**

The conference will be held at Western Michigan University 1-5 June 1992. All talks will be invited and selected for importance and relevance to the conference's theme of applicability of the mathematics presented. A refereed proceedings of the conference will be published in hardbound volumes by John Wiley and Sons.

**TITLE:** Discrete Structures in Classification and Other Topics in Discrete Applied Mathematics

**PI:** F. R. McMorris  
University of Louisville  
Mathematics Department  
(502) 588-5447

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111039---04

**CONTRACT NO:** N0001489J1643

**CURRENT END DATE:** 30 SEP 1994

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The objective is to develop and extend the theory of aggregation for discrete structured data. Since this theory encompasses the notion of "common agreement," the results have application to pattern recognition and the reconciliation of inconsistent data. Special attention will be given to waveform tree-coded data such as radar and sonar returns.

**Approach:**

The theories of social choice and multicriteria decision making will be used as a general axiomatic model. Existing results in numerical taxonomy will be extended to more general cases. New consensus methods will be developed based on numerical taxonomy and pattern recognition.

**Progress:**

The grantee gave several characterizations of the plurality rule for constructing consensus sequences. Using the semilattice of subtrees of a rooted tree, he also characterized those digraphs that are the acyclic intersection digraphs of subtrees of a directed tree. In addition, it was determined which graphs have  $p$ -vertex and  $p$ -edge clique cover numbers the same for all values of  $p$ , and it was shown that trees are closed sphere-of-influence graphs precisely when they have a perfect matching.

**TITLE:** Some Graph Theoretic Parameters Related to Network Problems

**PI:** Richard D. Ringeisen  
Clemson University  
Mathematical Sciences Department  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111042---03

**CONTRACT NO:** N0001490J1172

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The objective of this research is the development of techniques for designing communication networks with enhanced reliability. These will have applications in mobile packet radio and cellular telephone systems and the design of computer networks.

**Approach:**

Studies of cohesion and related graph theoretic parameters will characterize certain kinds of communication networks which are less vulnerable to loss of links and nodes. Studies in graph drawings should lead to improvements in computer representations of graphical structures, and improved ability to model complex networks in the plane.

**Progress:**

The grantee produced a new upper bound for the maximum number of crossings in a good drawing of the cube, 34, and a drawing achieving the bound. The grantee also determined exactly the binding number of all cycle permutation graphs and bounds for the toughness of such a graph. The crossing range of a graph yielded information concerning whether or not a good drawing of a subgraph can have more crossings than any such drawing for the original graph. Finally, the grantee produced many graphs which have drawings that meet the theoretical upper bound for the number of crossings as well as classes of graphs which have no such drawing.

**TITLE:** Some Problems of Golomb Concerning Costas Arrays

**PI:** Oscar Moreno  
University of Puerto Rico  
Department of Mathematics  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111043---05

**CONTRACT NO:** N0001490J1301

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The technical objective is to develop the theory of Costas arrays so as to show the existence of arrays with new orders and to create methods for constructing families of these arrays.

**Approach:**

Results concerning the primitive roots of finite fields will be used to limit the search for Costas arrays of certain orders. Necessary computer searching will be performed on a parallel system constructed by the research team.

**Progress:**

Grantee constructed a family of  $p$ -phase sequences of complex  $p$ th roots of unity of length  $(p \exp(n)) - 1$  with excellent periodic correlation properties. In particular, the family is asymptotically optimal with respect to the correlation properties and requires only an alphabet of size three. The new sequences are suitable for achieving code-division multiple-access and are easily implemented using shift registers.

**TITLE:** Mathematical Methods of Communication Signal Design

**PI:** Solomon W. Golomb  
University of Southern California  
Electrical Engineering Department  
(213) 743-2990

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111045---03

**CONTRACT NO:** N0001490J1341

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The objective is to develop the theory of Costas arrays, Florentine arrays, and Tuscan, Roman, and Vatican squares. Particular questions of interest include the existence of classes of these structures, the development of general techniques for their construction, and their properties. Also of interest is the relationship between these different types of combinatorial objects. For example: Do there exist square Florentine arrays which are not Vatican squares?

**Approach:**

Primitive roots in finite fields which sum to one guarantee the existence of Costas arrays of specific orders. Permutation matrices in which all vectors connecting pairs of ones have different slopes are also Costas arrays. The grantee will use these and similar results to construct Costas arrays of new orders, upper bound the number of such arrays, and construct the other combinatorial objects of interest.

**Progress:**

An infinite class of radar waveforms whose autocorrelation function is unity in-phase and close to zero out-of-phase was produced. These include arbitrarily long binary sequences as the modulating signals in which the out-of-phase correlation is identically zero. The signals are derived from cyclic Hadamard difference sets and are also useful for range-doppler radar, since they have nearly identical two-dimensional autocorrelation functions in both time and frequency. The grantee also showed that Legendre sequences of period a prime congruent to 1 modulo 4 can be used to obtain signals whose correlation is similar to those of period a prime two less. The grantee generalized these results from signals based on the Legendre symbol to some based on the Jacobi symbol modulo any squarefree positive integer.

**TITLE:** Fault Tolerance in Graphs and Discrete Systems

**PI:** Frank Harary  
New Mexico State University  
Dept. of Computer Sci. and Computer Res. Lab  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111049---05

**CONTRACT NO:** N0001490J1860

**CURRENT END DATE:** 31 MAR 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

This project will develop new parameters to measure fault tolerance in families of graphs as well as develop the concept of fault tolerance in groups. The intention is to investigate the relation of fault tolerance to extremal graph theory.

**Approach:**

The fault tolerance of a graph relative to a second, smaller graph will be investigated by examining conditions on the complements of the two given graphs. Fault tolerance of a graph will be examined relative to a family of graphs. Graceful degradation will be studied for fault tolerance in hypercubes. Fault tolerance in groups with specified subsets will be investigated.

**Progress:**

The grantees proved that any graphical structure guaranteed to contain a specified graph  $G$  after the removal of a fixed number  $k$  of edges must in fact contain multiple edges whenever  $k$  is large enough. They produced such multigraphs whenever the specified  $G$  is a cycle. They also produced optimal multigraphs for  $k = 1$  in the cases of multi-dimensional meshes and hypercubes, two popular computer architectures. They developed a new technique for incremental fault-tolerant design of networks that reduces a system's interconnection costs, and constructed a fast distributed algorithm for reconfiguration around faults.

**TITLE:** Combinatorial Matrix Theory

**PI:** Charles R. Johnson  
College of William and Mary  
Department of Mathematics  
(804) 221-2014

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111050---03

**CONTRACT NO:** N0001490J1739

**CURRENT END DATE:** 15 MAY 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

Combinatorial techniques will be applied in several areas of matrix theory. One goal is to determine from the signs of the entries when the eigenvalues of the matrix must be real. Another goal is to understand the properties of sparse matrices when information is given concerning the location of some of the zeros in the matrix.

**Approach:**

Two types of conditions on eigenvalues of real matrices will be examined with respect to properties of the entries. Matrix completion problems and determinantal inequalities will be addressed, especially the minimum rank completion problem. Analysis of sparse matrices will follow from analysis of the longest cycle in the associated non-zero digraph.

**Progress:**

The grantee characterized the sign patterns of matrices that force a matrix having that pattern to have its spectral radius among its eigenvalues, and identified a large number of patterns for which some matrices with that pattern have the same property. The grantee also gave simple bounds for the spectral radius of a product of matrices each of which has positive spectral radius which is an eigenvalue. He constructed expected-value generalized matrix norms and showed their applicability to error matrices in input-output modeling. He produced a complete classification for all square matrices for which zero is not in the field of values for any power of the matrix.

**TITLE:** Twenty-Third Southeastern International Conference on  
Combinatorics, Graph Theory and Computing

**PI:** Frederick Hoffman  
Florida Atlantic University  
Department of Mathematics  
(407) 391-7745

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 411105T---02

**CONTRACT NO:** N0001492J1003

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The objective is to advance the state of knowledge and disseminate the latest results in combinatorics, graph theory, and computing.

**Approach:**

The conference will be in Boca Raton, Florida on 3-7 February 1992. It will bring together researchers in discrete mathematics to discuss recent results in graph theory, combinatorics, computing and applications. The conference features a number of instructional lectures by leaders in these fields. This is now a major annual international conference in its disciplines, and plays a significant role in disseminating new results and in fostering collaborative work.

**TITLE:** Towards a Theory of Generalized Degrees with Applications to Graphs and Network Problems

**PI:** Ralph J. Faudree  
Memphis State University  
Department of Mathematical Sciences  
(901) 678-2482

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111052---02

**CONTRACT NO:** N0001491J1085

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The primary objective is to determine the relationship between new neighborhood union conditions and various graph properties and parameters. Of particular interest is deriving routing and scheduling information from these parameters.

**Approach:**

Neighborhood union properties yield bounds on the cardinalities of independent sets, arbitrary sets of determined cardinality, and cliques. These neighborhood union conditions will be used to obtain sufficient conditions for the existence of edge disjoint hamiltonian paths or cycles, s-matchings, and multiple edge disjoint matchings. The density of a graph is also bounded by degree and neighborhood conditions. These bounds will be determined.

**Progress:**

A generalization of the Ore condition for hamilton-connectedness of graphs was developed by utilizing both neighborhood union and intersection properties. A product lower bound was established for the domination number of the cartesian product of graphs when at least one graph has a special type of partition. Grantee proved that any nonbipartite two-connected graph on  $n$  vertices, with  $n$  sufficiently large, and minimum degree at least  $2n/(k+2)$ ,  $k$  odd, contains a  $k$  cycle. Neighborhood union conditions in claw-free graphs that are sufficient to guarantee that the graph be traceable or pancyclic were derived.

**TITLE:** A Graph Theoretic Approach to Stability

**PI:** Margaret B. Cozzens  
Northeastern University  
Department of Mathematics  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111053---02

**CONTRACT NO:** N0001491J1097

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The goal is to develop a theory of local node and arc stability, and in particular to determine optimal subgraphs relative to a variety of graphical stability parameters. Algorithms for finding optimal subgraphs for the most important of these parameters will be developed.

**Approach:**

Cases of node failure, arc failure, and combination node-arc failure will all be addressed. The first task is to determine which graphical parameters best preserve properties of interest. For those parameters, good algorithms will be written for constructing parameter-preserving subgraphs. These algorithms will be used to solve the problem of reconfiguring the network subject to the type of failure being considered.

**Progress:**

The grantees produced new bounds on the maximum number of crossings in a drawing of a graph. They also constructed some graphs that meet the upper bound even though they contain many 4-cycles. The graph parameter "tenacity" was introduced by combining the notions of graph integrity and graph toughness. They computed the tenacity of a large number of classes of graphs. Based on those computations they have conjectured that the tenacity is always determined by a maximum set of disjoint components in an induced subgraph of the graph. Preliminary work is complete on a Macintosh-based system to compute integrity and other vulnerability parameters of graphs.

**TITLE:** The Clemson Mini-Conference on Discrete Mathematics

**PI:** Renu Laskar  
Clemson University  
Mathematical Sciences  
(803) 656-5218

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111054---02

**CONTRACT NO:** N0001492J1021

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The objective is to advance the state of knowledge and disseminate the latest results in discrete mathematics.

**Approach:**

The conference will be held at Clemson University, Clemson SC, on 3-4 OCT 1991. It will bring together researchers from all areas of discrete mathematics to discuss recent results and attempt to extend them through sessions devoted to problem specific working groups.

**Progress:**

Last year's Clemson Mini-Conference on Discrete Mathematics was the fifth in the series, and was held during October 11 and 12, 1990. The conference featured twelve major addresses as well as ample discussion time for participants, and succeeded in its stated objective. The proceedings are available.

**TITLE:** Graphs and Matrices: Combinatorial Analysis,  
Competitions, Covers, and Ranks

**PI:** Richard L. Lundgren  
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Department of Mathematics  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111055---04

**CONTRACT NO:** N0001491J1145

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

A mix of graph theoretic and matrix theoretic techniques will be developed with an eye on applications to communication networks. Various clique covering methods will be extended.

**Approach:**

The pattern of zeros in a matrix will be used to determine the combinatorial properties of the matrix. Conditions will be found under which generalized competition graphs have special properties, such as being chordal graphs, or interval graphs. Further relationships between biclique covers of digraphs and matrix ranks will be produced.

**Progress:**

Grantees produced new results on minimum boolean and nonnegative integer rank of regular  $(0,1)$ -matrices giving equivalent results on minimum biclique covering numbers and partition numbers for regular bipartite graphs and digraphs. They produced bounds on the minimum number of complete bipartite subgraphs needed to cover and partition the edges of a regular bigraph. The competition graph of a digraph was generalized to the competition multigraph of a digraph and upper and lower bounds for the multicompetition number for several classes of multigraphs were computed. Grantees also characterized those graphs that are the conflict graphs of strongly connected or hamiltonian digraphs.

**TITLE:** The Fifth Annual Cumberland Conference on Graph Theory and Computing

**PI:** Linda Lawson  
East Tennessee State University  
Department of Mathematics  
(615) 929-4349

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111056---02

**CONTRACT NO:** N0001492J1031

**CURRENT END DATE:** 30 NOV 1992

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The technical objective is to advance the state of knowledge and disseminate the latest results in discrete mathematics and computer science.

**Approach:**

The conference will be in Johnson City, Tennessee during 14-16 MAY 1992. It will bring together researchers in discrete mathematics and computer science. A specific focus is on the applications of each discipline to the problems of the other. Discrete topics include graph models of computers, digraph scheduling models, graphical networks, and partially ordered data structures. The computer science focus is primarily on algorithms for discrete structures. This is a growing conference with increasing influence on reserach directions throughout the mid-south.

**TITLE:** Efficient Communication in Networks

**PI:** Roger C. Entringer  
University of New Mexico  
Department of Mathematics and Statistics  
(505) 277-4613

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111057---02

**CONTRACT NO:** N0001491J1385

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The objective of this research is to develop methods for measuring the efficiency of communication in both static and dynamic networks. The further objective is to integrate aspects of both vulnerability and efficiency into network design.

**Approach:**

Measures of efficiency in networks will be developed and analyzed. These include delay in trees, optimal trees in networks, and bisection properties of subgraphs. Enumeration of trees under optimality conditions will be used to extend results on trees to general networks.

**Progress:**

The subdivision threshold for a graph  $G$  is the maximum number of edges in a graph with specified number of vertices so that no piece of  $G$  is a proper subgraph of that graph. The grantees constructed the subdivision threshold for a class of graphs and characterized the extremal graphs belonging to the class. They also produced a list of all trees with eleven vertices and counted the internal paths of each tree. This significant computational result extends the results known for smaller trees and validates their tree-counting methods. They also determined which trees have maximum and minimum transmission, a quantity related to the number and distribution of internal paths of the tree.

**TITLE:** Efficient Algorithms for Searching a Family of Trees

**PI:** Allen J. Schwenk  
Western Michigan University  
Department of Mathematics & Statistics  
(616) 387-4532

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111058---02

**CONTRACT NO:** N0001491J1364

**CURRENT END DATE:** 31 MAR 1994

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The objective is to find optimal algorithms for searching a family of trees or computing a parameter for all members of a family of trees. Specific approaches will be sought for specialized families of trees, such as binary trees and trees with bounded degree.

**Approach:**

Attention will focus on alternative orderings for families of trees. Parameter specific orderings will be derived and compared with orderings known to be good for simple searching. Crude asymptotic bounds on the computational cost will be replaced with precise formal analysis. Partitionings for the family of trees will be considered so as to determine the value of parallelizing the search.

**Progress:**

The grantee found bounds for the number of multicolored spanning trees in the acyclic decompositions of a complete bipartite graph. It was also proved that the decompositions into  $n$  color classes, every one a star, are naturally in one-to-one correspondence with the tournaments of order  $n - 1$ . Bounds for their number were also found. The grantee also produced a matrix whose determinant yields a lower bound on the full number of multicolored spanning trees.

**TITLE:** Diametral Path Graphs and Incremental Distance Sequences

**PI:** Jitender S. Deogun  
University of Nebraska Lincoln  
Computer Science and Engineering Department  
(402) 472-5033

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111059---02

**CONTRACT NO:** N0001491J1693

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

This research will produce structural information about the class of diametral path graphs similar to the type of information known about distances in interval graphs. Other classes of graphs with well-behaved distance properties will be compared with this class. Efficient algorithms for computing distance properties for this class will be constructed.

**Approach:**

Incremental distance sequences for diametral path graphs will be constructed. Important parameters that are NP-hard to compute for graphs in general will be examined in diametral path graphs. These include the size of minimal hamiltonian completions, and the order of maximal cliques. It will be determined if every co-comparability graph is a diametral path graph, and if the strong perfect graph conjecture holds for this class.

**Progress:**

The problem of completing a hamiltonian path or cycle in a cocomparability graph was proved to be of polynomial time complexity. Grantee used this theorem to construct a polynomial time algorithm for determining when a cocomparability graph is hamiltonian. A jump number problem has been partially solved for the interval order case by creating a polynomial time algorithm for constructing a linear extension of an interval order that minimizes the number of jumps from the original partial order.

**TITLE:** Flows and Cycle Covers - Research in Graph Theory

**PI:** Hong-Jian Lai  
West Virginia University  
Department of Mathematics  
(304) 293-2014

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111060---02

**CONTRACT NO:** N0001491J1699

**CURRENT END DATE:** 31 MAY 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The goal of this research is to prove several outstanding conjectures about the existence of specific-valued integer flows on graphs and about the existence of cycle double covers in graphs.

**Approach:**

The kernel-reduction technique will be applied to the cycle double cover problem. Grantee's 4-cycle-reduction technique will be applied to the k-flow problem. Grantee will develop and apply reduction techniques based on the set of graphs with a k-flow for a specific value of k.

**Progress:**

Grantee proved Bondy's small cycle cover conjecture for the case of planar graphs, that is, that every planar graph with n vertices, n at least six, has a cycle cover with at most  $(2n - 1)/3$  cycles. Those non-supereulerian graphs in which every two-edge-connected induced subgraph is supereulerian were characterized. The grantee proved that in any two-edge-connected graph not having a minor of the complete graph on five vertices every partial cycle cover extends to a full cycle cover.

**TITLE:** On the Optimality of Clustering

**PI:** Uriel G. Rothblum  
Rutgers University  
Rutgers Center for Operations Research  
(908) 932-5633

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111061---01

**CONTRACT NO:** N0001492J1142

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The goal is to develop new methods for optimizing clustering techniques and applying these methods to problems such as partitioning and classification.

**Approach:**

Both conic hulls and convex hulls of partitions of point sets will be used to determine if a clustering method is optimal with respect to certain natural conditions. Methods used in operations research and mathematical programming will be applied to find extreme points of partition polytopes.

**TITLE:** Cluster Analysis Algorithms

**PI:** Pierre Hansen  
Ecole des Hautes Commerciales, Montreal  
Operations Research  
(514) 340-6053

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111062---01

**CONTRACT NO:** N0001492J1194

**CURRENT END DATE:** 30 SEP 1994

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

This research will develop algorithms for a wide variety of clustering problems. This includes methods for constructing dissimilarity indices, automated methods to select the best partitions among efficient ones, and new and informative ways to represent partitions and hierarchies.

**Approach:**

A wide variety of different families of clustering criteria will be examined, with a view to finding a uniform methodology for devising clustering algorithms. To test the methodology, algorithms will be written for many members of these families.

**TITLE:** International Conference on Random Mappings, Partitions,  
and Permutations

**PI:** Simon Tavaré'  
University of Southern California  
Department of Mathematics  
(213) 740-8766

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111063---01

**CONTRACT NO:** N0001492J1473

**CURRENT END DATE:** 30 NOV 1992

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The objective is to advance the state of knowledge and disseminate the latest results in random mappings, partitions and permutation.

**Approach:**

A conference will be held including contributed papers as well as invited addresses. The conference will be held at Los Angeles, California on 3-6 JAN 1992.

**TITLE:** Consensus by Voting; Tournaments; Centrality in Graphs

**PI:** Kenneth B. Reid  
California State University, San Marcos  
Department of Mathematics  
(619) 471-4164

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111064---01

**CONTRACT NO:** N0001492J1400

**CURRENT END DATE:** 31 DEC 1994

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The objective of this research is to understand several methods of consensus building and clustering by preference, specifically the impact of voting by agenda. Results will be applied to both desirable and non-desirable facility location problems.

**Approach:**

Tournaments will be used to model a wide variety of restricted preference schemes. Different rules for selecting aggregate tournaments will be competitively analyzed with respect to desirable qualities. To apply these results to facility location theory, centrality measures in trees will be extended to more general graphs. The notion of "centrality in a family" of structures will be analyzed as the basis for preference schemes.

**TITLE:** Image Representation, Clustering, and Search in Proximity  
Graphs and Pathfinder Networks

**PI:** Don Dearholt  
Mississippi State University  
Department of Computer Science  
(601) 325-2756

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111065---01

**CONTRACT NO:** N0001492J1509

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The objective of this research is to demonstrate the viability of the cluster-learning paradigm in pathfinder networks as a method for generating databases suitable for robotic vision systems. Pathfinder networks will be used to develop methods of representing images as networks and the method will be tested on a suitable set of objects.

**Approach:**

Research will be performed to improve the generation, representation, and presentation of pathfinder networks. They will be applied to MSNET, a vision database for robotics applications which supports sublinear search. Clustering in this database amounts to gathering similar images, and the representation of images as proximity graphs yields a new clustering methodology that will be investigated. Pathfinder networks will be built that reflect the knowledge inherent in the new clusters.

**TITLE:** ONR Workshop on Discrete Structures in Classification

**PI:** Fred R. McMorris  
University of Louisville  
Department of Mathematics  
(502) 588-6826

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4111066---01

**CONTRACT NO:** N0001492J1574

**CURRENT END DATE:** 30 JUN 1993

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The objective of the workshop is to determine the state-of-the-art in Discrete Structured Classification, and chart new directions of research relevant to Navy needs.

**Approach:**

The workshop will be held in Chantilly, VA during 5-6 MAY 1992. There will be presentations by both Navy laboratory researchers and ONR grantees in the area of Discrete Structured Classification (DSC). The laboratory presentations will focus on problem areas of importance to the Navy that may be solvable by the techniques of DSC, so the grantees will know where the applications are. Extensive one-on-one interactions between grantees and Navy personnel will be encouraged.

**TITLE:** Development of a Vector Extremal Model for the Navy's  
Awaiting Instruction Problem

**PI:** A. Charnes  
The University of Texas at Austin  
Center for Cybernetic Studies  
(512) 471-1821

**FUNDING AGENCY:** Office of Naval Technology

**R&T PROJECT CODE:** 4428039---01

**CONTRACT NO:** N0001492J1538

**CURRENT END DATE:** 29 MAR 1994

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The grantee will develop a vector extremal model for the Navy's Awaiting Instruction Problem that links all parts of the system and takes into account the diverse goals and constraints of the different schools. This model will permit computation of a dollar value for the delayed entry program based on instructor costs and awaiting instruction time.

**Approach:**

Vector extremal problem formulations of new multipage constrained directed networks will be essayed and computational methods developed to compute flows on these networks. Constraints on the flows will be used to model the effects of awaiting instruction time and delayed entry. Operations research techniques will then be applied to determine minimum costs for the system.

**Numerical Analysis**

**TITLE:** Computational Studies of Stratocumulus Layers

**PI:** Joseph Oliger  
Leland Stanford Junior University  
Department of Computer Science  
(415) 723-0571

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 411q001---04

**CONTRACT NO:** N0001490J1344

**CURRENT END DATE:** 30 JUN 1994

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to use computation to explore the structure and mechanisms of the marine boundary layer and in the process to develop new computational techniques which will have general applicability. A further objective is to provide predictive modeling capability.

**Approach:**

Initial research, aimed at basic understanding, will be carried out with a simple Boussinesq model of the sort that has been used in theoretical studies of shear flows. When the basic physics, parameterization, and turbulence modeling considerations have been sorted out, a model using the Browning/Kreiss equations with suitable adaptivity will be constructed for predictive use.

**Progress:**

A stability analysis of the equations governing stratus layers is largely complete and scaling analysis is underway using data supplied by meteorologists at Colorado State University. Prototype numerical models based on both the Boussinesq and compressible Navier-Stokes equations have been completed. All three of these tools will be used in a mutually supportive way to explore the stability behavior of the marine boundary layer and the appropriate mathematical model(s) for its description and prediction.

**TITLE:** Dynamics of and Characteristics of  
Numerical Models of Weakly  
Non-Linear Ocean Flows

**PI:** Leonard J. Walstad  
Oregon State University  
College of Oceanography  
(503) 737-2070

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 411u001---01

**CONTRACT NO:** N0001492J1265

**CURRENT END DATE:** 31 DEC 1996

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to characterize the performance of the reduced model and a primitive equations-based model (a surrogate for nearly all existing ocean models) for solving boundary value problems in oceanography and for forecasting using data assimilation.

**Approach:**

Six to ten different physical problems in the ocean will be considered. All are interconnected in ways which will shed light on the performance of the two classes of models. Most problems will be formulated in the context of the California Current so that the large scale ONR experimental efforts in the Current can be used both to supply data to the models and to check the accuracy/adequacy of the numerical results.

**TITLE:** Three Decades of Numerical Linear Algebra at Berkeley

**PI:** James Demmel  
University of California, Berkeley  
Electronics Research Laboratory  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 411u002---01

**CONTRACT NO:** N0001492J1561

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to bring together a distinguished group of researchers in the fields of numerical linear algebra and computer arithmetic so that the interface can be explored.

**Approach:**

A conference will be held with 12 invited speakers. Participants will be chosen both for expertise in their own fields and in light of the degree to which their research suggests the potential for interaction with the other topic of the meeting. The speakers will write review articles which will be published as a group in a special issue of the Journal of Numerical Linear Algebra with Applications, providing a valuable and lasting reference for other researchers in these fields and engineers in a broad range of applications.

**TITLE:** Research in Efficient Scientific Computation

**PI:** Beresford N. Parlett  
University of California, Berkeley  
Center for Pure and Applied Mathematics  
(415) 642-6655

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113324---07

**CONTRACT NO:** N0001490J1372

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

This work aims to reduce the substantial computer time required to do the numerical linear algebra required for the computer solution of partial differential equations. Among the equations addressed will be those used in vehicle design and in weather and ocean prediction.

**Approach:**

This research will concentrate on two distinct topics. The first is promoting the sort of computer system regularity which leads to a uniform interface for performing scientific and engineering computations. Here the work will build on previous research which was incorporated in the IEEE standard for computer arithmetic. Secondly, research on linear algebra will emphasize matrix exponential and block and asymmetric eigenvalue algorithms.

**Progress:**

A new and very efficient algorithm for the bidiagonal singular value problem was developed. The paper won the second Society for Industrial and Applied Mathematics Linear Algebra Prize (1991). This exceptional work will find application in both signal/array processing and engineering computation.

**TITLE:** Adaptive Approaches and Error Estimations in Finite Element Applications and Mathematical Modeling

**PI:** Ivo Babuska  
University of Maryland  
Institute for Physical Science and Technology  
(301) 454-4469

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113522---10

**CONTRACT NO:** N0001490J1030

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The objective is to develop algorithms for the computer solution of partial differential equations. This will make it possible to solve new classes and categories of equations (by providing the required speed) and, as a side benefit, speed up the solution of equations which are presently used. An equally important objective is to provide error estimates and error control procedures to assure the user of the methods that the solutions accurately reflect physical reality. Both objectives are crucial for improved vehicle design and for predictive capability in geophysical fluid mechanics.

**Approach:**

New and improved adaptive solution methods will be developed. Approaches to a posteriori error estimation, first developed for adaptive algorithms, will be extended to more general error estimation contexts. Other approaches, such as expert systems, for error control will be explored.

**Progress:**

Based on previous research under this grant, which developed the extraordinarily efficient HP finite element method, a very efficient method for predicting the propagation of cracks in structures was developed. This new method appears to make it possible for the first time to realistically implement the currently applicable milspec for cracks in aircraft structures.

**TITLE:** Adaptive Approaches and Error Estimates in Finite Element Applications and Mathematical Modeling

**PI:** W. C. Rheinboldt  
University of Pittsburgh  
Department of Mathematics and Statistics  
(412) 624-8381

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113562---09

**CONTRACT NO:** N0001490J1025

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The objective is to develop algorithms for the computer solution of partial differential equations. This will make it possible to solve new classes and categories of equations (by providing the required speed) and, as a side benefit, speed up the solution of equations which are presently used. An equally important objective is to provide error estimates and error control procedures to assure the user of the methods that the solutions accurately reflect physical reality. Both objectives are crucial for improved vehicle design and for predictive capabilities in geophysical fluid mechanics.

**Approach:**

New and improved adaptive solution methods will be developed. Approaches to a posteriori error estimation, first developed for adaptive algorithms, will be extended to more general error estimation contexts. Other approaches, such as expert systems, for error control will be explored.

**Progress:**

A general existence and uniqueness theory was developed for differential-algebraic equations which extends the well known ODE theory. It was shown that differential-algebraic equations carry a geometric content in that they are locally equivalent to ODE's on a constraint manifold.

**TITLE:** Computing Methods for the Approximate Solution  
of Time Dependent Problems

**PI:** Joseph Olinger  
Leland Stanford Junior University  
Department of Computer Science  
(415) 723-0571

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113629---09

**CONTRACT NO:** N0001489J1815

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The objective is to develop improved algorithms and programming techniques for the computer solution of problems in meteorology, oceanography, aerodynamics and hydrodynamics.

**Approach:**

The goals will be approached via adaptive methods, meta-algorithms, improved open boundary conditions, parallel algorithms and improved data structures.

**Progress:**

Substantial progress was made on the long term goal of producing a set of software engineering tools suitable for use by scientists implementing methods for scientific and engineering computing. A key part of this suite of tools which is nearing completion is a package for creating adaptive methods for the solution of partial differential equations; advanced methods for creating and graphically editing grids are included.

**TITLE:** Mathematical Treatment of Modeling in Computational Mechanics

**PI:** Soren Jensen  
University of Maryland  
Department of Mathematics  
(301) 455-3294

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113635---06

**CONTRACT NO:** N0001490J1238

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

Most vehicles and platforms undergo structural analysis which is essential for performance and durability. Computer limitations often dictate that three dimensional structural problems be solved via a 2-D approximation. This project will develop techniques which improve the computational gain from this approximation and tightly control the error involved.

**Approach:**

The energy asymptotic method was recently applied to relatively simple nonlinear monotone problems on simple domains. Under this grant more general nonlinear problems and more complex domains will be investigated. Adaptive methods will be explored, methods for systems of equations will be investigated and tight error estimates will be derived. Analysis will be extended from just "brittle" to "ductile" and "plastic" materials and to more general constitutive laws appropriate to layered and inhomogeneous materials. The previous restriction to special deformations (anti-plane shear) will be removed.

**Progress:**

A feedback method for dimensional reduction was developed for the numerical solution of a class of nonlinear boundary value problems associated with anti-plane shear, Hencky's theory of plasticity or Maxwell's equations for the magnetic field potential. Under appropriate smoothness conditions the procedure was shown to be adaptive, i.e., optimal with respect to convergence rate.

**TITLE:** Adaptive Multi-Level Techniques for Solving Partial  
Differential Equations

**PI:** Randolph E. Bank  
University of California, San Diego  
Department of Mathematics  
(619) 534-4204

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113638---05

**CONTRACT NO:** N0001489J1440

**CURRENT END DATE:** 30 SEP 1994

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to develop methods which will make possible the solution of broad classes of partial differential equations which are not now solvable either because operation counts are too large or because subtle nonlinearities preclude solution. Emphasis will be placed on equations relevant to semiconductor simulations.

**Approach:**

The approach will be via combinations of adaptive methods and multigrid methods and a variety of geometric approaches to nonlinear problems with parameters. Transformation techniques will be applied to the circuit simulation problem. Many of the methods developed will be incorporated into transportable software.

**Progress:**

A method was developed which is suitable for solving the linear equations of semiconductor device modeling in three dimensions -- a first. The complexity of general sparse Gaussian elimination via bordering was analyzed and substantial storage savings were documented. Progress was made in understanding the discretization of elliptic equations in three dimensions. Many improvements were made in the PLTMG nonlinear partial differential equations software.

**TITLE:** Numerical Solution of Radar Scattering Problems  
via Boundary Integral Equations

**PI:** Vladimir Rokhlin  
Yale University  
Department of Computer Science  
(203) 432-1200

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113640---05

**CONTRACT NO:** N0001489J1527

**CURRENT END DATE:** 31 OCT 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to devise an algorithm which is capable of accurately calculating the 3D microwave scattered field from most objects of engineering interest in something like one hour on an XMP-class computer.

**Approach:**

The approach is to reduce the Helmholtz equation on an object to a second kind integral equation on the boundary of the object. The resulting system of dense linear equations can then be solved with very high efficiency. The ultimate goal is a full three dimensional code, but as an interim measure, an axisymmetric code will be developed. The axisymmetric code will be useful in itself (e.g., for radome calculations) and will allow many of the problems of the 3D code to be anticipated and solved in a simpler context.

**Progress:**

Several methods were developed for the direct solution of the linear equations generated by the multipole method. For these problems and to the extent that the direct methods can be applied in 3D, they largely eliminate the very troublesome problem of ill-conditioning for scattering applications. The mathematics required to extend the fast multipole method to 3D scattering was completed; a simple demonstration of the ability to calculate the scattered field from an object of the order of one hundred wavelenths long will be forthcoming soon.

**TITLE:** Circuit and Semiconductor Simulation

**PI:** Donald J. Rose  
Duke University  
Department of Computer Science  
(919) 660-6544

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113641---04

**CONTRACT NO:** N0001489J1644

**CURRENT END DATE:** 31 OCT 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to develop numerical methods which will apply to a range of partial differential equations but will be especially effective for semiconductor and circuit simulations. These will increase the range of semiconductor phenomena which can be modeled and greatly increase the size of circuits which can be simulated.

**Approach:**

The most important idea to be pursued is that of operator theoretic methods, an innovation of the PI. The concept is to view a set of nonlinear equations as an operator in an appropriate Banach space and to apply the methods of functional analysis before proceeding to solution details. In this context it will likely prove possible to use different time scales for different collections of variables.

**Progress:**

The new norm decreasing approximate Newton method developed here, also known as waveform methods in the engineering literature, was shown to provide a three to ten fold efficiency increase for typical circuit simulation problems. For some applications such as smart power the advantage is likely to be much greater. The technique, which can be characterized as space sensitive time adaptivity, has been generalized beyond the circuit context.

**TITLE: Fast PDE Solvers**

**PI: Bjorn Jawerth**  
**University of South Carolina**  
**Department of Mathematics**  
**(803) 777-2632**

**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4113643---03**

**CONTRACT NO: N0001490J1343**

**CURRENT END DATE: 31 DEC 1992**

**SCIENTIFIC OFFICER: Richard L. Lau**

**Technical Objective:**

The aim is to explore both the range of applicability and the potential efficiency of methods for the solution of partial differential equations based on the phi transform.

**Approach:**

Four principal lines of research will be developed: 1) develop fast PDE solvers on nonsmooth domains, 2) incorporate adaptivity into these fast solvers, 3) investigate the applicability of phi transform-based methods to time dependent problems, and 4) integrate geometric modeling with other developments.

**Progress:**

Successful preliminary work was carried out to incorporate boundary conditions into fast wavelet methods for solving partial differential equations, thus removing the restriction of such methods to integral equations. A new form of wavelet-based image compression was developed, and transition to the SLAM Improvement Program already seems assured.

**TITLE:** Numerical Solution of Partial Differential Equations

**PI:** Heinz O. Kreiss  
University of California, Los Angeles  
Department of Mathematics  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113644---03

**CONTRACT NO:** N0001490J1382

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is both to understand turbulence better and to use this understanding to devise methods to compute a wider variety of turbulent flows. For flows with different time scales the aim is to better understand the interactions of the different scales, to devise better numerical methods and to apply these insights and methods to practical problems.

**Approach:**

Turbulence investigations will include: smallest scales near boundaries, maximal dissipativity, formation of inertial ranges, effect of compressibility, and stability of calculations. For multiple time scales new numerical schemes will be developed, viscosity will be included, interactions between scales will be explored, and applications will be made in oceanography and meteorology.

**Progress:**

A new approach to the computation of flow about a submarine, submarine wake calculations, and flow generated noise was developed. A new approach to the computation of high Reynolds number compressible flow was developed. This approach was able to predict certain experimentally observed flow features previously not accessible to theory; it was awarded a NASA "Superior Achievement" prize.

**TITLE:** Numerical Solutions of Partial Differential Equations

**PI:** Tony F. Chan  
University of California, Los Angeles  
Department of Mathematics  
(213) 825-2601

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113645---03

**CONTRACT NO:** N0001490J1695

**CURRENT END DATE:** 31 JAN 1993

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to improve the performance of the so-called multipole method for the solution of the Helmholtz and similar equations. Performance enhancement will be pursued by examining improved methods for solving linear equations of the sort encountered in scattering. The scope of the method will be expanded by the creation of boundary conditions appropriate to the physical conditions of practical modern scattering problems. The virtues of various ocean models and associated boundary and initial conditions will be examined and characterized in a way useful for both ocean modelers and experimenters.

**Approach:**

Various forms of the preconditioned conjugate gradient algorithm will be investigated. Implementation strategies which take account of the opportunities and constraints of modern high-speed computer architectures will be devised and tested. Boundary conditions which correctly model layered scatterers, inhomogeneous bodies, internal baffles, etc. will be devised. Ocean research will be based on constraints ("balances") applied to the Browning/Kreiss and other models.

**Progress:**

An alternative form of the multipole method, which does not use multipoles, was devised and is in the process of being implemented for the scattering problem. Much enhanced efficiency is anticipated. New iterative techniques for the efficient solution of the integral equations generated by the multipole method were devised and analysed. Moving Composite Overlapping grid techniques were developed for free surface gravity wave computations.

**TITLE:** Fast Wavelet Transforms and the Numerical Solution of Hyperbolic Equations

**PI:** Stanley Osher  
University of California, Los Angeles  
Department of Mathematics  
(213) 825-1758

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113651---05

**CONTRACT NO:** N0001491J1034

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to extend numerical techniques under development for use in microwave scattering computations to the very different case of hyperbolic equations, which typically describe fluid flow.

**Approach:**

The plan is to begin with the Kreiss equation, and then to extend this to an initial boundary value problem in one dimension. The research will then proceed to higher dimensions, to Maxwell's equation and finally perhaps to nonlinear equations, beginning possibly with Berger's equation. The basic approach involves the use of wavelets or other appropriate basis functions to "sparsify" the matrix representing the pde in a way that can be used to greatly reduce the computational complexity of the solution procedure.

**Progress:**

The wavelet matrix compression technique has been applied to boundary value problems for constant coefficient hyperbolic partial differential equations. Both analysis and computational experiments have been successful and show great increases in computational efficiency. The difficult issues involved in the non-constant coefficient case are understood, but remain to be resolved.

**TITLE:** Efficient Solution Methods for Electromagnetic  
and Acoustic Scattering

**PI:** Francis X. Canning  
Rockwell International Corporation  
(805) 373-4598

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113652---04

**CONTRACT NO:** N0001491C0031

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to enhance the Impedance Localization Method by extending it in various ways so as to apply in three dimensions and to non-conducting and rough surfaces.

**Approach:**

The approach to the three dimensional extension will be via two and a half dimensional problems--axisymmetric acoustic scattering and the "wire grid" model of three dimensional microwave scattering. These projects will be pursued with NRL and NWC respectively. By way of fundamental improvements in the method, two important approaches will be the consideration of multi-level numerical methods and symbiotic relationships with the multipole method.

**Progress:**

The impedance localization method has been successfully extended from two dimensions to 3D axially symmetric problems--in theory, at least. Prospects are excellent for a successful implementation next year for the inelastic acoustic scattering problem. Results have been obtained which suggest that the full 3D submarine problem is within reach in the next few years.

**TITLE:** Acousto-Elastic Scattering and Radiation

**PI:** Luise S. Schuetz  
Naval Research Laboratory  
Structural Acoustics Division  
(202) 767-3336

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113653---02

**CONTRACT NO:** N0001492WX24172

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to extend the Interaction Localization Method to the 3D axisymmetric case to solve the acousto-elastic problem. Other goals are to illuminate the basic method, to clearly draw implementation issues, and to facilitate comparisons with wavelet-based methods.

**Approach:**

Work will begin with the scattering problem and Neumann boundary conditions. Then an algorithm will be developed and implemented for the coupled acoustic-elastic problem. Analysis will be carried out of the difficulties involved and improvements required for applying these algorithms (codes) to problems of direct interest to the development community.

**Progress:**

The Interaction Matrix Localization(IML) method has been applied to the 3D axisymmetric submarine elastic radiation problem. The expected matrix sparsity was obtained. A storage problem remains, and a new approach has been devised, but not yet tested, for coping with this problem.

**TITLE:** Fast Algorithms for Elliptic Partial Differential Equations

**PI:** Leslie Greengard  
New York University  
Department of Mathematics  
(212) 998-3315

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113654---02

**CONTRACT NO:** N0001491J1312

**CURRENT END DATE:** 28 FEB 1993

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to characterize the best implementation techniques for applying the fast multipole method to differential and integral equations. Issues include: 1. techniques for transforming differential equations to integral equations, 2. quadrature methods, 3. linear algebra, 4. parallel implementation.

**Approach:**

Work will begin with the Poisson equation in two and three dimensions. Then the far more difficult biharmonic and Helmholtz equations will be analyzed and appropriate methods will be developed. The final stage will be to produce a general purpose solver for second order elliptic partial differential equations.

**Progress:**

An implementation technique was developed for the solution of Poisson's equation using the multipole idea, but in the case of irregular domains and allowing the use of adaptivity. Rough domains and adaptivity have not been compatible with past implementations of the multipole concept, and this implementation greatly extends the applicability of the method.

**TITLE:** Approximate Models of Ocean Acoustics

**PI:** Martin H. Schultz  
Yale University  
Department of Computer Science  
(203) 432-1200

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113655---02

**CONTRACT NO:** N0001491J1576

**CURRENT END DATE:** 31 MAR 1994

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to devise mathematical/computational models for ocean acoustic propagation such that the modeling and numerical errors are well understood and minimal, given the practical constraints of data gathering and storage. A further constraint on the model is that they must be capable of efficient execution on parallel computers, since such machines are required to realize acoustic computations in real time.

**Approach:**

The approach will be based on previous work by the PI on three dimensional parabolic equation approximations and their implementation in parallel (both unique research results). With these results goes a great deal of (still unimplemented) research on crucial subproblems and related issues such the treatment of interfaces and the bottom and the inclusion of backscatter.

**Progress:**

Great progress was made in understanding how to compute not only forward acoustic propagation but also the backscattered field. Within a year a complete numerical technology for the backscatter problem should be available, including algorithms of practical use and an analysis of the errors induced by breaking the Helmholtz equation into outgoing and backscattered components. A potentially revolutionary new algorithm for the parallel solution of partial differential equations (preconditioned conjugate gradient) was developed and used to solve a 3D problem on 10,000,000 grid points in a few minutes on a 1000 processor cube.

**TITLE:** Development of Overlapping Grid Techniques for the Solution of Ocean Models

**PI:** William D. Henshaw  
International Business Machines Corporation  
(914) 945-3446

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113656---02

**CONTRACT NO:** N0001491C0081

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to make composite grids, multigrids, and high order methods simultaneously available for ocean modeling computations. Whereas each technology separately might be implemented fairly easily, the combination requires substantial innovation.

**Approach:**

High order methods combined with multigrids and composite grids will be implemented for a new ocean model being developed under ONR support at NCAR. This model is being developed in close collaboration with experimental oceanographers and will be exercised in forthcoming experiments in the California Current.

**Progress:**

A successful two dimensional implementation of composite grid techniques for use in the Browning/Kreiss ocean model was carried out. This success points clearly to the way to achieve a good three dimensional implementation.

**TITLE:** Error Analysis in Numerical Solution  
of Fluid-Structure Interaction Problems

**PI:** Ralph E. Kleinman  
University of Delaware  
Department of Mathematics  
(302) 451-2000

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113657---02

**CONTRACT NO:** N0001491J1700

**CURRENT END DATE:** 14 APR 1993

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

To objective is to develop an analytical/numerical approach to the problem of error estimation arising from the large scale computations associated with the solution of integral equations. The research has a very strong emphasis on error analysis for fluid-structure interaction problems.

**Approach:**

The approach consists of analytic determination of the optimal error norms associated with a particular fluid/structure formulation, via an appropriate choice of the underlying function space. Numerical implementation of the theory on model problems will be performed.

**Progress:**

Error analysis was successfully carried out for the hypersingular boundary integral equations of the first kind. Numerical experiments were carried out to test the potential for using residual error as a measure of actual error in the case of Fredholm integral equations of the second kind.

**TITLE:** Development of an Ocean Model Based Upon  
the Reduced System of Equations

**PI:** Gerald Browning  
Colorado State University  
Center for Atmospheric Research  
(303) 491-8448

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113658---01

**CONTRACT NO:** N0001492J1089

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to fully implement the Browning/Kreiss reduced system of equations model and to test the model against standard ocean models such the quasi-geostrophic based models.

**Approach:**

The model will be implemented with bottom topography and for curved domains. The implementation will incorporate modern numerical methods such as a combination of multigrids and component grids. This combination will be developed at IBM and ported to the model under this effort. Testing and comparisons to other approaches will use new "ocean-like" exact solutions of the Navier-Stokes equations developed under the predecessor to this effort.

**TITLE: Numerical Methods for Flow Fields with Free Surfaces**

**PI: W. G. Szymczak  
Naval Surface Warfare Center  
Research Department  
(301) 394-2284**

**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4113659---01**

**CONTRACT NO: N0001492WX24138**

**CURRENT END DATE: 30 SEP 1992**

**SCIENTIFIC OFFICER: Richard L. Lau**

**Technical Objective:**

The aim is to develop a computational method for simulating three dimensional free surface flows. The method will be applicable to the prediction of cavitation damage, explosion bubble dynamics and water exit and entry of projectiles.

**Approach:**

A fixed domain method will be developed based on the Generalized Hydrodynamic Formulation of Rogers which solves the conservation laws subject to one sided constraints. Among the advantages of this formulation is that it can correctly model liquid on liquid collisions.

**TITLE:** Analysis and Convergence of Numerical Schemes for an Anti-Plane Shear Problem

**PI:** Sonia M. Garcia  
U.S. Naval Academy  
Department of Mathematics  
(301) 267-3703

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113660---01

**CONTRACT NO:** N0001492WR24029

**CURRENT END DATE:** 28 FEB 1993

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to develop a method to perform the computations required to predict the formation and propagation of wing cracks in materials such as ice and steel. The method(s) will also contribute to advancing the state-of-the-art in solving nonlinear parabolic equations.

**Approach:**

Several numerical schemes will be considered. First will be a modified Crank-Nicholson finite difference approximation in the time variable together with a combination finite element methods in stress, temperature and displacement variables. An implementation will be carried out.

**TITLE:** The 7th IMACS International Conference  
on Computer Methods for Partial Differential Equations

**PI:** Doyle Knight  
IMACS  
Department of Computer Science  
(908) 932-3998

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113661---01

**CONTRACT NO:** N0001492J1543

**CURRENT END DATE:** 30 MAY 1993

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim is to achieve communication and the sharing of ideas and techniques among numerically intensive scientific disciplines which do not ordinarily communicate.

**Approach:**

A conference will be organized which offers specialized sessions in such subjects as ocean acoustics or lattice gases combined with methodology sessions on subjects such as parallel computing or adaptive methods. This variety will attract the diverse group of attendees required.

**TITLE:** The Numerical Analysis of Evolution  
Equations Over Long Time Intervals

**PI:** Andrew M. Stuart  
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(415) 723-2273

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4113662---01

**CONTRACT NO:**

**CURRENT END DATE:** 31 OCT 1994

**SCIENTIFIC OFFICER:** Richard L. Lau

**Technical Objective:**

The aim of this effort is to study the numerical approximation of differential equations over a very long time interval. Because these equations either exhibit chaos or possess multiple steady-state solutions, the standard techniques give rise to spurious solutions. In the context of two special classes of differential equations, the main goal is to understand the class of nonlinearities that allow the development of discretizations that relate the numerical approximation to the underlying continuous problem.

**Approach:**

Local error control mechanisms will be developed that will act to vary the time step in the discretization in such a way that spurious solutions are avoided. For fixed time stepping schemes, the PI will generalize the theories of A, B, and G-stability to dynamical systems with complex limit sets. Approximation of homoclinic and heteroclinic orbits of such dynamical systems will be studied.

**Operations Research**

**TITLE:       Algorithm Design and Evaluation**

**Andrew V. Goldberg  
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Computer Science Department  
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**FUNDING AGENCY:       University Research Initiative**

**R&T PROJECT CODE:     400x081yip02**

**CONTRACT NO:         N0001491J1855**

**CURRENT END DATE:     31 MAY 1994**

**SCIENTIFIC OFFICER:   Donald Wagner**

**Technical Objective:**

This research will provide new and efficient algorithms, both sequential and parallel, for network flow problems and linear programming. Efficiency is measured in terms of time, memory and processors. Experimental evaluation of various implementations of the algorithms is intended.

**Approach:**

The approach for finding more efficient algorithms for linear programming is to design an interior-point algorithm that does not use transformations or projections since these operations are bottlenecks in current methods. For network flow problems, several techniques will be used in the design of better algorithms, such as improved data structures, scaling and parallelization.

**Progress:**

Progress has been made in the design of network optimization algorithms. Using a simple randomization strategy, the running time of a recent algorithm of Leighton et al. has been improved. Second, an algorithm for determining what is the minimum amount by which the capacities of an infeasible transportation problem must be increased to make it feasible has been found. Its running time significantly improves previous bounds. Work on a parallel implementation of a maximum flow algorithm and a sequential implementation of a minimum-cost flow algorithm are also in progress.

**TITLE:** Solving Integer Generalized Networks

**PI:** Michael A. Trick  
Carnegie-Mellon University  
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**FUNDING AGENCY:** University Research Initiative

**R&T PROJECT CODE:** 400x096yip01

**CONTRACT NO:** N0001492J1387

**CURRENT END DATE:** 30 APR 1995

**SCIENTIFIC OFFICER:** Donald Wagner

**Technical Objective:**

This research will provide new and efficient algorithms for integer generalized network flow problems. The objective is to build on previous research on cutting planes and linear generalized network flow algorithms, and combine these techniques in a optimization routine for the integer version. Particular attention will be given on how to properly exploit the underlying network structure of the problem.

**Approach:**

The research will employ a three-part approach. First, an efficient code will be developed for the linear generalized network flow problem. To be useful in the integer setting, the code will be designed for efficient reoptimization after adding constraints. Second, useful valid inequalities will be found, and third, algorithms for solving the separation problem over the inequalities will be developed.

**TITLE:** New Approaches to Linear and Nonlinear Programming

**PI:** Walter Murray  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 411k003---07

**CONTRACT NO:** N0001490J1242

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Donald Wagner

**Technical Objective:**

The objective of this research is to develop efficient interior-point methods for linear and quadratic programming. Particular emphasis will be in the development of efficient procedures for solving the linear least-squares problem, which occurs as a subproblem in interior-point methods.

**Approach:**

This research will develop primal and dual interior-point methods for linear and quadratic programming-problems. The approach will be to view interior-point methods as barrier-function methods. The associated linear least-squares problem will be solved using preconditioned conjugate-gradient methods based on either LU or Cholesky factorization techniques. Possible application of these new approaches to nonlinear problems will also be investigated.

**Progress:**

A primal-dual interior point method for linear programming has been developed that allows for an adaptive step length, which closes the gap between theoretically efficient short step methods and empirically efficient long step methods. An interior point method for nonlinear convex programming problems has been developed. The algorithm uses the predictor-corrector strategy, and maintains the sparsity of the matrices assuming that the functions are separable.

**TITLE:** Mathematical Aspects of Discrete Event Dynamic Systems

**PI:** Yu-Chi Ho  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4116651---07

**CONTRACT NO:** N0001490J1093

**CURRENT END DATE:** 30 NOV 1992

**SCIENTIFIC OFFICER:** Donald Wagner

**Technical Objective:**

The objective is to develop a theory of discrete event dynamic systems analogous to the control theory of continuous dynamical systems. Such a theory will provide a basis for the design of optimal controls for discrete systems and to increase our ability to infer behavior of such systems from simulated results.

**Approach:**

One important aspect involves deriving the capability to accommodate simulations in which small perturbations cause the order of events to change. This phenomenon makes the results of replications using different random number streams incomparable and the corresponding mathematical analysis more difficult. Experiments will be conducted to test the theoretical results.

**Progress:**

Computational experiments were conducted using the gradient surface method for optimization of discrete event dynamical systems. In the gradient surface method, the gradient estimation is obtained by either perturbation analysis or likelihood ratios, and the performance gradient surface is obtained from observations at various points in a fashion similar to response surface methodology. This yields greatly increased efficiency. Several previously computationally infeasible problems were solved with this new method.

**TITLE:** New Algorithmic Developments in Nonlinear Optimization

**PI:** Anthony V. Fiacco  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4116652---07

**CONTRACT NO:** N0001489J1537

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The objective of this research is to develop and test barrier and penalty methods for convex and non-convex programming problems. Emphasis will be on efficient implementations and proving convergence of these methods. A new method for non-convex fractional programming will also be developed.

**Approach:**

A theory for exterior-point methods will be developed that is parallel to that which exists for interior-point methods. Using the Courant quadratic-loss penalty function, exterior-point algorithms for both linear programming and convex programming will be developed with the goal of establishing a polynomial-time complexity bound. Techniques for solving non-convex fractional programming problems as a sequence of linear programming problems will be investigated. By using techniques like those developed for SUMT, the convergence rate of primal-dual methods for non-convex programming problems will be examined.

**Progress:**

A method that globally optimizes the sum of ratios of linear forms has been developed. It operates by transforming the decision space into an image space in which the optimization is easily performed along special search directions. In other work, methods for automatically generating bounds on variables in a nonconvex programming problem were found. A primal-dual algorithm for nonconvex programming problems was devised and implemented. It was shown to have a superlinear rate of convergence in the absence of primal and dual degeneracy.

**TITLE:** Intermodal Logistics

**PI:** H. D. Ratliff  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4116657---08

**CONTRACT NO:** N0001489J1571

**CURRENT END DATE:** 31 JAN 1992

**SCIENTIFIC OFFICER:** Donald Wagner

**Technical Objective:**

The technical objective is to create models and solution algorithms for operational distribution and logistics problems involving intermodal networks, which are distribution networks that allow for more than one type of transportation vehicle. Of particular interest are the problems of network design, routing and scheduling of vehicles and handling of material at the interface of different types of vehicles.

**Approach:**

The research will combine discrete optimization, optimization-based heuristics and object-oriented interactive modeling for solving the problems associated with intermodal networks. For example, new techniques need to be developed for determining optimal location of intermodal terminals, i.e. points where material is transferred from one mode of transportation to another. Standard network optimization techniques such as shortest path algorithms need to be extended to allow for quantity discounts and the capacity problems encountered when switching from one mode to another.

**Progress:**

Progress has been made in the area of guaranteed-time distribution networks, which are network problems in which the movement of items between any source-destination pair must be completed within a guaranteed period of time. Decisions have to be made regarding the location of accumulation points, which are where changes in the mode of travel occur. Customers are allocated to these points in such a way that travel time is minimized. For tree-structured networks, efficient algorithms have been developed that locate accumulation points, allocate customers and provide the best-possible time guarantee.

**TITLE:** Solution Procedures for Large-Scale Combinatorial Optimization Problems

**PI:** Karla L. Hoffman  
George Mason University  
Operations Research and Applied Statistics Department  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4116663---06

**CONTRACT NO:** N0001490J1324

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Marc J. Lipman

**Technical Objective:**

The objective of this research is to develop new techniques for solving large-scale integer optimization problems. Such problems are extremely important in logistics, financial planning, and resource allocation.

**Approach:**

Recently obtained results concerning the geometry of polyhedra will be used to develop tight formulations of integer-programming problems. Good upper and lower bounds on the optimal solution value will be obtained via numerical preprocessing. A branch-and-cut strategy using variable fixing is employed as a solution procedure. Heuristics techniques are used to obtain the violated inequalities needed in the cutting phase of the branch-and-cut procedure.

**Progress:**

Progress continues to be made on a branch-and-cut algorithm for solving large-scale integer programming problems. The branch-and-cut approach combines automatic reformulation procedures, heuristics for finding good feasible solutions and cutting-plane techniques in a tree-search format. It is currently being used to solve set-partitioning problems arising from crew scheduling in the airline industry. To date, the largest such problem that has been solved to optimality has over one million variables. A similar polyhedral approach is being devised for solving the set-covering problem with side constraints.

**TITLE: Production Systems Analysis**

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**Industrial Engineering Department**  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4116665---08**

**CONTRACT NO: N0001490J1009**

**CURRENT END DATE: 30 SEP 1994**

**SCIENTIFIC OFFICER: Donald Wagner**

**Technical Objective:**

The objective of this effort is the analysis of fundamental scheduling problems and related models. These include optimal resource planning and real-time scheduling of stochastic shop-floor processes. Scheduling systems will be developed that can adapt to the highly stochastic nature of the shop floor and constantly changing objectives of management.

**Approach:**

The grantee will model and optimize real, complex scheduling systems. This involves the development of specific models of the shop-floor process, real-time simulation of the induction scheduling and rework process, and development of optimization schemes for induction scheduling, resource planning and real-time shop floor scheduling. The models will be tested and evaluated at Cherry Point Naval Aviation Depot.

**Progress:**

Progress has been made in several areas, including scheduling of material handling systems and of Automated Guided Vehicles (AGVs). In a material handling system, the variability of products flowing through the system necessitates dynamic scheduling of the material handling devices. A branch-and-bound scheme was developed for effective real-time scheduling of these devices, which resulted in reducing manufacturing lead time. In the scheduling AGVs, a Markov decision process model was developed to aid in optimal control of the AGV system. Combined with a heuristic scheme, the resulting scheduling system dominated standard industry techniques when tested via simulation.

**TITLE:** Combinatorial Optimization: Algorithms and Applications

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4116666---06

**CONTRACT NO:** N0001489J1063

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Donald Wagner

**Technical Objective:**

The grantee will develop new computational methods for the solution of NP-complete integer-programming problems, including the traveling salesman problem and scheduling problems. This work will address the determination of facet-defining inequalities for these integer-programming problems, and will develop algorithms for parallel computers.

**Approach:**

The grantee will use techniques from polyhedral combinatorics to develop algorithms for certain integer-programming problem. The Cray supercomputer and the BBN Butterfly parallel computer will be used in computer testing of the algorithms.

**Progress:**

New facets for the three index assignment polytope and the precedence-constrained asymmetric TSP polytope have been found. A new sequential lifting-projection procedure has been developed for solving mixed-integer programming problems, and has been applied to solve a hard TSP problem. The column-subtraction method designed for set covering and packing problems was successfully adapted to solve satisfiability problems. TSPs having as many as 10,000 cities were solved using a two-matching-based branch-and-bound algorithm. A parallel version of the simplex algorithm was developed and is being tested.

**TITLE:** Issues in Strong Polynomiality: Approximation Algorithms and Graph Algorithms

**PI:** Dorit S. Hochbaum  
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School of Business  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4116671---07

**CONTRACT NO:** N0001491J1241

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Donald Wagner

**Technical Objective:**

The goal is to develop best-possible approximation algorithms for some important NP-complete combinatorial optimization problems. The emphasis is on theoretical properties of algorithms developed and on their practical application. A second goal is to develop strongly polynomial algorithms for optimization problems and determine which problems admit a strongly polynomial algorithm.

**Approach:**

The approach involves the use of results from complexity theory and graph theory to develop approximation algorithms for various graph optimization problems. Complexity theory and linear-programming theory will be used in the development of strongly polynomial algorithms for optimization problems, such as pre-Leontief linear-programming problems and quadratic network flow problems.

**Progress:**

An improved algorithm was developed for certain allocation problems defined on graphs. It improves the time bound of the best algorithm by a factor of  $\log n$ , and it comes within a factor of  $\log n$  of being optimal. In other work, the grantee is conducting an empirical analysis of a previously developed polynomial-time algorithm for certain constrained non-linear optimization problems. The analysis shows that the algorithm, which uses an interior-point algorithm as a subroutine, dominates the widely used reduced gradient method.

**TITLE:** Computational and Mathematical Issues in Optimization

**PI:** R. G. Bland  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4116674---03

**CONTRACT NO:** N0001490F0058

**CURRENT END DATE:** 31 MAR 1993

**SCIENTIFIC OFFICER:** Donald Wagner

**Technical Objective:**

The objective is to develop new theoretical and computational techniques to solve large, complex optimization problems both exactly and approximately. In particular, the emphasis will be on serial and parallel methods for discrete optimization, network flow and machine scheduling problems, and linear and nonlinear programming.

**Approach:**

Among other approaches, investigations of interior-point methods will extend to 1 sub p approximation and quadratic programming and also to direct solution of combinatorial optimization problems, e.g. bipartite matching. In addition, interior-point methods will be used as linear-programming solvers in polyhedral routines for combinatorial optimization. The interplay between efficient interior-point methods and methods of numerical linear algebra will be exploited. Network flow research will attempt to extend the work of Tardos on strongly polynomial algorithms to multi-commodity and generalized-network flows.

**Progress:**

This work has resulted in new and better algorithms for a variety of important optimization problems. A non-exhaustive list includes a polynomial-time dual simplex method for the transshipment problem, a parallel algorithm, based on interior point methods, for bipartite matching, a combined phase 1-phase 2 interior point method for linear programming, and interior and exterior point methods for convex quadratic programming.

**TITLE: Analysis of Vehicle Routing and Inventory Problems**

**PI: David Simchi-Levi  
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Operations Research  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4116675---03**

**CONTRACT NO: N0001490J1649**

**CURRENT END DATE: 30 SEP 1992**

**SCIENTIFIC OFFICER: Donald Wagner**

**Technical Objective:**

The objective is to develop worst case and probabilistic performance analysis for a class of heuristic algorithms for the vehicle routing problem. The goal is to identify classes of the routing problem for which a specific heuristic is highly efficient. Issues relating the routing problem with related problems in an integrated model such as inventory control will also be examined.

**Approach:**

Worst case bounds on the performance of heuristic algorithms for vehicle routing problems are obtained by modifying techniques used in related problems such as the traveling salesman problem on which the heuristics are based. Analytical results for the traveling salesman problem can then be applied to the routing problem.

**Progress:**

Progress has been in the development of heuristics for routing and inventory problems. For the bin-packing problem with a concave cost function, the so-called next-fit-increasing heuristic is shown to have good absolute and asymptotic worst-case bounds. For more specialized cost functions, the grantee has found two heuristics that achieve the best possible performance ratio. For the distance-constrained vehicle-routing problem, the grantee has developed a heuristic and has performed extensive computational testing with it. The testing shows that the heuristic is highly effective.

**TITLE:** Using Interior Point Methods in a Cutting Plane Approach for Solving Integer Programming Problems

**PI:** John E. Mitchell  
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Mathematical Sciences Department  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4116676---03

**CONTRACT NO:** N0001490J1714

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Donald Wagner

**Technical Objective:**

The objective is to show how interior point methods can be used in a cutting plane algorithm to solve integer programming problems. A major issue to be addressed is that for a cutting plane procedure to work efficiently, it is necessary to be able to resolve a linear program efficiently when an extra constraint is added.

**Approach:**

The approach is to apply the projective primal variant of Karmarkar's algorithm to the dual of the current relaxation of an integer programming problem. Cutting planes appear as extra constraints in the dual problem and as extra variables in the primal problem. A number of approaches for the early identification of cutting planes will be examined.

**Progress:**

The grantee has developed a column generation scheme for linear programming based on Freund's shifted-barrier interior point method. The method allows the solution of linear programming problems using only a selected subset of the variables, and so could be used in a cutting plane algorithm for integer programming. Under reasonable assumptions, the column generation scheme terminates in polynomial time.

**TITLE:** Mathematical Foundations of Combinatorial Search

**PI:** Fred Glover  
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Graduate School of Business & Administration  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4116677---03

**CONTRACT NO:** N0001492MP24018

**CURRENT END DATE:** 31 MAY 1993

**SCIENTIFIC OFFICER:** Donald Wagner

**Technical Objective:**

The objective is to pull together various approaches to combinatorial optimization into a unified mathematical framework based on probability theory and statistical inference. Attempts will be made to encompass present search procedures such as simulated annealing, genetic algorithms, enumerative tree search and tabu search. Based on this unified framework, new heuristic procedures will be developed, including parallel procedures.

**Approach:**

The approach involves the development of theoretical principles of search which, like axioms in a mathematical system, may be combined in various ways to produce alternative methods. The convergence analysis of existing search techniques will also be combined using techniques from probability theory.

**Progress:**

Several applications of a greedy randomized adaptive search procedure have been developed, including algorithms for graph coloring and single machine scheduling. A method that generalizes simulated annealing and incorporates ideas from tabu search has been developed. Several different forms of flexible memory structures for tabu search have been developed and tested. On certain routing and partitioning problems, these have yielded the best-known results. A principle of proximate optimality has been formalized, which provides a link between tabu search and dynamic programming. Techniques for applying tabu search in nonlinear and parametric optimization have been developed.

**TITLE:** Studies on the Complexity of Linear Programming and Related Problems

**PI:** Nimrod Meggido  
International Business Machines Corporation  
Almaden Research Center  
(408) 927-1271

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4116678---03

**CONTRACT NO:** N0001491C0026

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Donald Wagner

**Technical Objective:**

The objective is to develop and analyze new algorithms for linear programming and extensions. Particular emphasis will be on parallel complexity, strongly polynomial algorithms and probabilistic analysis.

**Approach:**

The approach employs recent results in complexity theory to analyze linear programming algorithms. Professor Megiddo will generalize his previous work in order to develop low-order polynomial-time parallel algorithms for linear programming in fixed dimensions. This will include the use of multidimensional search techniques and parametric analysis to develop classes of linear-programming problems that are strongly polynomial. A probabilistic analysis of interior-point algorithms for linear programming will be developed using the global properties of central paths associated with such algorithms.

**Progress:**

A new algorithm for the generalized circulation problem has been found. It iteratively solves a sequence of uncapacitated transshipment problems. It can be used to either find an optimal flow or an approximation. When used to find a constant factor approximation, it runs in strongly polynomial time. This is the first strongly polynomial approximation algorithm for the circulation problem. It is not known whether the general optimization version can be solved in strongly polynomial time.

**TITLE:** Cutting Planes for Mixed-Integer Programs

**PI:** Andrew E. Boyd  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4116679---02

**CONTRACT NO:** N0001491F00043

**CURRENT END DATE:** 31 MAR 1994

**SCIENTIFIC OFFICER:** Donald Wagner

**Technical Objective:**

The objective is to develop a theory of cutting planes for mixed-integer programming problems based on Fenchel and Lagrangian duality. An important part of the research is to develop procedures for solving the separation problem for Fenchel and Lagrangian cuts. Based on this theory, algorithms for mixed-integer programming will follow. Computer implementation of the algorithms, together with a collection of test problems will be made available.

**Approach:**

The approach to the separation problem for Fenchel and Lagrangian cuts involves ascent procedures that take advantage of the combinatorial structure found in typical mixed-integer programming problems. This requires the development of efficient procedures for choosing an ascent direction, handling degeneracy, and verifying optimality in the ascent procedure. Computer implementation will be done in a modular structure that will allow other researchers to use these cutting-plane procedures in the development of new mixed-integer programming algorithms.

**Progress:**

An integer-programming code is in its final stages and soon will be released through IMSL. Theoretical work includes a result that a natural extension of the widely used steepest ascent simplex pivot rule is provably finite. A second finite pivot rule having several computationally attractive features was also developed. Both procedures have the unique advantage that they choose the pivot element without explicit knowledge of the set of active constraints at a point of degeneracy, thus making them attractive in combinatorial settings where the linear programming problem is not explicitly written out.

**TITLE: Operations Research Methods for Logical Inference**

**PI: John N. Hooker  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4116680---01**

**CONTRACT NO: N0001492J1028**

**CURRENT END DATE: 31 OCT 1994**

**SCIENTIFIC OFFICER: Donald Wagner**

**Technical Objective:**

The grantee will develop new techniques for solving logical inference problems using methods from optimization. This work will include improved integer programming algorithms for propositional logic and nonlinear programming algorithms for reasoning with uncertainty. Extensions of constraint logic programming languages to deal explicitly with mixed integer linear constraints will also be derived.

**Approach:**

The grantee will use techniques from polyhedral combinatorics to develop improved cutting plane algorithms for propositional logic. Nonlinear programming and column generation techniques will be used to develop methods for probabilistic reasoning. A normal form for the encoding of logical constraints in a mixed integer programming model will be developed. This will yield tighter linear programming relaxations for the problem.

**TITLE: Operations Research Methods for Logical Inference**

**PI: Vijaya Chandru  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4116681---01**

**CONTRACT NO: N0001492J1026**

**CURRENT END DATE: 31 OCT 1994**

**SCIENTIFIC OFFICER: Marc J. Lipman**

**Technical Objective:**

The grantee will develop new techniques for solving logical inference problems using methods from optimization. This work will include improved integer programming algorithms for propositional logic and nonlinear programming algorithms for reasoning with uncertainty. Extensions of constraint logic programming languages to deal explicitly with mixed integer linear constraints will also be derived.

**Approach:**

The grantee will use techniques from polyhedral combinatorics to develop improved cutting plane algorithms for propositional logic. Nonlinear programming and column generation techniques will be used to develop methods for probabilistic reasoning. A normal form for the encoding of logical constraints in a mixed integer programming model will be developed. This will yield a tighter linear programming relaxation for the problem.

**TITLE: Large-Scale Optimization**

**PI: Gordon H. Bradley  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4116682---01**

**CONTRACT NO: N0001492WR24011**

**CURRENT END DATE: 30 SEP 1992**

**SCIENTIFIC OFFICER: Donald Wagner**

**Technical Objective:**

This research will develop theory and algorithms for the solution of large-scale optimization problems. One focus is on persistence of integer and nonlinear optimization solutions, automatic exploitation of special structure and communication of model structure from modeler to solver. A second focus is the development of optimization and game theoretic models and algorithms to solve network interdiction problems.

**Approach:**

The investigators will develop common themes in modeling, solution algorithm design and interpretation of solutions that will substantially strengthen the persistence of solutions. They will also synthesize useful results of known enumeration rules with new rules to obtain a form useful for general large-scale mixed integer enumeration. This will include developing and testing of an enumeration algorithm for problems exhibiting any or all of the following features: binary variables, general integer variables, semi-continuous variables and sets of variables precluding natural integer solution due to their involvement in odd cycles in set partition rows.

**TITLE: Satisfiability**

**PI: Peter L. Hammer  
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Center for Operations Research  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4116683---01**

**CONTRACT NO: N0001492J1375**

**CURRENT END DATE: 30 SEP 1994**

**SCIENTIFIC OFFICER: Donald Wagner**

**Technical Objective:**

The grantee will develop new techniques to analyze and solve satisfiability problems. This work will include the use of partially ordered sets, graph theory, polyhedral theory and pseudo-boolean optimization. Classes of satisfiability problems that can be solved in polynomial time will be identified. Approximation procedures and decomposition techniques will be developed for analyzing large-scale satisfiability problems.

**Approach:**

The grantee will use techniques from implicit enumeration, resolution and cutting planes to develop upper and lower bounds on the worst case complexity of the satisfiability problem. In addition, the stable set formulation of the satisfiability problem will be used to develop new analysis techniques and solution algorithms. Methods based on the majorization and minorization of Boolean functions will be developed and applied to the satisfiability problem.

**TITLE: High Speed Heuristics for Real-Time Personnel Assignment Models**

**PI: Jeffery L. Kennington  
Southern Methodist University  
Computer Science and Engineering Department  
(214) 692-3278**

**FUNDING AGENCY: Office of Naval Technology**

**R&T PROJECT CODE: 4428001---06**

**CONTRACT NO: N0001492J1619**

**CURRENT END DATE: 30 APR 1993**

**SCIENTIFIC OFFICER: Donald Wagner**

**Technical Objective:**

The objective of this effort is to develop and apply new optimization methods for solving manpower assignment problems in real time. The results will be implemented in software and evaluated across many computational platforms, including parallel machines.

**Approach:**

New heuristics will be developed for solving specialized integer programming models underlying manpower assignment problems. Several algorithmic approaches will be tested, including greedy procedures, local search and truncated branch-and-bound. Other possible approaches involve man-machine interaction. Several hardware configurations will be tested to find one appropriate for this application.

**Progress:**

A highly successful algorithm for the singly constrained assignment problem has been devised. It is based on Lagrangean duality theory and an elaborate scheme to update the Lagrange multipliers. A computer code of the two-tree version of Dijkstra's algorithm for the one-to-one shortest path problem has been developed, and is believed to be the world's best code code for this problem.

**TITLE:** The Retention Behaviour of Six-Year Obligor

**PI:** Patrick C. Mackin  
SAG Corporation (System-Analytics Group)  
(703) 538-4500

**FUNDING AGENCY:** Office of Naval Technology

**R&T PROJECT CODE:** 4428037---01

**CONTRACT NO:** N0001492-C-0132

**CURRENT END DATE:** 30 APR 1993

**SCIENTIFIC OFFICER:** Donald Wagner

**Technical Objective:**

The grantee will develop an econometric model portraying the retention behaviour of sailors in the Navy's Six-Year Obligor program. An early warning system will be designed to alert Navy manpower managers of potential retention problems so that remedial actions can be taken in time.

**Approach:**

Data will be collected from the Navy's Enlisted Master Record and other sources. Several econometric models will be built; five potential approaches have been identified. Each model will be tested and analyzed. Based on these results, an early warning system will be designed.

**TITLE:** Development of Domain Specific Rule Bases for Use in Rule-Based Forecasting.

**PI:** Fred Collopy  
Case Western Reserve University  
Department of Management Information & Decision Systems  
(216) 368-2048

**FUNDING AGENCY:** Office of Naval Technology

**R&T PROJECT CODE:** 4428038---01

**CONTRACT NO:** N0001492J1544

**CURRENT END DATE:** 30 APR 1993

**SCIENTIFIC OFFICER:** Donald Wagner

**Technical Objective:**

This research will develop techniques for capturing domain-specific knowledge for use in a rule-based forecasting system. The research is aimed at improving the accuracy of forecasts of Navy personnel length of service.

**Approach:**

Analysts from NPRDC will be observed using concurrent verbal protocols as they make forecasts for the length-of-service time series. Protocol analysis of these sessions will be used to identify relevant contextual features and to develop rules that specify actions to be taken in response to particular features. After discussions with the analysts, the rules will be revised and refined.

**Probability and Statistics**

**TITLE: Statistics and Oceanography**

**PI: John R. Tucker  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4110001---05**

**CONTRACT NO: N0001486C0256**

**CURRENT END DATE: 30 NOV 1992**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

With this report, research opportunities at the interface of statistics and oceanography will be identified.

**Approach:**

A group of statistics researchers and oceanography researchers will meet to identify and write a report on basic statistics research issues motivated by oceanographic applications.

**Progress:**

Preliminary work on this report has begun under current funding and will be completed under the expansion.

**TITLE: Applied Statistics**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114267---09**

**CONTRACT NO: N0001492J1264**

**CURRENT END DATE: 31 DEC 1994**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The objective of this research is the study of real-world problems involving estimation theory, probabilistic modeling, and multivariate data analysis in order to develop enhanced techniques across a broad range of statistical applications.

**Approach:**

A series of problems is formulated based on discussions with laboratory personnel and presented to a panel of distinguished statistical researchers. Methods from estimation theory, probabilistic modeling, and multivariate data analysis are developed and applied to these problems.

**Progress:**

Problems taken from discussions with Navy Lab and NSA personnel are presented to a panel of distinguished statistical researchers. Joint work using methods from estimation theory, probabilistic modeling, and multivariate data analysis are applied to these problems and to advance statistical science on topics closely related to the problem areas. For example, recent problems addressed single outlier detection in an acoustics application, measures of homogeneity of covariances in pattern recognition, and some questions in queuing theory related to computer system performance.

**TITLE:** Contingency Tables and Sampling Schemes for  
Auto-Regressive Processes

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114509---05

**CONTRACT NO:** N0001491J1229

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

Measures of association between random processes will be developed based on cross classification or contingency tables also incorporating auxiliary knowledge about the variables under study. Sampling schemes for process monitoring will be developed for autoregressive processes rather than the standard independent and identically distributed sequence situation.

**Approach:**

The effects of unequal marginals on contingency table measures of association will be corrected depending on the maximal and minimal values possible of the probability measure for the given set of marginals. Homogeneity of subpopulations will be used as auxiliary information in data compactification in contingency table analyses. Variable rate sampling schemes related to recent developments in quality control theory will be applied to monitoring of autoregressive models.

**Progress:**

Progress has been made on the analysis of paradoxes which arise in the pooling of data from subpopulations. Necessary and sufficient conditions are developed for various paradoxes such as "Simpson's paradox" in which spurious association between attributes can arise in a population as a result of amalgamation, even though the attributes are independent in the subpopulations.

**TITLE: Stochastic Methods in Neural Computation Problems**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114533---09**

**CONTRACT NO: N0001490J1646**

**CURRENT END DATE: 30 SEP 1992**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The technical objective is to develop realistic models for variability in the response characteristics of individual neurons. Since the individual neurons are nodes in a network, this will yield a better understanding of the overall activity of biological neural networks and their response to random inputs.

**Approach:**

A point process with non-uniform intensity will be used to model neural spike trains that exhibit dependence between events (after hyperpolarization). An important issue is whether such point processes can result from the level crossings of a continuous time stochastic process model for the cell membrane potential. This is a statistical issue referred to in the literature as a first passage time problem.

**Progress:**

Maximum likelihood parameter estimation was applied to point process models which describe neural spike trains. These models are point processes whose intensity functions are specific finitely parameterized functions of the last occurrence time of the process up to time  $t$ . The performance of the estimators was studied on simulated neural data obtained from a numerical neural model.

**TITLE:** Nonparametric Methods for Data Analysis in Three  
to Five Dimensions

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114535---07

**CONTRACT NO:** N0001490J1176

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The objective of the proposed research is to develop theory and methods for the analysis of large high dimensional data sets. Areas of interest include advanced visualization and parallel architectures, robust multivariate regression, non-parametric regression and kriging, and cross-validation.

**Approach:**

New visualization techniques will be developed based on animation of average shifted histogram estimates. Transparency algorithms that allow several contour levels to be visualized simultaneously and a stereo option will also be developed. Theoretical work on density estimation in high dimensions will address the conjecture that the curse of dimensionality is not so much the result of sparse data, but rather the tendency of high-dimensional data to fall in subspaces.

**Progress:**

The possibility of improving kernel density estimates by varying the window over the domain of estimation has been explored. Two general approaches have been considered: to vary the window width by the point of observation and by point of the sample observation. The first possibility is not promising, although the second is, and its properties have been investigated particularly for normal data.

**TITLE:** Regression and Stochastic Control

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114565---08

**CONTRACT NO:** N0001491J1005

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

Objectives include the development of techniques for regression analysis when there are missing variables; analysis of likelihood ratios for singular testing problems such as mixtures of distributions and change point detection; and stochastic control using techniques in sequential analysis.

**Approach:**

The approach to regression analysis with missing variables involves solving the reduced regression and checking the residuals for proper behavior. If the missing terms model positive (negative) effects, the residuals should be positive (negative). If the residuals exhibit poor behavior, an improved modified solution is calculated. The approach to stochastic control is based on the conjecture that nonlinear optimal control will be more stable and less sensitive to deviations between actual and estimated parameters than the Kalman filter.

**Progress:**

In the context of testing whether a mixture of two binomials is a single binomial, the distribution of the likelihood ratio is studied. It is shown that the asymptotic distribution of twice the log likelihood ratio corresponds to the square of the supremum of a particular Gaussian process.

**TITLE: Statistical Inference in Stochastic Processes**

**PI: Lynne Billard  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114568---06**

**CONTRACT NO: N0001490J1347**

**CURRENT END DATE: 31 DEC 1992**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The objective is to develop inference techniques for non-linear time series and space-time processes including nonlinear autoregressive processes with special emphasis on bilinear, threshold, and a wide class of exponential models. Inference will be approached through a common methodology; least squares, conditional least squares, minimum L2 distance, and maximum likelihood methods will be unified via appropriate approximating quadratic forms.

**Approach:**

For the nonlinear time series models studied a quadratic functional of the autoregression is selected and minimized to estimate the model parameters. This approach serves both to fit models to data and to develop predictors. In addition hypothesis tests based on these quadratic functionals will be developed and their performance analyzed.

**Progress:**

Progress has been made on several problems in inference for nonlinear time series including:

---derived a test of homogeneity for testing the equality of the parameters in several independent nonlinear autoregressive processes;

---introduced new models for spatial time series with long memory dependence and explored a number of estimation techniques for the model parameters;

---developed sequential procedures for hypothesis tests for slope and intercept of regression models.

**TITLE:** Asynchronous Computation of Fixed Points

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114572---08

**CONTRACT NO:** N0001491J1024

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The research will focus on the development of software to support distributed computation. Statistical models of the performance of distributed systems will be developed and asynchronous iterative methods will be studied and implemented on distributed systems.

In addition, context specific approaches to the development of dynamic graphics for the visualization of very large, high dimensional data sets will be a focus of the research.

**Approach:**

The approach will be to model asynchronous calculations probabilistically in order to determine the range of possible improvements that one might expect through their use as well as to better understand their convergence properties. Specific types of graphics for special types of data will be developed. For example, in the context of asynchronous iterations the data is represented as high dimensional vectors evolving in time on videotape displays.

**Progress:**

The issue of incorporating uncertainty into a rule-based expert system is investigated through the theory of belief functions. The resulting computational complexity is reduced through the notion of outer and inner approximations to the interval between "belief" and "plausibility". The properties of these approximations are studied, and a computer implementation in the expert system context is evaluated.

**TITLE: Research in the Theory and Applications of Bayesian Statistics**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114574---05**

**CONTRACT NO: N0001485K0202**

**CURRENT END DATE: 30 JUN 1993**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The objective is to develop: (1) optimum Bayesian multi-stage and sequential procedures for the release of computer software, (2) optimal control in linear filtering in one and two dimensions, (3) statistical inference for Poisson and other point processes, and (4) a game theoretic approach to the problem of pooling expert opinion.

**Approach:**

The general approach is Bayesian. This means that all forecasts, control strategies, point and interval estimators are based on the conditional distribution of the parameters given the data and some prior distribution.

**Progress:**

Progress has been made on the design of optimal life-testing experiments, optimal according to maximum information in the sense of Shannon. A paradox arises in assessing the information provided by a single item on test for failure or survival in that a survival may provide more information than a failure. The paradox is resolved using a subjective probability approach. In addition, prior distributions in the test context are chosen in order to maximize information in a given test time.

**TITLE: Time Series and Image Analysis**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114578---07**

**CONTRACT NO: N0001491J1074**

**CURRENT END DATE: 30 SEP 1993**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The technical objective is the development of robust methods for analyzing time series and spatial processes. Robustness is of critical importance when fitting models to real-world data corrupted by impulsive noise. Also, the objective is to develop new methods for feature detection in images using clustering and mathematical morphology.

**Approach:**

The approach to robust time series analysis involves influence functionals and parsimonious nonparametric models. Influence functionals measure the sensitivity of a parameter estimate to data contamination. Low sensitivity implies high robustness. Parsimonious nonparametric models yield autoregressions of any smooth function of the lagged time series. The approach to image analysis entails a radical expansion of the scope of cluster analysis to clustering around typical curves and not just points. Methods of mathematical morphology will be incorporated.

**Progress:**

Limitations of existing classification maximum likelihood procedures are overcome by developing a mechanism which allows the specification of certain features (orientation, size, and shape) to be common to all clusters while others may differ between clusters. For multivariate Gaussian data the key is a reparameterization of the covariance matrix in terms of its eigenvalue decomposition in order to isolate parameters specifying orientation of principal components from those which specify the size and shape of the density contours.

**TITLE:** Mathematical Methods for Object  
Recognition

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114579---09

**CONTRACT NO:** N0001491J1021

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

This research addresses problems in computer vision with emphasis on methods for object recognition and techniques for recovering structural information about a scene. A central issue is representation, the association of an object with a mathematical model which incorporates essential invariant features of the object and which is flexible enough to represent different instances or presentations of the object.

**Approach:**

The approach involves the use of relational templates for invariant object recognition and deformable templates for nonrigid one-dimensional objects, together with an analysis of generic aspects of deformable template models including their use in higher dimensions. In addition, Markov random field models will be used for recovery of intermediate level structure in a scene, motivated by the "shape from shading" problem for visible light images as well as by the problem of constructing surface maps from synthetic aperture radar images.

**Progress:**

A new method for the automatic detection of road, railway, and river networks in high resolution satellite imagery has been proposed and analyzed. Detection is formulated as a discrete optimization problem in which the cost functional is constructed from the output of local filters constructed to identify likely track pixels. In addition curvature and connectivity constraints are enforced. The method appears to have significant potential for automated cartographic systems.

**TITLE:** Acausal Stochastic Process Models:  
Structure and Inference

**PI:** Howard L. Weinert  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114585---05

**CONTRACT NO:** N0001489J1642

**CURRENT END DATE:** 30 SEP 1994

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The objective is to derive the probabilistic properties of stochastic partial differential equations with specified boundary conditions. It has been observed that for certain of these equations a transformation approach converts the estimation problem into an estimation problem for a collection of stochastic ordinary differential equations. The question of characterizing those PDE's for which the transformation approach works will be addressed.

**Approach:**

When the transformation of estimation problems for stochastic PDE's into estimation problems for a collection of stochastic ODE's applies, explicit smoothing algorithms will be developed based on Green's functions, Schur transformations, and other eigenvalue decompositions. If the transformation approach is not feasible, as in the case of nonuniformly spaced data, it is planned to address the discretized PDE as a multidimensional nearest neighbor model in the expectation that this will be a useful perspective for estimation problems.

**Progress:**

An efficient linear least squares algorithm for smoothing a two dimensional stochastic signal governed by the Poisson equation has been derived for the case of a finite number of regularly spaced noisy observations. The method of complementary models is used to derive the optimal estimator, and then the sine transform is used to convert the two dimensional problem into a family of coupled one dimensional problems which can be decoupled under various special case assumptions.

**TITLE: Workshops--Pathways to the Future**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114586---04**

**CONTRACT NO: N0001489J1687**

**CURRENT END DATE: 31 DEC 1994**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The objective is to provide guidance in career advancement and research directions to recent women Ph.D.'s in statistics and probability in order to increase research participation by women.

**Approach:**

The approach is to hold a series of three workshops concurrent with the major annual statistics meetings. Presentations will be made by senior women researchers in statistics and probability emphasizing research and career paths. Individual research projects currently underway by recent doctoral recipients will be presented and discussed. Finally, research funding opportunities will be described.

**Progress:**

A very successful 1991 workshop was held. Several junior women statisticians each presented a short talk on her research and heard talks from senior women statisticians and funding agency representatives. A number of "alumnae" from previous workshops also attended and participated. Plans for the 1992 meeting in conjunction with the Annual Joint Statistics Meetings are underway.

**TITLE:** Parameter Estimation and Model Selection  
for Gibbs Random Field in Image Analysis  
and Related Fields

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114590---04

**CONTRACT NO:** N0001489J1760

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The objective is to develop estimators for the potential function in Gibbs state models of one and two dimensional Markov processes. Both finitely parameterized models and infinitely parameterized models under various dependence assumptions will be considered.

**Approach:**

The approach will be to determine conditions on the functional parameters appearing in the potential function that insure convergence of empirical frequencies to the true underlying values. Also, linear models will be assumed, and maximum likelihood estimators for the coefficients and model order parameters will be developed and their convergence properties studied.

**Progress:**

Grenander's method of sieves has been applied to the problem of constructing strongly consistent estimators for certain infinite dimensional unknown parameters, such as interaction potentials, local characteristics, etc., in Gibbs random fields. Exponential rates of consistency have been established by using the conditional mixing property of the Gibbs random fields. This approach is applicable to texture image models.

**TITLE: Statistics and Oceanography**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114592---06**

**CONTRACT NO: N0001492J1449**

**CURRENT END DATE: 31 DEC 1992**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

Stable random variables which describe heavy tailed phenomena will be incorporated into time series models to provide models for data arising in turbulence modeling. Statistical inference techniques for these models will be developed.

**Approach:**

The statistical analysis of time series models based on stable innovations will be pursued via least squares, M-estimation, and least absolute deviations techniques with comparison among these approaches. Seasonal adjustment in the context of these models will be examined following preliminary work on the AR(1) case. Bayesian forecasting techniques for traditional ARMA models will be extended to the stable innovations case. The expansion provides for a special conference session at the annual joint statistics meetings on Statistics and Oceanography.

**Progress:**

Progress has been made on the problem of specifying prior distributions in Bayesian statistics via the use of a class of priors wide enough to represent the diversity of reasonable opinion. New results on computing bounds on expectations permit the use of one-dimensional Monte Carlo integrations to bound the expectation of a random variable over a class of priors, even if the parameter space is multidimensional.

**TITLE: Gaussian and Related Random Fields**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114593---04**

**CONTRACT NO: N0001489J1870**

**CURRENT END DATE: 31 DEC 1993**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The objective is to conduct research on Gaussian and related random fields constructed as limits of sums of functionals of simpler blocks, e.g., intersection local times. This representation permits the analysis of prediction problems for these fields. In addition, the computer simulation of field sample paths will be undertaken.

**Approach:**

Previous work by the proposer showed how to construct random fields from the intersection local times of Markovian particle paths. The goal here is to extend this work to address intersection local times for martingales. This will be done using a combination of the stochastic calculus methods traditionally used to study local times for continuous semi-martingales with the spectral domain techniques developed for local times of Gaussian processes. Simulations of random field sample paths will be used to provide insight into sample path behavior.

**Progress:**

The distribution of the first exit value has been derived for a class of Markov processes. In particular the method provides the characteristic function of the first passage distribution for a class of symmetric Levy processes which includes those with symmetric stable distributions. The method combines prediction theory for Gaussian processes with the theory of Dynkin which relates Markov processes to Gaussian processes associated with them.

**TITLE:** Virtual Reality for Exploratory Data Analysis

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114594---06

**CONTRACT NO:** N0001492J1303

**CURRENT END DATE:** 30 SEP 1994

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The objective is to develop parallel coordinate density plots as a tool for graphical analysis and statistical inference on large and high dimensional data sets. Exploratory data analysis will be pursued via data set mapping or the selection of analysis procedures from within a specified set automatically determined by the nature of the data. Of particular interest is the representation of higher dimensional data in 3 rather than 2 dimensions through the use of virtual reality technology at the human-computer interface.

**Approach:**

The approach is to use computer implementations of statistical procedures as well as computer graphics displays of large and high dimensional data sets in order to gain mathematical insight. Formal proofs of the statistical properties of the analysis techniques will be derived. While previous work has concerned 2-D representations of high dimensional data, the current effort will focus on using virtual reality technology to understand high dimensional data sets through 3-D representations.

**Progress:**

The grand tour, a method for searching for structure in D-dimensional data by projecting the data sequentially into all possible 2-planes, has been generalized to the notion of a k-dimensional grand tour for k less than or equal to D. The generalization is a technique to search for k-dimensional substructures in the data. The basic algorithms are given and the k-dimensional parallel coordinate plot is used to represent visually the projections of the data into k-flats.

**TITLE:** Modeling and Estimation of Reciprocal Diffusions  
and Gauss-Markov Random Fields

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114595---06

**CONTRACT NO:** N0001489J3153

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The goal is to develop random field models and estimation methods based on reciprocal diffusions, a class of acausal random processes obtained as the solution of stochastic ordinary differential equations with boundary value conditions. These will be extended to the multiparameter case. A necessary intermediate step is to formulate the notion of transition functions for Markov field models based on Gibbs distributions.

**Approach:**

Reciprocal processes have optimal smoothers (estimators) which are themselves acausal in that they are solutions of dynamical systems with boundary conditions whose input is the process to be smoothed. The approach is to develop such acausal smoothers for the multiparameter case. It is expected that transition functions of Markov fields can be used to construct multiparameter analogs to reciprocal processes having optimal estimators that resemble the underlying field model.

**Progress:**

It is shown that if a stationary multivariate Gaussian process is reciprocal over the entire real line, then it is necessarily Markov. The demonstration is for a discrete index set, and the regularity condition is imposed that the process is regular; i.e. is not completely predictable from its infinitely remote past and future. This resolves a conjecture in the literature.

**TITLE:** Analysis of Temporal Symmetry in Non-Gaussian  
Random Fields

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114596---03

**CONTRACT NO:** N0001489J3152

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The objective is to extend previous work on identifying temporal symmetries and exploiting temporal asymmetries in estimation problems for time series models to multiparameter random fields. In particular, the stochastic wave equation will be examined both for Gaussian and non-Gaussian excitation as it is expected that non-Gaussianity will correspond to asymmetries in space as well as time.

**Approach:**

For time series, the P.I. has shown that conditional expectations of the present value given past data and of the present value given future data are the appropriate tool for identifying models with temporal asymmetries and for enhanced estimation when temporal data is not confined to past information. The approach is to study conditional expectations of random fields at a point given data at arbitrary subsets of the argument space.

**Progress:**

Non Gaussian Markov time series are analyzed by expressing the conditional density functions in terms of bivariate density expansions involving orthogonal polynomials. In contrast with previous applications of these expansions, the orthogonal functions differ for each of the two arguments, and this is the mechanism by which temporal asymmetry is incorporated into the model.

**TITLE:** Fitting Stochastic Partial Differential Equations  
to Spatial Data

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114597---03

**CONTRACT NO:** N0001490J1011

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The objective is to develop methods for fitting stochastic partial differential equation models to unequally spaced spatial data. Based on these models, techniques for predicting random fields at unobserved locations with well defined confidence intervals will be derived.

**Approach:**

The approach is based on the observation that fitting a two-dimensional smoothing spline corresponds to fitting the Laplace equation driven by white noise. This correspondence will be applied to other stochastic partial differential equations. The first extension will be to incorporate trends in random fields by concentrating the linear parameters out of the likelihood. Then the methodology will be extended to more complicated error structures.

**Progress:**

Progress has been made on methods for fitting continuous ARMA models to unequally spaced observations in 2 dimensions. These are models with rational 2 dimensional spectra. For Gaussian input noise and observational errors, maximum likelihood methods are used to estimate the ARMA parameters and the regression coefficients of the deterministic trend. When the number of observations is too large for exact maximum likelihood estimation, approximate maximum likelihood is used based on nearest neighbors.

**TITLE:** Morphological Modeling and Analysis of  
Discrete Random Shapes

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114599---05

**CONTRACT NO:** N0001490J1345

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The objective is to develop a unified theory for stochastic mathematical morphology particularly for discrete random shapes. Towards this end, research will be conducted on a theory of random sets defined on discrete spaces, random set models which are capable of describing important image characteristics, statistical inference techniques which will allow an optimal fit of the models developed to real image data, and image analysis techniques at the interface of mathematical morphology and random set theory.

**Approach:**

The approach is to define and analyze the discrete generating functional for a discrete random set in terms of probabilities of hitting each element of a family of test sets. These probabilities can be estimated directly from the given image data, and this is not the case for the corresponding quantities in the older, continuous random set theory. Morphological skeletons will form the basis for a new approach to random shape modeling.

**Progress:**

A general theory for the representation of discrete binary images has been developed. The theory is based on the generation of a set of nonoverlapping segments of an image via repeated erosions and set transformations, which in turn produces a decomposition that guarantees exact reconstruction. The morphological image representation transform is introduced and related to various forms of digital morphological skeletons used in a variety of approaches to image representation.

**TITLE: Probability, Statistics, and Convex Geometry**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114601---06**

**CONTRACT NO: N0001490J1641**

**CURRENT END DATE: 30 SEP 1992**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

Ideas from convex geometry will be applied to stochastic problems in order to obtain new theoretical results about statistical procedures and to improve the modeling of random shapes. In particular, notions of sphericity will be used for estimation and hypothesis testing problems on directional data. Also, new models of random closed curves will be developed for use in image processing and shape modeling.

**Approach:**

One approach to the development of statistical methods for directional data is the construction of convex structures about the data combined with tests for sphericity of the structure. Sums of random vectors selected according to various schemes sweep out flexible classes of closed curves and thereby generate random shapes for analysis.

**Progress:**

A novel approach from stochastic geometry is used to study the properties of random matrices, for example expected absolute determinants. In particular a matrix whose columns are independent and identically distributed copies of a random vector has an expected absolute determinant given in terms of the volume of the expected value of a particular random set constructed from the random vector. The result may be interpreted as a kind of interchange between volume evaluation and the taking of expectations.

**TITLE: Applications in Random Fields and Image Analysis**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114602---06**

**CONTRACT NO: N0001490J1639**

**CURRENT END DATE: 30 SEP 1992**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The project will develop techniques for the prediction of random fields. The optimal estimator is given by the solution to a partial differential equation with stochastic boundary conditions when the field itself is stationary Gauss-Markov. Approximate solutions to the predictor equations will be developed. Also, a notion of shape in three dimensions based on Markov processes on graphs will be developed and applied to create prior distributions for image analysis.

**Approach:**

Approximate solutions to the stochastic prediction equations will be analyzed from the viewpoint of stochastic approximation theory in order to determine accuracy compared with the true optimal predictor. Considerations of tradeoff between accuracy and cost will be investigated as a function of number of boundary data values incorporated into the predictor. Also, shape information will be analyzed via limit theorems for compact manifolds and stochastic differential equation based methods.

**Progress:**

Progress has been made on the prediction of Gauss Markov random fields from observations on the boundary of a general domain. The estimator is closely related to the solution of a generalized elliptic boundary value problem. To overcome the difficulties caused by the irregular boundary, an equivalent boundary value problem has been introduced which can be solved via an approximation scheme. In other work, families of deformations of smooth manifold templates are constructed using the machinery of differential geometry.

**TITLE: Theory and Applications of Random Fields**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114604---06**

**CONTRACT NO: N0001490J1712**

**CURRENT END DATE: 30 SEP 1992**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The objective is to develop mathematical techniques for the analysis and representation of random fields. In particular prediction theory in the Wiener and Kalman formulations will be addressed for higher dimensions, both in the standard and robust settings.

**Approach:**

The Wiener filter appears most amenable to generalization to higher dimensional problems via Kolmogorov's analysis. Necessary is the Wold decomposition of the field and a particular factorization of the spectral density. In addition, dependency properties of fields will be studied, with special attention to the effects of discretization of the parameter space on the field of interest.

**Progress:**

The problem of minimum mean squared error estimation of a random variable given random field (partially ordered) observations is considered. Several "counterexamples" are constructed which highlight the role of regularity conditions in these types of problems. One example exhibits a random variable which can be precisely written as a nonzero function of the random field at any point in space yet the corresponding estimator is zero almost surely.

**TITLE:** Optimal Rank-Based Procedures in Time Series Analysis  
and Random Fields

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114606---04

**CONTRACT NO:** N0001491J1020

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The technical objective is the development of methods for time series and spatial process analysis that are less dependent on assumptions regarding the underlying distribution of the data than conventional model-based parametric methods. These will be more robust against departures from normality.

**Approach:**

The approach employs nonparametric methods, including rank-order statistics, central-order statistics, serial-rank statistics, and signed-rank statistics. These will be applied to problems in time series and spatial process analysis, including model identification and tests for pure randomness. Robustness of the techniques, large deviations and Bahadur efficiencies, and small sample performance will all be derived.

**Progress:**

Asymptotic normality has been established for L-statistics for a large class of time series. A new approach to the specification of the dependence structure known as  $m(n)$ -decomposibility avoids the difficulties of the usual mixing conditions and is particularly appropriate for linear, bilinear, and processes with a finite order Volterra series expansion.

**TITLE:** Statistical Regularization of Inverse Problems  
in Physical Oceanography

**PI:** Jose Moura  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114607---05

**CONTRACT NO:** N0001491J1001

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The goal is to develop a stochastic relaxation approach to the reconstruction of random fields from sparse, noisy measurements. Sources of randomness include random forcing terms, random initial conditions, and random measurement noise. The field models are Markov random fields obtained by the differencing of stochastic partial differential equations with particular emphasis on Navier-Stokes type equations.

**Approach:**

For the Markov random field models obtained as discretized versions of stochastic partial differential equations, a stochastic matrix equation of particular form is to be solved for the unobserved random field. Techniques for fast recursive solutions which exploit the special structure of the matrices will be developed using ideas from stochastic relaxation and simulated annealing.

**Progress:**

Necessary and sufficient conditions have been obtained for the parameter space of a noncausal Gaussian Markov random field by analysis of the eigenstructure of the inverse of the covariance matrix, known as the potential matrix. The potential matrix is conveniently decomposed as the sum of two matrices, one of which exhibits the Markov structure in a sparse block banded form while the other exhibits the type of boundary conditions assumed and is also sparse and highly structured.

**TITLE: Probabilistic Modeling and Statistical Inference for  
Random Fields and Space-Time Processes**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114608---04**

**CONTRACT NO: N0001491J1004**

**CURRENT END DATE: 30 SEP 1993**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The goal is to fit multiple scale random field models from data taken at the boundary of a region based on wavelet transform ideas and hierarchical data structures. This will involve the development of techniques for multiscale estimation and inference, particularly using coarse resolution data to interpolate fine resolution fluctuations. Markov random fields on lattices will be used as hierarchical data models.

**Approach:**

Boundary value stochastic models lead to a class of Markov random fields (MRFs) with special structure whose parameters depend on the underlying stochastic partial differential equation. Multiresolution features of the MRFs will be used to develop fast estimation algorithms moving inward from boundary data using wavelet type techniques. Also, closed curves in higher dimensions will be developed to "snake" in from the boundary data and describe the evolution of stochastic geometric features within the region of interest.

**Progress:**

Recursive estimation techniques have been developed for a general class of linear differential equations driven by white Gaussian noise. The special feature of this class of models is that the dimensionality of the system is variable with time. Thus this class of models is a precursor to the development of corresponding results for 2-dimensional problems in which the natural direction of propagation is inward or outward from the boundary, and therefore the boundary and the dimensionality of the problem change in size.

**TITLE: Probabilistic Analysis of Random Hyperbolic Equations**

**PI: Rene Carmona  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114609---04**

**CONTRACT NO: N0001491J1010**

**CURRENT END DATE: 30 SEP 1993**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The goal is to derive Markov properties of solutions to stochastic partial differential equations and exploit such properties in the context of filtering problems. The nature of the boundary with respect to which Markov properties hold, particularly when the boundaries are themselves random, is an important issue.

**Approach:**

A variety of approaches will be employed including random Shrodinger operators, function valued processes, eigenfunction expansions, and limits of discretized field approximations. These will lead to an understanding of Markov properties of the stochastic pde solutions. The Markov property will be exploited in solving the filtering problem.

**Progress:**

A particular stochastic partial differential equation of parabolic type is considered as a model for non-interacting particle systems. Existence and uniqueness of the solution are established, and a closed form expression for the moments is obtained. Asymptotically in time, the behavior of the solution and its moments is intermittent, that is, there are places where the concentration of particles is very high, the distances between these places are very large, and most of the mass of the ensemble of particles is concentrated in these places.

**TITLE:** Random Fields and Stochastic PDE's in  
Oceanography and Geophysical Fluid  
Dynamics

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114611---04

**CONTRACT NO:** N0001491J1386

**CURRENT END DATE:** 31 DEC 1993

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The objective is to conduct research on several problems in stochastic modeling for oceanographic applications. In particular these topics are: nonlinear amplitude equations for geophysical waves and instability of zonal flows in presence of external noise; modeling complex topography--random, fractal, and "high temperature" boundaries for ocean basins; random vortex models of turbulent oceanic flows and the "internal noise" randomization of the Navier-Stokes equation; and sparse sampling and prediction problems for non-Gaussian random fields.

**Approach:**

Mean field theory will be extended to 2-dimensional problems and will be analyzed in the presence of non-Gaussian models for ocean basins and boundaries. In addition to ocean wave propagation problems in domains with highly irregular boundaries, the inverse problem will be examined in this context. Random Schrodinger operators describe the evolution of the spectral content of the model and will be employed in both the forward and inverse problem analyses.

**Progress:**

Progress has been made on an analysis of the effect of random bottom topographies on the propagation of long period, linear surface waves, that is, topographic Rossby waves. Both ocean depth and its derivatives enter as coefficients in the governing equations so that perturbation methods which can handle small random coefficients are not appropriate for the incorporation of the effects of the derivatives. Instead a new method is proposed to substitute an "average slope" for the random derivative terms.

**TITLE:** Random Fields Governed by Stochastic  
Partial Differential Equations and their  
Applications to Oceanography

**PI:** Boris L. Rozovskii  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114613---04

**CONTRACT NO:** N0001491J1526

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The objective is to solve quasi-geostrophic type and other related nonlinear partial differential equations when forced by a random field, particularly multiparameter white Gaussian noise. Questions of steady state solutions and sample path behavior will be addressed. Statistical estimation in the context of linearized approximations to these equations will be developed.

**Approach:**

Numerical experimentation has suggested conditions on the terms in the equations which guarantee the existence of a steady-state solution. This part of the problem will be addressed via the construction of the invariant measure. Large deviation techniques will be used to gain insight into the sample path behavior of the solutions. Maximum likelihood and other techniques for parameter estimation will be pursued for models with random parameters.

**Progress:**

A new approach to the uniqueness of solutions to a class of stochastic partial differential equations has been developed by working in the space of signed measures rather than the space of probability measures. The equations studied are the Kushner and Zakai equations of nonlinear filtering.

**TITLE: Stochastic Models for Ion Channel Kinetics**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114615---01**

**CONTRACT NO: N0001492J1263**

**CURRENT END DATE: 31 DEC 1994**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The objective is to derive maximum likelihood estimators for parameters such as conductance and subconductance levels from the kind of digitized data which arises in patch clamp recordings, without going through an intermediate signal reconstruction stage. In addition problems of identifiability for Markov models of channel kinetics will be addressed in order to study questions related to the nonuniqueness of models consistent with observable records of patch clamp recordings.

**Approach:**

Patch clamp recordings are modeled via a smoothed two state Markov chain with data dependent smoothing. The extension to an underlying multistate model and the maximum likelihood estimation of the model parameters which correspond to neural features will be addressed. For a family of such models, goodness-of-fit techniques will be developed and analyzed. Issues of identifiability will be pursued through analysis of the eigenstructure of the rate matrix of the underlying Markov chain.

**TITLE: Statistics Methods for the Estimation  
of the Motion of Rigid Bodies**

**PI: Theodore Chang  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114616---01**

**CONTRACT NO: N0001492J1009**

**CURRENT END DATE: 30 SEP 1994**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The objective is to develop a variety of different statistical methodologies for the analysis of the rotation and Euclidean motion of rigid bodies in the plane and on the surface of the sphere. In particular confidence bands for paths of rotations, computer intensive methods for constructing confidence regions of rotations or Euclidean motions, robust estimation techniques, and estimation techniques for misspecified models will be examined.

**Approach:**

Reasonable error models for data do not lead to independent estimates of the translational and rotational part of the motion, and thus previous work on confidence bands for fitted rotations will be extended to the case of the group of Euclidean motions of  $p$ -dimensional space. The quality of the asymptotics used to develop confidence regions is not well understood due to the role of the geometry of the data points, and computer intensive methods such as bootstrap confidence regions should be applicable to this class of problems.

**TITLE:** High Level Excursions of a Random Field  
with Application to Sea Surface  
Whitecap Modeling

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114617---01

**CONTRACT NO:** N0001492J1007

**CURRENT END DATE:** 30 SEP 1994

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The objective is to derive expressions for high level excursions for various models of random fields satisfying types of dependence structure. Analysis of these expressions will lead to techniques for fitting models to data, particularly satellite data of whitcap occurrences.

**Approach:**

A random measure, called the excursion random measure, which simultaneously describes the local and global behavior of high level excursions of a random field will be characterized for families of random fields exhibiting a dependence structure described by types of mixing conditions. The fitting of models to data will be developed both nonparametrically and parametrically through Gaussian and stable field models.

**TITLE:** Statistical Problems in Single Neuron  
Activity

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114618---01

**CONTRACT NO:** N0001489J1496

**CURRENT END DATE:** 30 SEP 1994

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The objective is to develop techniques for the estimation of physically significant parameters in neural models from high dimensional data. Dependence between neurons in a multidimensional point process setting will be incorporated.

**Approach:**

Graphical techniques, projection pursuit methods, and specific parametric approaches will be used to estimate the dependence and related parameters of multiparameter point process neural models. One model of particular interest is based on level crossings of n-dimensional Brownian motion as a potentially tractable n-dimensional diffusion process.

**Progress:**

For a multivariate point process model of the simultaneous activity of a collection of neurons, a gravitational clustering algorithm is used to detect and describe the nature of the neural interactions. Using simulation, it has been shown that the presence of noise and of time varying interactions can affect the performance of the algorithm, while the effect of charge dynamics appears to be negligible.

**TITLE: Stochastic Methods for Analyzing Ion Channels and Spike Train Data**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114619---01**

**CONTRACT NO: N0001492J1097**

**CURRENT END DATE: 30 SEP 1994**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The objective is to develop statistical procedures for analyzing voltage activated channel experiments with special emphasis on multi channel data. A class of models given by the superposition of several independent Markov chains will be investigated. Measurements from spike trains will be modeled through the use of nonstationary, non Poisson point processes with refractory periods. The effects of the refractory periods in the model on the neuron firing rate will be investigated.

**Approach:**

A kinetic model for channel experiments based on a superposition of Markov chains will be fit to data by means of Le Cam's large sample optimal estimation procedure. For this class of models the marginal and joint distributions of neurally significant parameters such as open dwell time, first passage time, etc., will be derived. Identifiability of the models will be addressed, and it is expected that these mixture models will not necessarily be identifiable, leading to difficulties with standard parameter estimation techniques. Appropriate modifications will be investigated.

**TITLE: Computational Properties of Auditory  
Neurons**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114620---01**

**CONTRACT NO: N0001492J1251**

**CURRENT END DATE: 31 DEC 1994**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The doubly stochastic Poisson process driven by fractal shot noise which models spontaneous neural firings will be extended to accommodate time varying and information carrying signals as models for the refractory behavior encountered in biological neurons. Techniques for evaluating the goodness-of-fit of models in these classes to data will be examined. Estimation techniques which are explicitly designed to distinguish between stochastic variability and deterministic components to the temporal variability of the data will be developed.

**Approach:**

The extended model will be a triply stochastic Poisson process with three forms of stochasticity arising from rate variations associated with adaptation and/or stimulus variability, a biophysical mechanism involving long term correlations, and an action potential generation mechanism involving intrinsic neuron fluctuations and refractoriness. The moment generating functional for cascades of filtered Poisson point processes will form the basis for the analysis.

**TITLE: Particle Systems Over Stochastic Flows**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114621---01**

**CONTRACT NO: N0001492J1088**

**CURRENT END DATE: 30 SEP 1994**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

Questions related to the theory of stochastic flows will be addressed with emphasis on vortex approximations to stochastic flows, the effect of a flow on a system of particles drifting with the flow, and the description of the flow from the point of view of observers riding on those particles. The motivation comes from problems in oceanography: stochastic modeling of ocean currents and turbulent mixing, models for the motion of drifters employed in data collection, etc.

**Approach:**

A stochastic flow is a family of random transformations  $F(s,t)$  of a space into itself such that  $F(t,u) \circ F(s,t) = F(s,u)$ . The flows encountered in fluid mechanics are specified via differential equations expressing physical relationships among position, velocity, etc. For turbulent flows the velocity fields are random fields over space and time. Flow models of particular relevance in oceanography will be analyzed by relating the model specification to its stochastic behavior.

**TITLE: Random Fields in Oceanography Workshop**

**PI: Arthur J. Mariano  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4114622---01**

**CONTRACT NO: N0001492J1005**

**CURRENT END DATE: 30 SEP 1992**

**SCIENTIFIC OFFICER: Julia Abrahams**

**Technical Objective:**

The objective of this workshop is to advance the state of knowledge in the area of random fields for oceanographic modeling with emphasis on stochastic partial differential equation models and prediction and interpolation for them.

**Approach:**

A research workshop will be held on Random Fields for Oceanographic Modeling. Tutorial and research presentations will be made.

**TITLE:** Computing Science and Statistics:  
Symposium on the Interface

**PI:** H. J. Newton  
Interface Foundation of North America  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4114623---01

**CONTRACT NO:** N0001492J1459

**CURRENT END DATE:** 31 MAY 1992

**SCIENTIFIC OFFICER:** Julia Abrahams

**Technical Objective:**

The objective is to advance the state of knowledge in statistics at the interface with computing sciences with special emphasis on cross-disciplinary applications.

**Approach:**

A research conference will be held, the 1992 Symposium on the Interface of Computing Science and Statistics. Invited and contributed papers will address visualizing stochastic algorithms, visualizing multivariate data, geographic information systems, visualization in climate research, among other topics.

**Signal Analysis**

**TITLE:** Spectral Analysis, Estimation, and Prediction of  
Multiple Harmonizable Random Fields and Time Series

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 411m001---08

**CONTRACT NO:** N0001490J1705

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The technical objective is the development of new techniques for spectral analysis and characterization of harmonizable time series and random fields. Problems of detection, classification, and prediction are of particular interest.

**Approach:**

The structure theory of harmonizable stochastic processes will be extended to random fields with emphasis on frequency domain properties. Methods for estimation of the associated spectral density functions will be developed and their asymptotic properties derived. Rational and factorizable densities are of particular interest. This will permit the development of techniques for prediction of isotropic random fields in n-dimensional Euclidean space and on n-spheres.

**Progress:**

In recent work it was shown that the concept of  $L(2,2)$ -boundedness introduced by Bochner leads to a class of generalized harmonizable random processes. These generalized harmonizable processes are noteworthy because of the straightforward nature of the linear filtering problem for the class. A natural extension of  $L(2,2)$ -boundedness brings in the Cramer-Karhunen processes, but for these latter processes the linear filtering problem presents difficulties. Thus the work shows the key role played by  $L(2,2)$ -boundedness in linear-filtering.

**TITLE: Model-Based Analysis and Applications of Random Signals and Fields**

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Electrical & Computer-Engineering Department  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 411m003---07**

**CONTRACT NO: N0001491J1072**

**CURRENT END DATE: 30 SEP 1993**

**SCIENTIFIC OFFICER: Neil L. Gerr**

**Technical Objective:**

The first objective is the development of improved methods for detecting and classifying transient and nonstationary signals in noise. The second objective is the development of new stochastic models and estimators for the velocity field of a fluid in motion.

**Approach:**

The approach to signal analysis uses scale space representations, the Haar transform being particularly attractive due to its computational simplicity. Scale space representations provide a basis for automating detection and classification, for example, by a neural network. The approach to estimating the stochastic velocity field of a moving fluid is based on the noisy Navier-Stokes equation. For the low Reynolds number case, the nonlinear terms will be lumped with the noise and the linear part estimated using generalized splines. For the high Reynolds number case, a nonlinear filtering formulation will be used.

**Progress:**

A two-stage design methodology for artificial neural networks was introduced. The first stage is a recursive least squares algorithm which determines the optimal configuration of the network. The second stage involves the fine tuning of the synaptic weights acquired during the first stage. In other work, the convergence of an expansion method for calculating the innovation process required for the solution of nonlinear filtering problems was established.

**TITLE:** Modeling, Detection and Estimation of Transient  
and Non-Stationary Signals

**PI:** Stuart C. Schwartz  
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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 411m006---05

**CONTRACT NO:** N0001491J1144

**CURRENT END DATE:** 30 NOV 1993

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The technical objective is the development of new methods for characterizing nonstationary signals. These will yield new techniques for detecting and classifying transient signals in noise.

**Approach:**

The Gabor representation gives a signal as a series expansion in a non-orthogonal but time-localized basis. The biorthogonal function associated with the Gabor window greatly simplifies computation of the Gabor coefficients. However, an alternative maximum likelihood approach appears to offer estimates with lower mean-square error when the signal is received in noise. For quickest detection, the CUSUM test first considered by Page will be generalized and analyzed as a method for detecting transient signals in noise.

**Progress:**

The CUSUM test for quickest detection of a change in the distribution of a random sequence was generalized to arbitrary discriminant functions. Performance was derived in terms of the worst-case expected delay in detection of a change and the mean time between false alarms when no change occurs. A simple analytic formula was obtained which can be useful in comparing the performance of different discriminant functions for various distributions.

**TITLE:** Characterization of Wideband Transient Acoustic Signals

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 411m007---07

**CONTRACTNO:** N0001491J1161

**CURRENT END DATE:** 31 DEC 1993

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The technical objective is the development of more effective methods for detecting and classifying transient signals.

**Approach:**

Conventional scale-space analysis and more modern wavelet transform techniques yield filters whose bandwidth is proportional to their center frequency ("constant-Q filters"). Cochlear models also employ constant-Q filters, but with several interesting differences: cochlear filters are more nearly minimum phase, group delay is much less for high frequencies than for low frequencies, and the magnitude of the frequency response has much sharper cutoff at the high end of the frequency band than at the low end. It is not clear how such properties can yield improved detection and classification in general applications.

**Progress:**

It was shown that convolving the Wigner distribution with a general smoothing function is equivalent to computing a weighted sum of spectrograms. For approximation in the least-squares sense, the best set of windows is the set of eigenfunctions of a linear operator determined by the smoothing function, and the weights are the eigenvalues of the operator. When the smoothing function is the indicator function of a rectangle in time and frequency, the linear operator is related to the time-limiting and band-limiting operators studied by Landau, Pollak, and Slepian.

**TITLE: Statistical Learning Theory and Algorithms**

**PI: John E. Moody**  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 411p005---04**

**CONTRACT NO: N0001489J1228**

**CURRENT END DATE: 30 NOV 1991**

**SCIENTIFIC OFFICER: Neil L. Gerr**

**Technical Objective:**

The two characterizing features of a neural network are its topology and its learning algorithm. The objective here is to develop new methods for self-organized learning.

**Approach:**

The approach involves the k-means clustering algorithm. For a given data set of  $n$  points, the k-means clustering algorithm finds the set of  $k$  cluster centers (means) and associated widths (standard deviations) that minimizes the sum of the squared distances from each data point to its cluster center. The technique will be tested on the problem of predicting the chaotic time-series generated by the Mackey-Glass differential delay equation.

**Progress:**

Many of the most popular schemes for recursive real-time learning, including the least-mean-squares (LMS), k-means clustering, and back-propagation algorithms, involve optimizing an objective function via stochastic gradient descent. The learning rate schedule  $d(t)$  controls the size of the update made at time  $t$ . Fixed learning rate schedules  $d(t)=d$  yield vector estimates that do not converge but instead exhibit random residual misadjustment. The running average schedule  $d(t)=d/(1+t)$  taken from the theory of stochastic approximation (Robbins-Monro) overcomes this shortcoming but may yield very slow convergence. Recent work under this grant has lead to the formulation of a new adaptive learning rate schedule. The new adaptive schedule is based on the fact that correlation in the update vectors indicates the learning rate is too small. Preliminary experiments are encouraging as to the potential for achieving optimal rates of convergence.

**TITLE: Neural Computations: Temporal Aspects**

**PI: Pierre Baldi**  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 411p006---04**

**CONTRACT NO: N0001492MP24004**

**CURRENT END DATE: 30 SEP 1993**

**SCIENTIFIC OFFICER: Neil L. Gerr**

**Technical Objective:**

The objective is to develop statistical models for the activity of neural networks. Specific areas of interest include optimizing feed-forward networks with a hidden layer, neural systems employing broadly tuned sensory maps such as those found in echolocating bats, and optimal input-output pairs for training robotic neural network controllers to handle inverse kinematics problems that are ill-defined.

**Approach:**

Feed-forward networks with a single hidden layer are modeled by successive matrix multiplications where the matrix entries give the interconnection weights. The matrices that minimize the global error can be expressed in terms of the principal eigenvectors of products of the auto- and cross-covariances of the input and desired output. Sensory maps with enhanced resolution are derived in terms of discrete receptor cells with parameterized tuning. The inverse kinematics problem is modeled in terms of rectangular matrix inversion. The Moore-Penrose pseudo-inverse provides a starting point for the analysis.

**Progress:**

The concept of contrastive learning was developed as a family of learning algorithms for neural networks. During learning the network oscillates between two phases. One phase has a teacher signal and one phase has no teacher signal. The weights are updated according to a learning rule that corresponds to gradient descent on a contrast function that measures discrepancy between the free network and the network with the teacher signal. A possible analog implementation, simulation results, and extensions were obtained.

**TITLE: Statistical Learning Networks**

**PI: Andrew R. Barron**  
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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 411p007---06**

**CONTRACT NO: N0001489J1811**

**CURRENT END DATE: 30 SEP 1992**

**SCIENTIFIC OFFICER: Neil L. Gerr**

**Technical Objective:**

The statistical properties of artificial neural networks, adaptive learning networks, and related nonparametric estimation methods will be derived. This will allow the performance of learning networks to be studied analytically. In addition, algorithms for efficient network estimation will be developed.

**Approach:**

Sequences of network classes will be derived for which the approximation error converges to zero. The rate of convergence of the error will be related to the smoothness properties of the associated network functions.

**Progress:**

For a class of artificial neural networks and target functions satisfying a given smoothness condition, the mean integrated squared error was shown to be bounded by  $O(1/n) + O(nd/N)\log N$ , where  $n$  is the number of nodes,  $d$  is the input dimension of the network, and  $N$  is the number of training observations. The two contributions to this total are approximation and estimation error, respectively. Approximation error refers to the distance between the target function and the nearest function realizable by a given neural network architecture, while estimation error refers to the distance between this nearest realizable function and the estimate actually generated by the network. The order of the bound is minimized with  $n = \text{SQRT}\{N/(d\log N)\}$ .

**TITLE: Mathematical Models of Auditory Processing and Recognition**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 411s001---04**

**CONTRACT NO: N0001491J1003**

**CURRENT END DATE: 30 SEP 1993**

**SCIENTIFIC OFFICER: Neil L. Gerr**

**Technical Objective:**

The objective is to develop mathematical models for the processing and recognition of acoustic signals by the auditory nervous system. Both early auditory processing (front-end processing by the cochlea) and central auditory processing (extraction of perceptually significant features by the auditory cortex) will be addressed.

**Approach:**

The approach is both mathematically rigorous and respectful of auditory neurophysiology. For monaural processing, wavelet transforms will be used to model the cochlea, particularly its ability to suppress noise and enhance spectral features. For binaural processing, spatial correlation models employing lateral inhibition will be used, in contrast to the more traditional idealized tap-delay line models.

**Progress:**

Mappings of the spatial distribution of responses in the primary auditory cortex revealed that both the gradient of the acoustic spectrum and sensitivity to FM sweep direction are encoded in an orderly manner along isofrequency planes. Psychoacoustical tests also demonstrate a potential perceptual correlate of the gradient maps, namely the threshold stability and heightened sensitivity of human subjects to the detection of changes in the symmetry of spectral peaks.

**TITLE: Mechanisms for Bioacoustic Signal Classification**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 411s002---02**

**CONTRACT NO: N0001491C0035**

**CURRENT END DATE: 31 JAN 1994**

**SCIENTIFIC OFFICER: Neil L. Gerr**

**Technical Objective:**

The objective is to develop new models for bioacoustic signal processing. Specific goals include creation of a statistical framework for cochlear preprocessing, determining the relationship between cochlear preprocessing and animal echolocation, wavelet analysis as a model for bioacoustic processing and as a signal processing tool (e.g., for the design of wideband active sonar signals), and the role of cortical maps in signal classification.

**Approach:**

A cochlear model is proposed in which a feedback loop is used to synthesize a Wiener filter. Under the new model, data can be processed continuously (rather than in blocks) and the filter bandwidth can be readily adapted to the signal/noise environment. Wavelets will be used to design active sonar waveforms with specified properties. An example of the utility of the approach is the derivation of a waveform for testing a specific Doppler (scale) hypothesis. Finally, lateral inhibition and Hebbian learning will be used to model the development of cortical maps for signal discrimination.

**Progress:**

Interactive activation (IA) networks are cognitive models for data interpretation. Competition and association of different features and hypotheses are represented by mutual inhibition and excitation of nodes. Interpretation of nodal activations as likelihoods or probabilities relates IA networks to statistical hypothesis testing. A recently developed formulation of IA networks in terms of Bayesian sequential hypothesis tests shows that, while suboptimal, IA networks may be more robust with respect to errors in estimated probability distributions.

**TITLE:** Bioacoustic Signal Detection and Estimation  
Using Wavelet Theory

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 411s003---06

**CONTRACT NO:** N0001491J1602

**CURRENT END DATE:** 31 DEC 1993

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The ability of animals such as bats, whales, and dolphins to use acoustic signals to locate and recognize objects motivates work in bioacoustic signal processing. Since the process by which animals manipulate and interpret acoustic signals cannot be directly observed, inferences may be made using modern signal processing theory. The goal of this project is to develop detection, estimation, and classification algorithms based on models of the auditory processing mechanism.

**Approach:**

The relationship between multiscale signal analysis and current models for the peripheral processing in auditory systems motivates an approach based on the wavelet transform. The wavelet transform describes a signal as a superposition of shifted and contracted/dilated versions of an analyzing waveform ("wavelet") often chosen to have bounded support. Signal enhancement and acoustic imaging will be addressed in the wavelet domain. Comparisons to conventional spectral domain methods will be performed using real bioacoustic data.

**Progress:**

The problem of detecting short duration transients characterized by a model with unknown parameters was addressed. Both linear and nonlinear signal models were considered. The transients undergo a linear transform prior to the application of a detection algorithm. Examples of such transforms include the short-time Fourier transform, the Gabor transform, and the wavelet transform. Closed form expressions were derived for the worst-case detection performance across all transients in a given class.

**Title:** Structure, Estimation and Prediction for Random Sequences and Fields

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119324---10

**CONTRACT NO:** N0001490J1371

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The objective of the research is the development of random field solutions for classes of ordinary and partial differential equations subject to random initial and boundary conditions and forcing functions. The Burgers and Navier-Stokes equations are of particular interest. Techniques for prediction and estimation will be developed.

**Approach:**

The approach involves both the time and spectral domains. In the time domain, the differential equations of interest will be discretized yielding systems of difference equations. Parametric solutions for the discrete systems will be derived, and the relation between stochastic solutions of the discrete systems and the corresponding differential equations will be determined. In the spectral domain, high order cumulant spectral estimates will be used to measure nonlinear transfer of energy between different wavenumbers in random fields.

**Progress:**

Derived the asymptotic behavior of a nonparametric measure of independence for the component random variables of independent and identically distributed bivariate random vectors. This involved application of a central limit theorem for degenerate U-statistics. Asymptotic normality is proved for the case of independent components.

**Title:** Matched Subspace Filtering for Detection,  
Estimation, and Time Series Analysis

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119343---07

**CONTRACT NO:** N0001489J1070

**CURRENT END DATE:** 30 SEP 1994

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The objective is to develop improved methods for signal detection and source localization. Multirank estimators for multidimensional spectra (e.g., frequency-wavenumber and range-depth spectra) and matched subspace filters for matched field processing will be developed.

**Approach:**

The linear statistical model is used to derive low rank approximants for random and deterministic signals. By matching to the structure of this low rank subspace, a matched subspace filter is derived. The dimension of the subspace provides a mechanism for reducing noise at the expense of introducing bias, but with a net gain in signal-to-noise ratio. These concepts are particularly powerful for known modal signals, for which the low rank subspace is determined by the dominant modes. The problem is much more difficult when the modes are not known, e.g., when the medium is deterministic but modeled with error or subject to stochastic spatial/temporal variation.

**Progress:**

Showed the relationship between low rank modeling and multiple window spectrum estimation via maximum likelihood estimates of structured covariance matrices. The power in a narrow spectral band is estimated using a low rank signal plus noise covariance model. This model is swept through the entire frequency band to obtain an estimate of power as a function of frequency. The resulting spectrum estimates are given by weighted combinations of eigenspectra. Each eigenspectrum results from projecting the data onto an orthogonal component and squaring. The multiple window spectrum estimates of Thomson correspond to a particular choice for the low rank signal model.

**Title: High Order Spectral Analysis of Random Signals**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4119350---09**

**CONTRACT NO: N0001492J1086**

**CURRENT END DATE: 30 SEP 1994**

**SCIENTIFIC OFFICER: Neil L. Gerr**

**Technical Objective:**

The technical objective is the development of more effective high order spectral methods for detecting, estimating, and classifying non-Gaussian signals in non-Gaussian noise. Of primary importance are better methods for high order spectral density estimation.

**Approach:**

The approach is based on high order cumulant polyspectra. K-th order ( $k$  greater than 2) spectral density estimation will be addressed using both non-parametric and model-based approaches. In particular, new non-parametric estimation procedures have been proposed with faster rates of convergence than currently known procedures.

**Progress:**

High order spectral density estimation from irregularly spaced data was addressed. Consistency results and alias-free sampling schemes were derived. In particular, it was shown how the information of the sampling process comes into play with respect to consistent estimation of the bispectrum of a continuous time process. Estimates under a Poisson sampling scheme were derived in detail.

**Title:** Numeric and Symbolic Signal Representation  
and Processing

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**FUNDING AGENCY:** Defense Advanced Research Projects Agency

**R&T PROJECT CODE:** 4119351---07

**CONTRACT NO:** N0001489J1489

**CURRENT END DATE:** 30 JUN 1993

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The technical objective is to develop and analyze numerical and symbolic algorithms for processing and interpretation of signals and images. This will yield an interactive computing environment for signal processing system design. The ultimate goal is the development of a fully automated system for signal processing system design.

**Approach:**

Techniques for symbolically manipulating and evaluating signal processing expressions will be developed. The problem of finding functionally equivalent expressions that can be implemented at reduced computational cost is of particular interest. Another area of emphasis involves automatic compilation of signal processing algorithms, including those that use extensive linear algebra, to architectures such as systolic or cellular arrays. Applications include noise cancellation for speech and sonar signal enhancement.

**Progress:**

Using maximum likelihood estimation, a wavelet-based Weiner filter was introduced for reconstructing fractal signals received in noise. It gives a least-squares reconstruction for fractional Brownian processes in terms of the associated sequences of data expansion coefficients and expected signal and noise energy at different scales. The technique is applicable in a broad range of signal and image processing settings and provides a basis for new approaches to communication signal design and reception.

**Title: Nonstationary Time Series**

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**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4119353---08**

**CONTRACT NO: N0001492C0019**

**CURRENT END DATE: 30 APR 1994**

**SCIENTIFIC OFFICER: Neil L. Gerr**

**Technical Objective:**

The objective is to develop techniques for analyzing nonstationary and non-Gaussian time series. Such techniques have the potential to yield performance superior to methods based on the power spectrum, which is only optimal for stationary Gaussian signals.

**Approach:**

The notion of high order crossing will be extended to filtered signals, with exponential smoothing filters of particular interest. The spectral and high order crossing crossing properties of recursively filtered random processes will be determined.

**Progress:**

The contraction mapping method for estimating narrowband frequencies in noise was developed, analyzed, and applied. The method employs parametric filters that are adaptively tuned by successive zero-crossing counts or first order sample autocorrelations yielding convergent frequency estimates. In an application to a well known data set, the method successfully detected a diurnal cycle that other methods often fail to detect.

**Title:** Efficient Signal Processing Algorithms - Analysis and Implementation

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**FUNDING AGENCY:** Naval Research Laboratory

**R&T PROJECT CODE:** 4119357---10

**CONTRACT NO:** N0001489J1327

**CURRENT END DATE:** 30 DEC 1992

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The technical objective of this effort is to develop and analyze new algorithms and architectures for very fast on-chip signal and image processors. These will yield improved adaptive and multidimensional filters with payoff for surveillance and communications. The development of efficient techniques for performing the a posteriori optimization required in Markov random field image segmentation based on the Gibbs distribution is of particular interest.

**Approach:**

For least-mean-squares (LMS) adaptive filters, a design in which the multiplier is constrained to be a power-of-two or a sum of power-of-two terms will be analyzed. A second simplification to be considered places a power-of-two quantizer at the input to the multiplier. This reduces the multiplication to a simple shift. Similar modifications of the variable step size LMS algorithm will be studied. For image analysis based on Gibbs-Markov random fields, a multiple resolution segmentation approach will be used. Implementations of these algorithms in very fast low power chips will be developed.

**Progress:**

Adaptive smoothing filters are used for the removal of narrowband interference and in spectral estimation. Two popular least-mean-square (LMS) adaptive filters, one that is constrained to have symmetry and one in which each tap adapts independently, were evaluated. The constrained filter requires only one-half as many multiplications as the unconstrained filter for adaptation. Moreover, the analysis shows that the constrained filter has better convergence characteristics than the unconstrained version.

**Title:** Statistical Inference from Sampled Data

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119359---05

**CONTRACT NO:** N0001490J1175

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The objective of this effort is the development of techniques for sampled data systems, including those involving probability density estimation, filtering and prediction of stochastic signals in noise, spectrum estimation, and design and evaluation of vertical arrays for range and depth localization of a radiating source in a noisy ocean.

**Approach:**

The statistical properties of probability density estimators based on B-splines, the method of sieves, and truncated singular value decompositions will be derived in the case of noisy data. In the area of adaptive filtering, attention will turn to the adaptive sign algorithm, a variant of Widrow's LMS algorithm that uses only the polarity of the output error to update the coefficient estimate. Finally, will evaluate several schemes for estimating the range and depth of a radiating source using a vertical array. Optimal non-uniform sampling designs that make use of the spatial covariance structure of the noise, in contrast to the equally-spaced design, will be derived.

**Progress:**

The L1 and L2 strong consistency of recursive kernel density estimators was established for mixing and ergodic stationary processes. Rates of convergence were obtained in the L2 case for mixing processes. Finally, the notion and properties of Hilbert space valued mixingales were developed, and strong laws of large numbers were derived.

**Title:** Signal Detection Using Polyspectra

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119361---05

**CONTRACT NO:** N0001491J1276

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The technical objective is the development of more effective methods for detecting, classifying, and localizing nonlinear, nonstationary, and transient signals received in additive noise. In addition, techniques for defining white noise filters yielding outputs with specified polyspectra will be derived.

**Approach:**

The approach to localization involves cross-polyspectral processing of the signals received by adjacent sensors in a horizontal linear array. The finite Fourier transform is applied to the output of each sensor, the cross-bispectrum and cross-trispectrum are computed for adjacent sensors, and the phases of the cross-polyspectra are fitted to yield estimates of the propagation direction as a function of frequency.

**Progress:**

A bispectral approach to deconvolution of voiced speech when the signal is not minimum phase and the sampling is not synchronous with the pitch frequency was introduced. Voiced speech is modeled as the output of a linear filter driven by a sequence of impulses. Results of tests on both synthetic and real speech show that the algorithm is capable of estimating the phase as well as the amplitude of the linear filter that generates the speech waveform.

**Title:** Information and Stochastic Systems

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119363---05

**CONTRACT NO:** N0001492C0094

**CURRENT END DATE:** 30 SEP 1994

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The technical objective is the development of new techniques for detecting and classifying random signals and improved models for the non-Gaussian communication channel.

**Approach:**

Likelihood ratio tests for the detection of random signals in non-Gaussian noise will be derived using a model based on a sum of filtered independent increment processes. This model will also be considered in a study of multi-user communication channels.

**Progress:**

Two new signal detection algorithms, one fully adaptive to the signal-plus-noise (S+N) process, were evaluated using both simulated and passive sonar data. The algorithms make no assumptions regarding the statistical properties of the S+N process, but instead require estimating the drift function of an underlying diffusion model as described by Cramer-Hida multiplicity theory. Comparisons with several reference algorithms show the potential of the approach.

**Title:** Modulation and Coding Techniques for Atmospheric and Underwater Optical Communications

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119364---04

**CONTRACT NO:** N0001489J1375

**CURRENT END DATE:** 30 NOV 1994

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The technical objective is to develop effective methods for atmospheric and underwater optical communications. This includes the development of effective modulation and coding design methodologies.

**Approach:**

The work begins with identifying the most appropriate models for the atmospheric and underwater optical channels. Analytic and computational techniques for evaluating the performance of various modulation schemes capable of dealing with the intersymbol interference and statistical amplitude fluctuation characteristic of each of these channels will then be derived. Finally, wavelength division schemes for random multiple-access in the free-space setting will be developed.

**Progress:**

Analyzed the performance of coherent dense wavelength division multiple access (WDMA) schemes for optical networks. The effects of interference from other signals due to instability in the laser carrier frequency, phase noise, and thermal noise are all taken into account. Dense WDMA is then coupled with direct-sequence spread-spectrum (DSSS) modulation in order to mitigate the effects of interference from other signals. The performance results quantify for the first time the multiple access capability of dense WDMA and the performance advantages offered by hybrids of DSSS and WDMA.

**Title:** P-th Order Weakly Stationary Processes  
and their Harmonic Representation

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119367---04

**CONTRACT NO:** N0001489J1824

**CURRENT END DATE:** 31 DEC 1994

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

While there is much work relating to second order stochastic processes, there is little relating to general p-th order processes, p less than two. Such processes provide models for impulsive signals such as acoustic signals encountered under cracking ice in the arctic and static discharges from thunderstorms at radio frequencies. This work aims to develop the harmonic representations that can serve as the basis for detection and prediction methodologies for p-th order processes.

**Approach:**

For a second order stationary stochastic process  $X(t)$ , the shift operator is unitary on the Hilbert space  $H = \text{span}\{X(s)\}$ . The spectral theory of unitary operators then gives a harmonic representation for  $X$ . For p-th order stationary processes, p less than two,  $H$  is a Banach space but not a Hilbert space and the shift operator is isometric but not unitary. Spectral representations for operators on Banach spaces will be used to develop harmonic representations for p-th order stationary processes, p less than two.

**Progress:**

The correlation-autoregressive (CAR) class of stochastic processes was introduced. In short, a process  $X(n)$  with autocorrelation function  $R(m,n) = E\{X(m)X(n)\}$  is CAR when there exist scalars  $a(i)$ ,  $i=1, \dots, r$ , such that

$$R(m,n) = \sum_{i=1}^r a(i)R(m+i,n+i).$$

Initial results include the development of a useful representation for the correlation function of a CAR process.

**Title:** Detection and Classification of Signals and Noise with Long Memory

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119368---04

**CONTRACT NO:** N0001490J1287

**CURRENT END DATE:** 30 NOV 1992

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

Long-range dependence, evidenced by self-similar sample paths and  $1/f$  power spectral density, has been observed in many physical phenomena, including underwater acoustic ambient noise. The technical objective of this project is to develop new statistical tests for long-range dependence and new methods for estimating the asymptotic behavior of the power spectrum near zero for stochastic processes with long-range dependence.

**Approach:**

For time series with spectral density given by  $f(w)=C*\exp\{-d*\ln(w)\}$  in the neighborhood of zero, a parametric family of models, for which the exponent  $d$  is one of the parameters, will be derived. Robustness of the resulting maximum likelihood or method of moments estimators will be addressed since non-Gaussian data with long-range dependence typically obey non-central limit theorems whose speed of convergence is a function of the degree of long-range dependence.

**Progress:**

While the covariance function characterizes the dependence structure of a stationary Gaussian process, a non-Gaussian symmetric alpha-stable (SAS) process has infinite variance and so its covariance function does not exist. It was proposed to use the function  $r(t)$  defined as the difference of the joint characteristic function of  $(X(0),X(t))$  and the product of the characteristic functions of  $X(t)$  and  $X(0)$  as a measure of dependence for SAS processes. It was shown that  $r(t)$  is particularly useful as  $t$  goes to infinity for distinguishing among the asymptotic structures.

**Title:** Information Theory of Wideband Channels

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119370---04

**CONTRACT NO:** N0001490J1734

**CURRENT END DATE:** 31 MAR 1993

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The goal is to develop an information theory for multi-user random access wideband channels that incorporates the cost of transmitting a single bit. This will allow the calculation of transmission rate bounds for shared optical channels and the subsequent design of coding strategies that yield performance approaching these bounds.

**Approach:**

The first step is to develop a general criterion that characterizes the most economical way to communicate reliably. Preliminary work shows that the tools of Shannon theory are inadequate. For example, the role of mutual information is taken over by Kullback-Leibler divergence. Results on the asymptotic performance of binary hypothesis tests can then be used in the proof of coding theorems.

**Progress:**

Recent work addressed multiple access channels with memory. The capacity region and optimal spectral densities were determined for a Gaussian linear multiple access channel where the inputs of the users pass through respective linear systems and are then superimposed before being corrupted by an additive Gaussian noise process. This involved the formulation of a geometric method which can be viewed as a generalization of the single-user water-filling argument. In contrast to the memoryless channel, the capacity region of the channel with memory is not in general a pentagon.

**Title**      **Image Processing Applications of Seamless Resampling**

**PI:**            **Raoul LePage**  
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**FUNDING AGENCY:**      **Office of Naval Research**

**R&T PROJECT CODE:**      **4119373---03**

**CONTRACT NO:**            **N0001491J1087**

**CURRENT END DATE:**      **30 SEP 1993**

**SCIENTIFIC OFFICER:**    **Neil L. Gerr**

**Technical Objective:**

The goal is to develop new techniques for analyzing alpha-stable processes. Such non-Gaussian processes provide realistic models for a wide range of physical phenomena, particularly those that exhibit impulsive behavior. The development of a viable spectral theory and associated methods for spectrum estimation are of primary interest. In addition, these techniques will be applied to image processing.

**Approach:**

The approach is based on a series representation for alpha-stable processes in which each term is the product of a random sign, an alpha-stable point process, and a simple stationary process with classically defined spectrum. This representation permits evaluation of spectrum estimation by both standard kernel methods and by a newly derived statistical resampling (bootstrap) technique that has been called "seamless resampling". In particular, seamless resampling facilitates estimation of the sampling distributions of contrast deconvolution operations on noisy image data.

**Title:** 1992 NATO Advanced Study Institute on  
Wavelets and their Applications

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119375---02

**CONTRACT NO:** N0001492J1286

**CURRENT END DATE:** 31 JAN 1993

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The objective is to encourage and enhance U.S. research efforts in the area of wavelet analysis.

**Approach:**

Five young U.S. researchers (senior graduate students and post-docs) will receive travel grants to the NATO Advanced Study Institute on Wavelets and their Applications to be held 16-29 August 1992 in Il Ciocco, Italy.

**Title:** Mathematical Algorithmic Research for Full  
Spectrum Sonar Signal Processing

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119376---02

**CONTRACT NO:** N0001492WX24051

**CURRENT END DATE:** 30 SEP 1993

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The goal is to develop signal processing techniques appropriate for use in a stochastic acoustic waveguide. Detection and localization are of particular interest.

**Approach:**

The first step is to model stochastic variation in the waveguide transfer function through the specification of random delay and attenuation coefficients in the multipath channel. In this setting, the performance of the conventional deterministic-channel log-likelihood ratio detector (LRD) deteriorates rapidly with increasing variance of the random multipath channel model parameters. The appropriate random-channel LRD will be determined and evaluated.

**Progress:**

The likelihood ratio detector for the random multipath channel was developed and analyzed under the assumption of low signal-to-noise ratio (SNR). Using Monte Carlo techniques, the performance of the detector was evaluated for a single source-single sensor configuration and channel with random multipath delay uniformly distributed between 90 and 110 msec. The signal and noise sequences have spectra flat from 0 to 100 Hz with spectral heights 1 and 10, respectively (SNR=-10dB). The random multipath channel likelihood ratio detector outperforms both previously developed ad hoc random channel detectors and the deterministic channel likelihood ratio detector in this setting.

**Title:** Adaptive Array Processing In Uncertain  
Inhomogeneous Media

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119377---02

**CONTRACT NO:** N0001491J1628

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

This project addresses the most important issues encountered in beamforming and matched field processing with large arrays in real underwater acoustic environments. Specifically, random environmental fluctuations and uncertainty limit the ability to coherently process the acoustic field. This will be addressed by the development of robust processors based on realistic random propagation models.

**Approach:**

The approach is two-fold. First, robust array processors will be designed using a minimax performance criteria, where the array weights are those which optimize performance over a range of environmental parameters. Second, an inherently stochastic approach termed stochastic beamforming will be developed. Specifically, random ocean acoustic propagation models will be used to derive stochastic models for signals received at both horizontal and vertical arrays, and an appropriate detection theory will be developed and applied to this random signal in noise problem.

**Progress:**

An adaptive minimax matched field processor was developed which yields the interference rejection characteristic of adaptive processors while limiting the sensitivity of the processor to environmental mismatch. The derivation of the processor is based on several new theorems regarding the solutions to a class of minimax approximation problems. The theorems lead to the development of a technique for solving for the optimal array weights and the associated estimate of the power emitted by the source at the array focal point.

**Title:** Gabor Expansion/Zak Transform Classification  
in Multipath Underwater Acoustics

**PI:** Jose' M. F. Moura  
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**FUNDING AGENCY:** Defense Advanced Research Projects Agency

**R&T PROJECT CODE:** 4119378---02

**CONTRACT NO:** N0001491J1833

**CURRENT END DATE:** 31 MAY 1994

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The objective is to develop array processing techniques for detection, localization, and classification in the underwater acoustic waveguide. Multipath propagation and aperiodic signals are of particular interest.

**Approach:**

The approach involves integrating matched field processing with Gabor signal analysis. Matched field processing will allow the energy in acoustic multipath arrivals to be coherently combined so as to yield maximum array gain. Subsequent processing by the Gabor/Zak transform will allow analysis of complex aperiodic (e.g., transient) signals.

**Progress:**

A simple algorithm was developed for recovering the multipath structure in a horizontally stratified waveguide. The sound velocity is approximated by a multilinear profile. Though the algorithm currently assumes ray acoustics, the extension to modal propagation is in progress and further extensions to more complex environments are planned. In addition, work has begun on applying the Gabor and wavelet transforms to real acoustic data (the unclassified DARPA Standard Transient Data Set 1).

**Title:** Higher-Order Spectra in Signal Processing

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119379---04

**CONTRACT NO:** N0001492J1034

**CURRENT END DATE:** 30 SEP 1994

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The goal is to develop and extend high order cumulant spectral analysis methods. In particular, issues of robustness of polyspectral estimates, stochastic propagation effects in cross-polyspectra-based array processing, and nonstationarity will be addressed. In addition, a high order spectral theory for alpha-stable processes will be developed.

**Approach:**

Non-parametric methods will be used to develop robust polyspectral estimators. High order polyspectral bearing estimation will be addressed in the context of nonlinear transfer function models that have random parameters. Wigner polyspectra will be developed and applied to problems of nonstationary signal analysis. The notion of the "covariation" (vs covariance) function for an alpha-stable (vs Gaussian) process will be used as the basis for defining high order spectra for alpha-stable processes.

**Title:** Matched Field Source Localization in a  
Random Ocean Channel

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**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119380---01

**CONTRACT NO:** N0001492J1090

**CURRENT END DATE:** 30 NOV 1994

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The goal is to improve the performance of sonar signal processing systems by fully exploiting attainable knowledge of the ocean acoustic propagation channel. In particular, issues relating to acoustic propagation in the random ocean waveguide, representation of oceanographically realistic sound speed profile perturbations, and the design of robust array processing techniques will be addressed.

**Approach:**

A realistic model for acoustic propagation in a random ocean channel will provide the basis for matched field processing methods which are robust to perturbations in a range dependent sound speed profile. The model combines adiabatic normal mode theory and first order perturbation analysis. This full wave model will be used to assess the utility of multiply-constrained maximum likelihood beamforming and optimal quadratic processing.

**Title:** Beamforming on Transient and Non-Stationary Signals  
in Inhomogeneous Acoustic Environments and Data Driven  
Boundary Value Problems

**PI:** Stephen L. Hobbs  
Naval Ocean Systems Center  
Signal Processing Technology Branch  
(619) 553-2018

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119381---01

**CONTRACT NO:** N0001492WX24131

**CURRENT END DATE:** 30 SEP 1991

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

Array processing (beamforming) methods will be developed for nonstationary signals in realistic ocean environments. Models for such environments involve the use of stochastic boundary value problems. In this context the objective is to evaluate statistical properties of the random field which is obtained when the boundary values are replaced by discrete, noisy observations.

**Approach:**

Beamforming techniques will be developed for nonstationary signals that exhibit spectral correlation. Transient signals will be addressed through the use of the Gabor representation and appropriate time-frequency transforms. For stochastic boundary value problems, smoothing the discrete observations on the boundary yields a continuous random boundary function. The statistical properties of the boundary are used to derive the statistical properties of the interior by the classical methods of mathematical analysis.

**Progress:**

The asymptotic distribution of location estimates of a source under weak assumptions about the signal processing method and ambient noise was derived. The location estimates are the peaks of the array output (ambiguity surface) while the signal plus noise process is assumed strictly stationary. The estimates are shown to be consistent, asymptotically normal, and the asymptotic covariance was obtained. Use of these statistics was illustrated by the construction of an approximate confidence region for the true source location.

**Title:** Research on Nonstationary Random Processes and Applications of Spectral Coherence

**PI:** Harry L. Hurd  
Harry L. Hurd, Associates, Inc.  
(919) 846-9227

**FUNDING AGENCY:** Naval Undersea Warfare Center, RI

**R&T PROJECT CODE:** 4119382---02

**CONTRACT NO:** N0001492C0057

**CURRENT END DATE:** 15 OCT 1994

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The goal is to develop new spectral analysis methodologies for nonstationary stochastic processes, particularly those that provide realistic models for transient, broadband, and chaotic signals. In addition, recently developed spectral coherence based analysis techniques will be refined and evaluated in tests on real world data.

**Approach:**

The approach is based on the notion of spectral coherence as it arises in the context of harmonizable and periodically correlated stochastic processes. That is, whereas the spectral representation theorem shows that stationary stochastic processes are generated by integrating  $\exp(i\omega t)$  with respect to a random spectral measure  $B(\omega)$  that has independent increments, the spectral measure for nonstationary but harmonizable processes has correlated increments (spectral correlation). These concepts will be extended to chaotic (i.e., deterministic) signals. In particular, preliminary work shows that the output of a periodically perturbed dynamical system may exhibit spectral coherence as previously observed in periodically correlated stochastic signals. The periodic perturbation may be either deterministic or random in nature. The spectral coherence structure of such chaotic processes may serve to characterize them and so provide a basis for new analysis methodologies.

**Title:** Ocean Acoustic Signal Processing: A  
Model-Based Approach

**PI:** James V. Candy  
U.S. Department of Energy  
(510) 422-8675

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119383---01

**CONTRACT NO:** N0001492C0055

**CURRENT END DATE:** 30 SEP 1992

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The goal is to develop methods to make it computationally feasible to estimate ocean acoustic environmental parameters from pressure-field-only measurements on-line.

**Approach:**

The approach is based on the normal mode model for acoustic propagation. A state-space formulation is used to provide a recursive estimator for the sound speed profile. The validity of the approach and approximations (e.g., piece-wise linearity of the sound speed profile) associated with the implementation of the recursive estimator (extended Kalman filter) will be determined by tests using real ocean acoustic data.

**Title:** New Time-Frequency and Time-Scale Methods for  
Bio-Acoustical Signal Processing

**PI:** G. F. Boudreaux-Bartels  
University of Rhode Island  
Electrical Engineering Department  
(401) 792-5805

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4119384---01

**CONTRACT NO:** N0001492J1499

**CURRENT END DATE:** 31 DEC 1994

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The objective is to develop more effective methods for analyzing transient and nonstationary signals received in noise. Detection, characterization, and classification are of particular interest.

**Approach:**

The approach is based on time-frequency representations such as the Wigner distribution and time-scale representations such as the wavelet transform. Connections between the two types of representations will be developed and used to create new types of transforms with the favorable properties of each. Constant-Q (i.e., proportional bandwidth) properties, which are characteristic of auditory processing in mammals, are of particular interest.

**Progress:**

A generalization of the Choi-Williams (time-frequency) Exponential Distribution (ED) and a new Butterworth distribution (BUD) were introduced. The Generalized Exponential Distribution (GED) and BUD were shown to satisfy all the desirable properties of the ED while being superior by reducing the appearance of spurious cross-terms. In related work, the various constant-Q transforms introduced by Altes, Flandrin, and Bertrands were placed within the common framework of hyperbolic-class distributions, characterized by scale invariance and hyperbolic time shift properties.

**Division Projects**

**TITLE: Mathematical Olympiad Training Session**

**PI: Marcia P. Sward  
Mathematical Association of America  
(202) 387-5200**

**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4110000---06**

**CONTRACT NO: N0001492J1295**

**CURRENT END DATE: 31 JAN 1993**

**SCIENTIFIC OFFICER: Neil L. Gerr**

**Technical Objective:**

The objective is to prepare a team of U.S. high school students to compete in the International Mathematical Olympiad to be held 10-22 July 1992 in Moscow, Russia. Those selected will be introduced to a wide range of mathematical problems and theory at the Mathematical Olympiad Training Session, 9 June to 7 July 1992 at the U.S. Naval Academy in Annapolis, Maryland.

**Approach:**

The selection process starts with the 400,000 high school students who take the annual American Mathematics Examination. Those with the top scores (about 4,000) proceed to the American Invitational Mathematics Examination, and from this group 140 participate in the USA Mathematical Olympiad (USAMO). The 24 USAMO finalists then participate in the Mathematical Olympiad Training Session, a four week workshop of intensive university-level training. This serves to familiarize them with more advanced mathematical problems, theory, and methodology.

**Progress:**

In the 1991 International Mathematical Olympiad, held 12-23 July in Sigtuna, Sweden, the U.S. team finished fifth with a score of 212. The U.S. team trailed the USSR (241), PRC (231), Romania (225), and Germany (222).

**TITLE: Board on Mathematical Sciences (BMS)**

**PI: John E. Lavery  
National Academy of Sciences  
Board on Mathematical Sciences  
(202) 334-2421**

**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4110002---05**

**CONTRACT NO: N0001486C0762**

**CURRENT END DATE: 31 DEC 1992**

**SCIENTIFIC OFFICER: Neil L. Gerr**

**Technical Objective:**

The Board on Mathematical Sciences is designed primarily to keep ONR and the other federal funding agencies up-to-date on the latest developments in the mathematical sciences, including pure and applied mathematics and probability and statistics. The Board identifies and analyzes the most important trends and discoveries.

**Approach:**

The Board provides information to ONR regarding new developments in mathematics and cross-disciplinary areas of Navy interest. In addition, it coordinates activities with the academic mathematics community, federal funding agencies, and professional societies.

**Progress:**

The Board issued the report "The Mathematical Sciences: A Resource for American Technology and Economic Competitiveness", National Academy Press, 1991. The report traces the role of mathematical methods in the aircraft, computer, petroleum, automotive, and telecommunication industries. It emphasizes the importance of technology transfer from mathematicians to engineers and designers. The President's Science Advisor cited the report in his address to the 1991 International Conference on Industrial and Applied Mathematics.

**TITLE: Mathematical Sciences Education Board (MSEB)**

**PI: Ray C. Shiflett  
National Academy of Sciences  
Mathematical Sciences Education Board  
(202) 334-3294**

**FUNDING AGENCY: Office of Naval Research**

**R&T PROJECT CODE: 4110003---05**

**CONTRACT NO: N0001487J1251**

**CURRENT END DATE: 31 MAR 1992**

**SCIENTIFIC OFFICER: Neil L. Gerr**

**Technical Objective:**

The objective of this research is to develop improved methods for mathematics education. These will have payoff in all areas of science and so will strengthen the scientific infrastructure of the United States.

**Approach:**

The MSEB will carry out research on mathematics curriculum, instruction, testing, and teacher education. The application of computer technology to each of these areas, particularly instruction and testing, will be a major focus. A "holistic" approach, spanning all aspects of mathematics education, will be employed.

**Progress:**

The NRC is preparing to expand MSEB's nationwide electronic and human networks to include science as well as mathematics. The principal networks involved are

- State Mathematics Coalitions
- Mathematical Sciences Education Leadership Network
- Corporate Council for Mathematics and Science Education
- Alliance to Involve Minorities in Mathematics

It is the NRC's intention to develop each of these into a national network serving both mathematics and science, rather than just mathematics as at present. The NRC effort will be headed by Dr. Kenneth M. Hoffman, the former MSEB Executive Director and now NRC Associate Executive Officer for Education.

**TITLE:** A Summer Program in Mathematics and Computer Science for Academically Oriented Students

**PI:** Bernis Barnes  
University of the District of Columbia  
Department of Mathematics  
(202) 282-3171

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4110004---04

**CONTRACT NO:** N0001492J1322

**CURRENT END DATE:** 31 DEC 1992

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

This effort aims to improve the United States' technology manpower base by creating a framework for academically talented students to pursue research in mathematics, statistics, and computer science.

**Approach:**

The PI has conducted similar programs during the ten previous summers and the same plan will be utilized for the summer of 1992. He will first conduct a survey of eligible students that have the greatest promise in mathematics and computer science. Approximately forty will be selected to take part in a five week summer research program in mathematics, statistics, and computer science. A follow-up survey will be conducted to assess the subsequent academic success of each student.

**Progress:**

Thirty-seven students enrolled in the 1991 UDC Summer Program in Mathematics and Computer Science and thirty-six completed it successfully. The students participated in a variety of classroom activities and made field trips to the Naval Research Laboratory and the David Taylor Research Center. Subject areas covered included geometry, algebra, computer programming (BASIC), and statistics.

**TITLE:** Workshops to Encourage and Support Young Women  
in Mathematics

**PI:** Jill P. Mesirov  
Association for Women in Mathematics  
(617) 876-1111

**FUNDING AGENCY:** Office of Naval Research

**R&T PROJECT CODE:** 4110006---02

**CONTRACT NO:** N0001491J1305

**CURRENT END DATE:** 30 NOV 1992

**SCIENTIFIC OFFICER:** Neil L. Gerr

**Technical Objective:**

The objective is to increase the rate of retention of young women mathematicians in research-oriented careers. This will benefit the manpower base and scientific infrastructure of the U.S.

**Approach:**

The approach is to hold a series of workshops concurrent with the major annual mathematics meetings. These will bring together young researchers with more senior researchers. Ten young mathematicians will make technical presentations on their current research. The more senior participants will provide feedback and encouragement.

**Progress:**

A workshop was held 7 JULY 1991 in conjunction with ICIAM 91 in Washington DC. The workshop featured technical presentations by 10 women post-docs, a poster session with 12 women graduate students, and a panel discussion on research opportunities and support that included representatives from ONR (Dr. Julia Abrahams) and NSF (Dr. Deborah Lockhart).

**INDEX**

## INDEX

Ablowitz . . . . .	25
Alavi . . . . .	45
Altes . . . . .	175
Babuska . . . . .	75
Baggeroer . . . . .	193
Baker . . . . .	185
Balas . . . . .	107
Baldi . . . . .	172
Bank . . . . .	79
Barnes . . . . .	206
Barron . . . . .	173
Bellout . . . . .	16
Billard . . . . .	131, 137
Bland . . . . .	109
Bleistein . . . . .	12
Block . . . . .	32
Bogart . . . . .	43
Boudreaux-Bartels . . . . .	200
Boyd . . . . .	114
Bradley . . . . .	117
Browning . . . . .	92
Byrnes . . . . .	191
Candy . . . . .	199
Canning . . . . .	86
Carmona . . . . .	152
Carter . . . . .	192
Chan . . . . .	84
Chandru . . . . .	116
Chang . . . . .	156
Charnes . . . . .	68
Chartrand . . . . .	42
Chen . . . . .	21
Cheney . . . . .	5
Chernoff . . . . .	130
Cinlar . . . . .	161
Collopy . . . . .	121
Cozzens . . . . .	54
Dafermos . . . . .	30
Dearholt . . . . .	66
deFigueiredo . . . . .	168
Demmel . . . . .	73
Deogun . . . . .	60
Devore . . . . .	18
Duffus . . . . .	38
Eddy . . . . .	132
Entringer . . . . .	58
Faudree . . . . .	53
Feldman . . . . .	140
Fiacco . . . . .	103

Foias . . . . .	19
Friedlander . . . . .	176
Garcia . . . . .	94
Geman . . . . .	135
Geraniotis . . . . .	186
Glover . . . . .	112
Goldberg . . . . .	99
Golomb . . . . .	49
Goodman . . . . .	29
Goutsias . . . . .	145
Greengard . . . . .	88
Gunzburger . . . . .	23
Hammer . . . . .	118
Hansen . . . . .	63
Harary . . . . .	50
Henshaw . . . . .	90
Herron . . . . .	6
Hinich . . . . .	184
Ho . . . . .	102
Hobbs . . . . .	197
Hochbaum . . . . .	108
Hoffman, F . . . . .	52
Hoffman, K . . . . .	105
Hooker . . . . .	115
Hsing . . . . .	157
Hurd . . . . .	198
Iyengar . . . . .	158
Jacobson . . . . .	40
Janowitz . . . . .	41
Jawerth . . . . .	82
Jensen . . . . .	78
Ji . . . . .	138
Johnson, C . . . . .	51
Johnson, D . . . . .	143
Jones, C . . . . .	30
Jones, R . . . . .	144
Kadane . . . . .	139
Kedem . . . . .	181
Keller . . . . .	4
Kennington . . . . .	119
Kierstead . . . . .	36
King . . . . .	106
Kleinman . . . . .	91
Klibanov . . . . .	26
Knight . . . . .	95
Knightly . . . . .	11
Kreiss . . . . .	83
Krener . . . . .	142
Kriegsman . . . . .	14
Krolik . . . . .	196
Lai . . . . .	61
Laskar . . . . .	55

Lavery . . . . .	204
Lawson . . . . .	57
LePage . . . . .	190
Li . . . . .	22
Lii . . . . .	179
Liu . . . . .	182
Lucier . . . . .	20
Lundgren . . . . .	56
Mackin . . . . .	120
Majda . . . . .	7
Malek-Madani . . . . .	15
Mariano . . . . .	162
Martin . . . . .	134
Masry . . . . .	183
McKee . . . . .	44
McLaughlin . . . . .	5
McMorris . . . . .	45, 67
Meggido . . . . .	113
Mesirov . . . . .	207
Miamee . . . . .	187
Mitchell . . . . .	111
Mittal . . . . .	127
Moody . . . . .	171
Moreno . . . . .	48
Moura . . . . .	150, 194
Murray . . . . .	101
Nachman . . . . .	17
Newton . . . . .	163
Nikias . . . . .	195
Ockendon . . . . .	9
Oliger . . . . .	71, 77
Oppenheim . . . . .	180
Osher . . . . .	85
Parks . . . . .	170
Parlett . . . . .	74
Pitt . . . . .	147
Plummer . . . . .	37
Puri . . . . .	149
Ramm . . . . .	13
Rao . . . . .	167
Ratliff . . . . .	104
Rauch . . . . .	28
Reid . . . . .	65
Renardy . . . . .	31
Rheinboldt . . . . .	76
Rice . . . . .	155
Ringeisen . . . . .	47
Rokhlin . . . . .	80
Rose . . . . .	81
Rosenblatt . . . . .	177
Rothblum . . . . .	62
Rozovskii . . . . .	154

Scharf . . . . .	178
Scheinerman . . . . .	39
Schuetz . . . . .	87
Schultz . . . . .	89
Schwartz . . . . .	169
Schwenk . . . . .	59
Scott . . . . .	129
Shamma . . . . .	174
Shiflett . . . . .	205
Simchi-Levi . . . . .	110
Singpurwalla . . . . .	133
Smith . . . . .	128
Solomon . . . . .	126
Stuart . . . . .	96
Svobodny . . . . .	24
Sward . . . . .	203
Symes . . . . .	8
Szymczak . . . . .	93
Taqqu . . . . .	188
Tavare' . . . . .	64
Teich . . . . .	160
Trick . . . . .	100
Tucker . . . . .	125
Verdu . . . . .	189
Vitale . . . . .	146
Walstad . . . . .	72
Wegman . . . . .	141
Weinert . . . . .	136
Wiggins . . . . .	27
Wilf . . . . .	35
Willsky . . . . .	151
Wise . . . . .	148
Wollkind . . . . .	10
Woyczynski . . . . .	153
Yagle . . . . .	3
Yang . . . . .	159