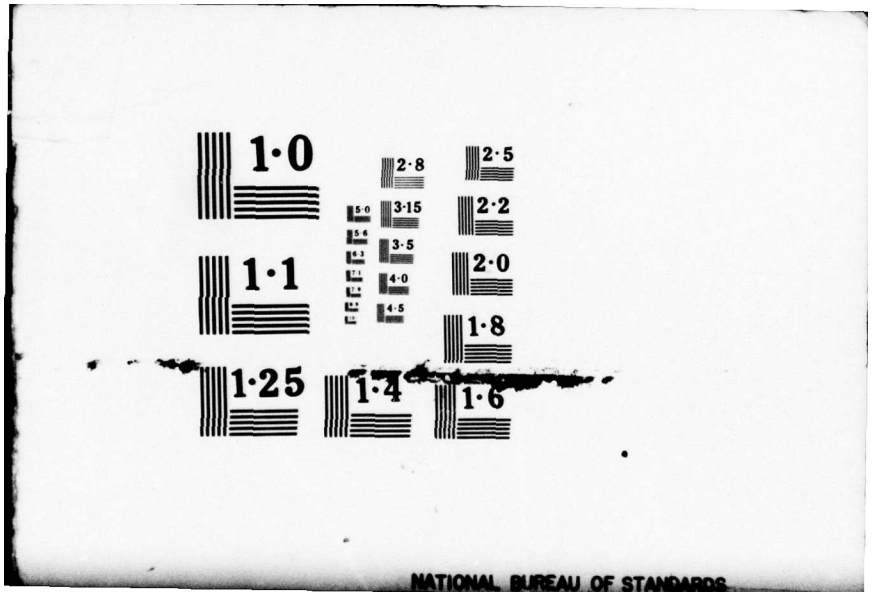
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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
RESEARCH LABORATORY OF ELECTRONICS
CAMBRIDGE, MASSACHUSETTS 02139

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This report, No. 120 in a series of progress reports issued by the M. I. T. Research Laboratory of Electronics, reviews the research progress and states the research objectives of the laboratory for the year ending December 31, 1977. The source of support is indicated for each project.

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
RESEARCH LABORATORY OF ELECTRONICS

# RLE PROGRESS REPORT No. 120

January 1978

Submitted by: P. A. Wolff
J. Allen

## FOREWORD

This report, No. 120 in a series of Progress Reports issued by the Research Laboratory of Electronics, contains the customary annual statement of research objectives and summary of research for each group. The report covers the period January 1, 1977-December 31, 1977, and the source of support is indicated for each project. On the masthead of each section are listed the academic and research staff and the graduate students who participated in the work of the group during the year. The listing of personnel in the back of the book includes only members of the laboratory at the time (late February 1978) when the list was prepared for the printer.

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GENERAL PHYSICS

# I. MOLECULE MICROSCOPY

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Dr. Stanley J. Rosenthal
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## 1. DEVELOPING MOLECULE MICROSCOPY

National Institutes of Health (Grants 5 SO5 RR07047-11, 5 RO1 GM22633-03, and 5 RO1 GM22633-04)

Health Sciences Fund

John G. King

### a. Introduction

Measuring the variations in space and time of fluxes of neutral molecules from a sample can give information not otherwise obtainable concerning, for instance, biological systems. We call the group of techniques used molecule microscopy (MM) and we believe that when fully developed it will have the same kind of revolutionary impact on biology that electron microscopy and x-ray diffraction have had.

Why biology rather than, say, material science? Because in biology there are structures of interest – inhomogeneities – of various sizes, from microns to angstroms, and neutral molecules are a natural (if not very agile) conveyor of information about surfaces, binding properties, permeability, metabolism, and enzymatic processess. In materials science, angstrom resolution, which we do not yet have, is needed to reveal features of interest, and the refractory nature of the material (often made up of atoms with medium to high Z) permits the use of more energetic probes.

### b. How Molecule Microscopy Works

Insofar as neutral molecules emitted by the sample are ionized, the resulting ions are selected by charge-to-mass ratio in a mass spectrometer, and counted by an electron multiplier, MM is a form of mass spectrometry. Spatial resolution is obtained in three ways:

(i) The sample emits molecules in all directions, but only those molecules from a given region on the sample pass (see Fig. I-1) through an aperture to strike the detector (the ionizer-mass spectrometer-multiplier combination). By moving the aperture back and forth in one direction and displacing it at right angles after each pass, one scans the entire sample. A synchronously moving cathode ray oscillator (CRO) spot is brightened

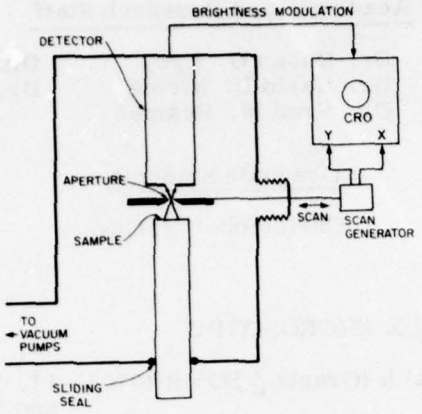



Fig. I-1. Scanning pinhole molecule microscope.

in proportion to the flux of neutral molecules at each point, thus producing a picture (a molecule micrograph) which can be photographed. We have built a crude form of such an instrument, the scanning pinhole molecule microscope (SPMM), and published some results.

(ii) The sample emits neutral molecules when locally heated (or otherwise stimulated) by either focused radiation or particles, or by heating from below with a matrix of addressable microheating elements (see Fig. I-2). A large aperture detector is used, and as the sample is scanned, i.e., one region after another on the sample is stimulated to emit, the picture of where molecules *came from* is built up by displaying the detector output on a CRO as before. We have not built such an instrument, a scanning desorption molecule microscope (SDMM), but have tried out various parts of it, and studied various aspects of the desorption and readsorption mechanisms.

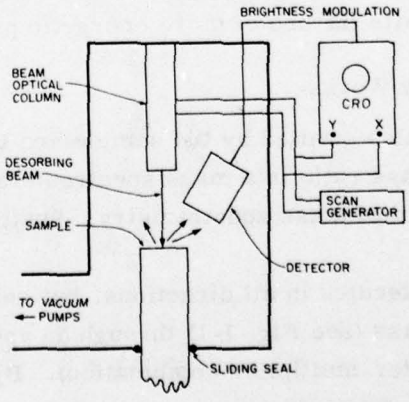



Fig. I-2. Scanning desorption molecule microscope.

(iii) The two methods described require that the sample be in vacuum, which causes denaturation. Some samples must be studied in vitro, which we do by sampling the emitted molecules with a membrane-covered micropipette connected to the mass spectrometer (see Fig. I-3). Such a scanning micropipette molecule microscope (SMMM)

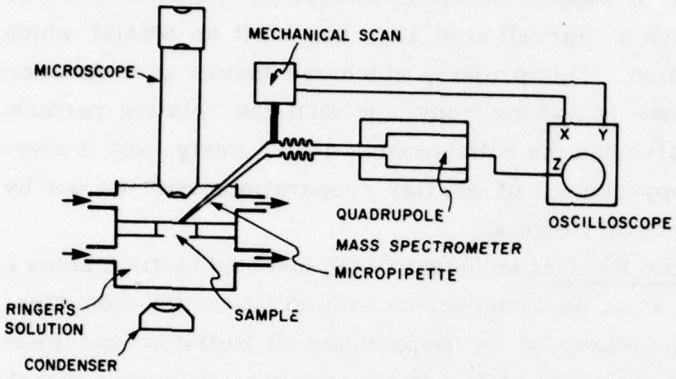



Fig. I-3.
Scanning micropipette molecule microscope.

is now under study and has readily detected pores in nucleopore filter, and in a first experiment, spatial variations in permeability in frog bladder, a commonly studied epithelium.

c. Applications of Molecule Microscopy to Biology

As the instruments are developed, characterized, and simplified, we believe that the number of applications will grow until the whole thing is taken for granted (as in electron microscopy). To get started we have been working on several collaborative projects:

(i) Cell Surface Studies will lead eventually to the application of SDMM to the identification of patches on erythrocyte ghosts and later to the identification of various regions in freeze-fracture preparations. At present Dr. Dusan G. Lysy is continuing his study of the contrast mechanism, based on the common experience that oil and water don't mix or, rather, that water does not stick to lipide surfaces. Besides the preparation of a compendium of staining molecules (any volatile species) and surfaces to be stained, he is about to study the desorption properties of cells – normal and transformed, as supplied by our collaborator, Dr. Phillips W. Robbins of the Department of Biology, M.I.T. This work is being supported for one year by a grant from the M.I.T. Health Sciences Fund.

(ii) Molecule Fluxes in Tissue is a collaborative project with Dr. Alvin Essig of the Department of Physiology at Boston University Medical Center. Dr. Stanley J. Rosenthal has built the molecule flux apparatus which makes possible the simultaneous

measurement of $CO_2$ production and $O_2$ uptake by surviving epithelia mounted in Ussing chambers. We are able to relate our results to previous measurements by other methods, and new phenomena are now being revealed. Further studies will be made by Dr. Ying-Tung Lau. This work is being supported by NIH training grants and the Francis Friedman Chair of Physics at M.I.T. We expect also to apply to the M.I.T. Health Sciences Fund for support of this B.U.-M.I.T. collaboration. In a closely related project, Mr. Joseph A. Jarrell at M.I.T. has built an SMMM which is nearly ready to be put into operation. This project, which can answer such questions as where the $CO_2$ emitted by the tissue is coming from, and what the relative permeabilities of cells and junctions are, also has the collaboration of Dr. Essig, and is complementary to the optical microscopy studies of similar preparations carried out by Dr. D. DiBona at Massachusetts General Hospital.

(iii) Finally, the Volatile Enzyme Product technique (VEP) invented by Dr. James C. Weaver and being developed by him as an assay technique with collaboration from Drs. Charles L. Cooney and Anthony J. Sinskey of the Department of Nutrition and Food Sciences, M.I.T., can eventually be applied to MM. It removes the restriction that the molecules be volatile and makes possible the detection of either enzymes or substrates as long as the reaction yields volatile products. The VEP project has NIH support, and is described more fully in Section I-2.

(iv) Problems. The fact that the first SMMM produced pictures with the triple disadvantages of the loss imposed by the duty cycle of scanning ($10^{-3}$), the optical inefficiency of a pinhole ($10^{-5}$), and the mismatch of the detector size (i.e., inefficiency) ($10^{-4}$) shows that much higher performance in terms of resolution and contrast is possible. We have recently invented better detectors which are expected to have high efficiency, the right size aperture, and low background. For SDMM some thought has been given to matrix heaters to produce localized thermal desorption. These can be constructed by using modern electron beam etching techniques which provide spatial resolution of 10's of Å. Molecular photography, in which distributions of molecules captured on a surface are made visible by chemical amplification would be useful, as one could then use the shadow of Fresnel zone plates instead of pinholes to obtain greater molecule collecting power, as well as spatial resolution.

## 2. VOLATILE ENZYME PRODUCT ASSAY

National Institutes of Health (Grant 5 RO1 GM22633-03)

James C. Weaver

Configurations for the assay of either enzyme activity or substrate concentration have been explored during the past year. Most experiments utilized either urease or catalase; acetylcholinesterase was used occasionally. Major problems that continue to

be dealt with include continuous degassing of preexisting volatile contaminants (mainly a problem with oxygen and carbon dioxide), and reduction of background associated noise by use of larger liquid-nitrogen-cooled traps.

Recently, work has focused on the use of conveniently and temporarily immobilized microorganisms, particularly Saccharomyces cerevisiae. In experiments related to those reported by Mattiasson et al.,[1] we have observed the transient response of the microorganisms to pulses of either glucose or fructose, following either carbon dioxide or ethanol production. Since many microorganisms are involved with the utilization and production of a variety of low molecular weight volatile compounds (e.g., hydrogen, methane, formaldehyde, methanol, acetone, acetic acid, propinic acid, etc.), this approach should provide considerable utility in studying many microorganisms in real time.

References

1. B. Mattiasson, P.-O. Larsson, and K. Mossbach, Nature 268, 519-520 (1977).

## 3. THERMAL ENZYME PROBE

National Institutes of Health (Grant 5 SO5 RR07047-11)

James C. Weaver

During the past year a flow-through version of the thermal enzyme probe (TEP) was successfully used with immobilized urease (EC 3.5.1.5) to assay urea concentrations with a resolution of approximately $10^{-4}$ M, corresponding to a temperature difference, $\Delta T$, resolution of less than $10^{-5}$ °C.[1] In order to achieve this performance it was necessary both to continuously degas the sample stream, and also to provide a very steady flow by means of a gas-pressure-driven pump and reservoir. By use of better matched, commercially available thermistors, there is reason to believe that a $\Delta T$ resolution of $10^{-6}$ °C is realistic. This capability, in combination with a microprocessor-controlled miniaturized version of flow-through devices[2,3] which carry the enzyme-catalyzed reaction to completion (and thereby provide two orders of magnitude more sensitivity), should allow one to perform rapid assays on 100-microliter samples at the $10^{-7}$ M level.

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1. S. P. Fulton, J. C. Weaver, C. L. Cooney, and S. R. Tannenbaum (submitted for publication).
2. K. Mossbach, B. Danielson, A. Borgerud, and M. Scott, Biochim Biophys. Acta 403, 256-265 (1976).
3. L. D. Bowers and P. W. Carr, Clin. Chem. 22, 1427-1433 (1976).

# II. DEVELOPMENTAL ELECTRON OPTICS LABORATORY

Academic and Research Staff

Dr. John W. Coleman

Graduate Students

Michael R. Graham

## 1. ULTRAHIGH-SENSITIVITY ELECTRON OPTICAL DETERMINATION AND LOCATION OF IMPURITY ATOMS IN Si AND GaAs

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

John W. Coleman

During the past year we have used specimens of gold-on-carbon substrates to calibrate our instrumentation. We have obtained images of these specimens due to secondary electrons, and at present we are trying to photograph them. We also have specimens on hand of Si-Al on Si, Si-Al on Ta, and P glass on Si. A chronic major problem has been vacuum, which has precluded until now the predominant usage of Auger electrons for producing the images. Plans are now under way to change over to an oil-free system; when this is complete, we will be able not only to produce Augers but also to install our channeltron-array image intensifier, which will help us to see and photograph the low-level intensity images.



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# III. SEMICONDUCTOR SURFACE STUDIES

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Eugene Mele
William B. Pollard

## 1. ELECTRONIC STRUCTURE OF HOMOPOLAR AND HETEROPOLAR SEMICONDUCTING SURFACES

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

John D. Joannopoulos, Eugene Mele

We are interested in the intrinsic and extrinsic surface states at surfaces of Group IV, III-V, and II-VI semiconductors. In these studies we are using a theorem we developed which reduces the semi-infinite surface system to an effective one-dimensional problem that can be solved with transfer matrix techniques. The electrons are studied with realistic tight-binding Hamiltonians which provide an attractive and physical real-space description of the states.

Specifically, we have recently studied the effects of bad cleaves on surfaces of GaAs (110). The results explain the strange behavior of the Fermi level position as a function of cleave quality for both n-type and p-type samples. In addition, the effects of O and $O_2$ adsorbates on GaAs (110) have been studied. Previous conflicting experiments regarding the nature and position of the oxidation process have been resolved. Finally, the nature of a semiconductor-metal interface is being studied. A new ionicity scale is introduced that accounts for the remarkable covalent-to-ionic behavior of Schottky barriers with metal work functions.

## 2. SURFACE PHONONS IN BONDED SOLIDS

U.S. Navy – Office of Naval Research (Contract N00014-77-C-0132)

John D. Joannopoulos, Robert B. Laughlin

The nature of surface phonons in bonded solids is being investigated. Particular attention to disordered systems with large internal voids is given. These materials (e.g., $SiO_2$) have a massive internal surface area that makes them amenable to studies with conventional phonon probes (e.g., Raman, infrared, etc.). The theory involves



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treating the system in terms of Bethe lattices which are attached to surface atoms in various ways and describing the potential energy of the atoms in terms of force constant models. Local densities of states along with theoretical Raman, IR and neutron cross sections are being calculated.

# IV. PHOTOEMISSION SPECTROSCOPY


Academic Research Staff

Prof. F. Read McFeely

Graduate Students

Michael R. McClellan
Michael J. Sayers
Richard P. Vasquez



Joint Services Electronics Program (Contract DAAB07-76-C-1400)

F. Read McFeely


During the past year we have completed the design of our new angle-resolving photoemission instrument and have completed 95% of the construction of it. This spectrometer will be capable of 360° rotation in the horizontal plane and 110° rotation in the vertical plane, and will incorporate a multichannel detector. This multichannel detection system, which was successfully tested over the past year, will provide a factor of 80 increase in sensitivity over conventional single-channel instruments. We have also completed construction of an ultrahigh vacuum rotatable polarizer which will provide us with polarized photons with which to perform our experiments. We have also completed the design and construction of a high-resolution electron monochromator which we shall use in conjunction with the photoemission experiments.

In addition to the design and construction of photoemission apparatus, we have completed some theoretical work in angle-resolved photoemission spectroscopy. The new model we have developed was found to be far superior to earlier equipment because of our accurate treatment of the final-state wave function in the vicinity of the atomic cores. We were also able to show, using second-order time-dependent perturbation theory, that the statistical sampling of the Brillouin zone in angle-resolved photoemission experiments could not be attributed to thermal phonons but was instead due to the nature of the final-state electronic wave functions.

# V. ATOMIC RESONANCE AND SCATTERING

## Academic and Research Staff

Prof. Daniel Kleppner
Prof. David E. Pritchard
Dr. Stuart S. B. Crampton*
Dr. Richard D. Driver
Dr. Theodore W. Ducas†
Dr. Michael G. Littman
Dr. Harold J. Metcalf‡
Dr. William D. Phillips
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Walter P. Lapatovich
Philip E. Moskowitz
John A. Serri
Neil Smith
William P. Spencer
A. Ganesh Vaidyanathan
Robert E. Walkup
Myron L. Zimmerman

## 1. FIELD IONIZATION AND PHOTOIONIZATION

U.S. Energy Research and Development Administration (Contract EG-77-S-02-4370)

Daniel Kleppner, Michael G. Littman, Michael M. Kash, Harold J. Metcalf

We have constructed a new tunable dye laser system for the study of field ionization in highly excited atoms. Pump power is provided by a Quanta Ray Nd:YAG laser with second, third, and fourth harmonic generators. A new type of dye laser has been devised which has important advantages of simplicity and economy. Work has begun on a study of field ionization of lithium. The atom is prepared in a Rydberg state by a three-step excitation process, using two fixed-frequency and one tunable dye lasers.

## 2. HIGHLY EXCITED ATOMS

U.S. Air Force – Office of Scientific Research (Contract F44620-72-C-0057)

Daniel Kleppner, Theodore W. Ducas, Michael G. Littman, Myron L. Zimmerman

We have carried out a study of the Stark structure of barium. The aim of this work was to study a two-electron atom in a region where a valence state (a low-lying state of the excited core) interacts with a Rydberg progression. The interactions of the valence state with the Rydberg manifolds were clearly displayed. The system was analyzed by combining a simple configuration-interaction picture with a calculational method

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previously developed for analyzing one-electron Rydberg Stark structure. A paper on the work[1] will appear in J. Phys. B.

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1. M. L. Zimmerman, T. W. Ducas, M. G. Littman, and D. Kleppner, "Stark Structure of Barium Rydberg States."

## 3. SUBMILLIMETER PHOTON COUNTING

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Daniel Kleppner, Theodore W. Ducas, William P. Spencer,
A. Ganesh Vaidyanathan

We have constructed a FIR laser and have observed resonance transitions in Rydberg atoms at 118 μm and 496 μm. A number of transitions at $CO_2$ wavelengths near 10 μm have also been observed. Work has begun on a study of noise sources and the resonance line shape of the proposed detection. A millimeter wave phase-locked klystron system is under construction; it will be used for the study of millimeter wave resonance transitions.

## 4. STUDIES IN OPTICAL PHYSICS

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Daniel Kleppner, Michael G. Littman, William P. Spencer,
A. Ganesh Vaidyanathan

We have developed methods for producing highly excited states of a variety of atoms, including all the alkalis and several of the alkaline earths. Both cw and pulsed laser techniques have been used. A new apparatus has been constructed for high-resolution spectroscopic studies, and techniques have been developed for introducing infrared and millimeter-wave radiation to the atomic beam interaction region.

## 5. STUDIES IN ATOMIC PHYSICS

National Science Foundation (Grant PHY75-15421-A01)

Daniel Kleppner, Myron L. Zimmerman, Jarbas C. Castro Neto

We have obtained initial results on a study of a highly excited one-electron atom in a high magnetic field. The problem is of interest because the system is fundamentally

simple, yet no comprehensive theory exists. An atomic beam of sodium was excited by tunable dye lasers in the center of a superconducting solenoid, and the structure of levels with principal quantum numbers in the vicinity of n = 25 was studied in magnetic fields up to 65 kG. The diamagnetic interaction, normally an extremely small perturbation, was large enough to mix several terms. We have analyzed the data using a perturbative approach based on all terms in the range $22 \leq n \leq 31$. Quantitative agreement is good. The work is being extended to larger values of n, where the structure starts to resemble Landau levels.

## 6. SPECTROSCOPY OF VAN DER WAALS MOLECULES

National Science Foundation (Grant PHY77-09155)

Riad N. Ahmad, Walter P. Lapatovich, William P. McGrath, Philip E. Moskowitz, David E. Pritchard

The sodium neon (NaNe) data obtained from our seeded molecular beams machine[1] has been analyzed in some detail. The ground state well depth of this weakly bound molecule is found to be $D_{0X} = 10^{-3}$ eV, and the equilibrium separation of Na and Ne atoms is $r_e = 5.3 \times 10^{-8}$ cm; for the first excited state we find $D_{0A} = 1.74 \times 10^{-2}$ eV and $R_e - 2.7 \times 10^{-8}$. This means that NaNe is, by almost an order of magnitude, the weakest diatomic molecule to be studied in an isolated condition. Experimental determination of these interatomic potentials shows several theoretical calculations[2,3] to be in error and provides a method of determining the applicability of certain techniques used to analyze earlier rare gas-alkali scattering data.[4] Our apparatus is now undergoing substantial modification so that we may conclude our study of the NaNe complex and continue on to investigate other systems.

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(V. ATOMIC RESONANCE AND SCATTERING)

## 7. COLLISIONAL BROADENING OF THE Na D LINES

National Science Foundation (Grant PHY77-09155)

Douglas J. Ely, William D. Phillips, Robert Walkup, David E. Pritchard

Collisional broadening of the Na D lines has long been a subject of intensive theoretical and experimental investigation, both because of interest in the fundamental process and for application to the study of such lines in stellar atmospheres. We have begun experiments which, in contrast to most previous work on the subjects, employ techniques to study sub-Doppler collision broadening. One is saturated absorption spectroscopy, which can be used selectively to observe only those atoms having a specific velocity along a given axis. Thus the velocity dependence of line broadening processes can be studied with increased resolution over current methods which use temperature dependence to infer velocity dependence. Four-wave mixing, a technique in which three laser beams create a polarization in Na vapor which radiates a fourth coherent beam, can also be used to study line broadening and has the advantage of being able to select more than one component of the Na velocity. Finally, using photon counting techniques to observe laser-induced fluorescence in Na vapor, one can detect the small Lorentzian absorption wings of the collisionally broadened Na line at frequencies well beyond the Doppler width. These various techniques all yield information about the collisional linewidth for widths small compared with the Doppler width. The last technique can also easily be used for linewidths greater than the Doppler width, so we can make contact between the two regimes of collisional broadening. Work is in the preliminary stages. We have observed saturated absorption and fluorescent signals, as well as four-wave mixing signals.

## 8. DIFFERENTIAL CROSS-SECTION MEASUREMENTS USING DOPPLER SELECTIVE LASER FLUORESCENCE ANALYSIS

National Science Foundation (Grant CHE76-81750)

David E. Pritchard, Douglas J. Ely, William D. Phillips, John A. Serri, Kermit R. Way, James L. Kinsey
[James L. Kinsey is Professor in the Department of Chemistry, M.I.T.]

By placing a cw narrow-band dye laser along the relative velocity axis of two atomic beams in a crossed-beam experiment, we are able to detect the scattered velocity distribution of one of the beams by Doppler-tuning the atoms into resonance and detecting their subsequent fluorescence. Atoms are excited into resonance when the projection of their velocity along the direction of the laser beam, $v_\ell = v \cos \theta_{cm}$, is equal to

$c(\nu-\nu_o)/\nu_o$. The frequency $\nu_o$ represents the rest frame resonance frequency and $\nu$ selects a certain velocity component. By recording the fluorescence signal as a function of $\nu$, we directly obtain the center of mass differential cross section versus $\cos\theta_{cm}$. Transformation from laboratory angles to center-of-mass angles is not required in the analysis. The collision we studied was

$$Na^*(3P_{1/2}) + Ar \rightarrow Na^*(3P_{3/2}) + Ar - .002 \text{ eV}.$$

The first excited state of sodium was produced by a velocity selective laser beam, Doppler-tuned to excite the $3S_{1/2}$ to $3P_{1/2}$ transition. Another laser, tuned to the $3P_{3/2}$ to 4D transition, detected $Na^*(3P_{1/2})$ that underwent the fine structure changing collision. The detection signal resulted from the 4P → 3S transition after the atom decayed from the 4D → 4P state. Our measured cross sections yielded oscillatory structure which seems to be in approximate agreement with recent theoretical calculations. Construction of a new beams machine is now under way to use this technique (coined VADS, Velocity Analysis using the Doppler Shift) on molecular systems. We plan to measure the angular differential cross section for state-to-state, vibrational, and rotational changing collisions of $Na_2$ upon collision with a rare gas atom. Supersonic oven sources will be utilized to provide a cold $Na_2$ beam of high density, and to provide a narrow velocity distribution for both beams.

## 9. STUDIES OF ROTATIONAL ENERGY TRANSFER

U.S. Air Force – Office of Scientific Research (Grant AFOSR-76-2972A)

Ibrahim Al-Agil, Timothy Brunner, Richard D. Driver, David E. Pritchard, Neil Smith, Mark D. Wainger

We have studied the rotational energy transfer process

$$Na_2^*(vj) + Xe = Na_2^*(v, j+\Delta j) + Xe - \Delta E$$

where a $Na_2$ molecule, in the excited A electronic state and with vibrational and rotational quantum numbers v and j, respectively, collides with a xenon atom and changes its rotational quantum number to $j + \Delta j$ with a corresponding loss $\Delta E$ in translational energy. We have used the velocity selection by Doppler shift technique[1] to obtain the velocity dependence of the rotational changing rate constants. The experimental rate constants obtained using the VSDS technique have some thermal averaging present from the velocity components which are unspecified by the exciting laser. We have developed a Fourier transform deconvolution technique which permits us to obtain the dependence of the rate constants on relative velocity from the experimental data. An example of this experimental data, together with the deconvoluted rate constant, is shown in

Fig. V-1 for the v = 18, j = 38 state for a collision with $\Delta j = -2$. A paper describing this work is in preparation.

We have studied the dependence of the cross sections for a given initial j on $\Delta j$ and noted how our data change with different initial j within a given vibrational state. These

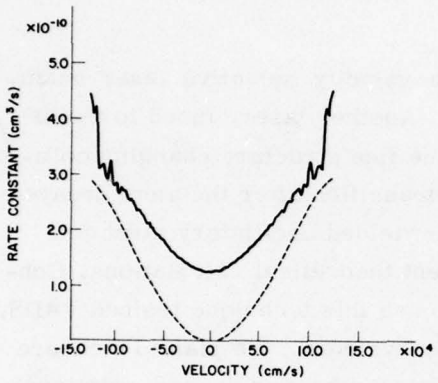



Fig. V-1.

Plots of the experimental and deconvoluted rate constants with collision velocity for $j_{initial} = 38$ and $\Delta j = -2$.

— — — Deconvoluted data vs $v_z$.

——— Experimental data vs $v_{rel}$.

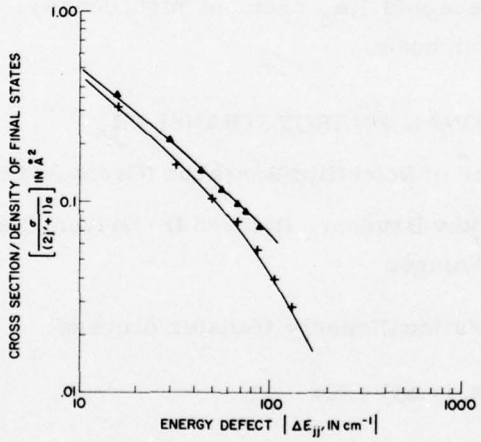



Fig. V-2. Plot of the cross section/density of final states against the energy defect of the collision. The density of the final states is the product of the rotational final state density (2j'+1) and the momentum state density $\alpha = [E-E_{j'}/E-E_j]^{1/2}$.

▲ Experimental data $\Delta j < 0$ collisions.

\+ Experimental data $\Delta j > 0$ collisions.

——— Parametrized fits of the form $+\ln[\sigma_{jj'}/(2j'+1)\alpha] = -a \ln|\Delta E_{jj'}| - b|\Delta E_{jj'}| - c$.

For $\Delta j < 0$ the parameters are a = −0.789, b = −0.00219, c = 1.142. For $\Delta j > 0$ the parameters are a = −0.642, b = −0.0095, c = 0.754.

data are extremely valuable in the light of recent theories of rotational energy transfer using the information-theoretic-based prediction of surprisal theory.[2] We have proved conclusively that the linear surprisal model is not adequate to describe our experimental data, and we will shortly be in a position to differentiate between a number of the alternative surprisal theories recently proposed (see Fig. V-2). Our experiment represents the most definitive experimental study of atom-diatom energy transfer so far undertaken: selections of the initial and final vibrational-rotational levels of the diatomic have been made and we have studied the velocity dependence of the collision cross section.

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# VI. INTERFACIAL CHEMISTRY

## Academic Research Staff

Prof. Ralph H. Staley

## Graduate Students

Roger W. Jones
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## 1. WORK FUNCTION OF CHEMICALLY MODIFIED SURFACES

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Ralph H. Staley

We have initiated this project to investigate the effects of oriented monolayers of molecules containing strong internal dipole moments on the work functions of semiconductor and metal surfaces. The project is designed to identify the factors that should be incorporated in a model for molecular effects on work function and to learn how to produce chemically stable surfaces with very high and very low work functions.

We have constructed an apparatus which can be used to prepare samples and measure their photoelectric work function under ultrahigh vacuum conditions. Design, construction, and initial testing have been completed. We have also been investigating preparation of surfaces using both clean vacuum techniques and wet chemistry. Methods for covalently attaching various organic functionalities to surfaces with chlorosilane reagents have been tested. The project is now beginning to study work functions of silicon and platinum surfaces with various molecular functionalities attached.

## 2. PHOTOACOUSTIC SPECTROSCOPY OF SURFACES

Joint Services Electronics Program (Contract DAAB07-76-C-1400)
National Science Foundation (Grant DMR-76-80895)

Ralph H. Staley

We are initiating this project to develop photoacoustic spectroscopy as a method to identify and characterize molecular species on or near surfaces. This technique has only recently been developed and its potential for use in studying surfaces demonstrated. We are in the process of acquiring a photoacoustic spectrometer system. Work has also begun on design of sample cells for use with liquid-solid interface samples and other nonstandard sample arrangements and on design of modifications and accessories needed to exploit the potential of this technique in the infrared. An initial application of this new spectroscopic tool will be to monitor extent of coverage and chemical state of molecular species at the surface in our project on work functions of chemically modified surfaces.



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# VII. X-RAY SCATTERING SPECTROSCOPY

## Academic and Research Staff

Prof. Robert J. Birgeneau
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Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Robert J. Birgeneau

During the past year we have constructed and implemented a versatile high-resolution x-ray spectrometer system. This x-ray spectrometer is based on a Rigaku 12 kW rotating anode x-ray source, a Huber high-precision 2-circle goniometer and an on-line PDP 11/34 computer control system with Camac interfacing. The spectrometer angles may be scanned through 360° with a step size of 1.8 seconds of arc and an absolute accuracy of about 10 seconds. We are constructing a second spectrometer of somewhat lower resolution for surface layer studies and for experiments on structural phase transitions. As ancillary equipment we have constructed temperature control equipment which enables us to study samples at temperatures from 10 K to 500 K with a relative accuracy of 1 to $3 \times 10^{-3}$ K. Our initial experiments have been directed primarily toward phase transitions in liquid crystals and in lower dimensional solids. The liquid crystal experiments show special promise and, indeed, they demonstrate that high-resolution x-ray techniques will have a major impact on that area of research. We have also initiated a project on the structure and scattering phenomena in physiadsorbed layers on surfaces. We now discuss our individual projects.

## 1. NEMATIC-SMECTIC-A TRANSITION IN CBOOA

A number of experiments, especially in cyanobenzylideneoctyloxyaniline (CBOOA), suggested the N-A transition was characterized by two, rather than one, divergent correlation lengths. This would seem to conflict with our current ideas on scaling near second-order transitions and would greatly complicate any attempt at a theoretical description of the transition. The salient result of our experiments is that, by direct measurement with x rays, the correlation lengths along and transverse to the molecules diverge with identical exponents; thus the transition is characterized by a single length. This is perhaps the simplest example of melting in nature and we hope that these studies, besides elucidating the nature of phase changes in liquid crystals, will also give insight into the general phenomena of melting.[1]



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## 2. NATURE OF THE SMECTIC-A PHASE

Whether, in nature, bodies can exist for which the density functions depend not on three but only on one or two coordinates is a classic problem which has occupied theorists since the 1930's. A closely related problem is the establishment of a one-dimensional density wave in a three-dimensional system, as occurs in a smectic-A liquid crystal. It is believed that in two-dimensional systems and also in the smectic-A phase there should be a second-order transition to a state characterized by long-range correlations but without long-range order in the usual sense. Our experiments provide the first direct experimental evidence that the theoretical conjectures are correct. We found that the instantaneous density correlations for a one-dimensional density wave in a three-dimensional liquid exhibit not long-range order but rather an anisotropic power law dependence on molecular separation. Thus smectic liquid crystals are materials in which these ideas may fruitfully be studied experimentally. Further experiments and much more theoretical efforts are called for. This work is described more fully elsewhere.[2]

## 3. SPIN-PEIERLS TRANSITION IN TTF-BDT (Cu)

The organic charge transfer salt TTF-BDT (Cu) is believed to provide an ideal example of a spin-dimerization transition in an $S = 1/2$ one-dimensional antiferromagnet. This system is of interest both because of its role as an archetype for magnetism in organic materials and also because of the analogy with the more familiar electronic Peierls transition as observed, for example, in TTF-TCNQ. In a collaborative experiment with D. E. Moncton (performed at Bell Laboratories) we have succeeded in observing this structural transition at 12 K using x-ray diffuse scattering techniques. We have monitored both the magnitude and spatial variation of the critical fluctuations above $T_c = 12$ K together with the growth of the order parameter below $T_c$. The measured order parameter agrees well with that calculated for a BCS superconductor. Further, the experiments demonstrate clearly that the transition involves a fundamentally different pairing than that inferred by others from simple molecular stacking considerations. This in turn necessitates that the dominant exchange paths differ from those which are suggested by a naive consideration of the TTF molecular orbitals. This work has been published.[3]

## 4. STRUCTURAL PHASE TRANSITION IN SQUARIC ACID

The compound $H_2C_4O_4$ is a hydrogen-bonded system with a planar structure. Neutron scattering experiments have indicated that it exhibits an unusual quasi two-dimensional structural phase transition. We have performed initial x-ray measurements which show

resolvable two-dimensional critical scattering with a variety of unusual features. Further x-ray experiments are under way to elucidate the nature of this most interesting hydrogen-bonded system.

## 5. ELECTRONIC EXCITATIONS IN LIQUID HELIUM

We have now completed our inelastic x-ray scattering study of electronic excitations in liquid helium (collaborators: P. E. Eisenberger and W. Marra of Bell Laboratories). We find that the electron density response function $S(\vec{q},\omega)$ can be understood quantitatively by using a simple hydrogenic atomic theory. No many-body or multielectron excitation effects are observed above a significance level of approximately 10%. This is in sharp contrast to simple metals like aluminum where many-body effects play a central role and where theory is still able to provide at best a qualitative understanding. Thus this study in liquid helium provides one physical system where theory and experiment for the electron density fluctuations are in accord. This work has been published.[4]

## 6. MEAN FIELD THEORY AND THE GINZBURG CRITERION

As part of our studies of phase transitions we have also carried out the following theoretical analysis. By applying a real space version of the Ginzburg criterion it is possible to assess the relative importance of critical fluctuations and thence the probable limitations of mean field theory for a wide variety of phase transitions. For example, for ferroelectrics and for certain soft acoustic phonon structural transitions the Ginzburg arguments predict that mean field theory should be valid for spatial dimensionalities greater than $d^* = 3$ and 2, respectively. These "marginal dimensionalities" follow directly from the geometry of the critical fluctuations in phase space. We show also that this approach provides a simple technique for assessing the self-consistency of Landau theory in a vast range of physical systems.

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# VIII. QUANTUM ELECTRONICS

## A. Laser Applications

### Academic and Research Staff

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Dr. Frederick Y. Wu

### Graduate Students

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James L. Davis
Stephan C. Goldstein
Richard P. Hackel
Andrew M. Hawryluk
Philip R. Hemmer
Bruce W. Peuse
Jack Wolosewicz

### 1. PRECISION MEASUREMENTS OF ATOMIC LEVEL SPLITTING AND LEVEL SHIFTS IN INTENSE OPTICAL FIELDS

National Science Foundation (Grant PHY77-07156)

Shaoul Ezekiel, Frederick Y. Wu, Philip R. Hemmer

We have performed high precision measurements of level splitting and level shifts of an excited atomic state in the presence of an intense optical field.[1] Such measurements are important to the understanding of the details of atom-field interaction and in the development of high precision optical clocks. The level we studied is an isolated single magnetic sublevel $3\,^2P_{3/2}$ ($F = 3$, $m_F = 3$) in sodium when subjected to a strong laser field coupling this level and the $3\,^2S_{1/2}$ ($F = 2$, $m_F = 2$) level in the ground state. Doppler and collisional broadening were eliminated by employing atomic beam techniques.

The experimental arrangement has a highly collimated sodium atomic beam prepared in one magnetic sublevel $m_F = 2$ in the $3\,^2S_{1/2}$ ($F = 2$) ground state. The prepared sodium atoms are subjected simultaneously to two collinear but counterpropagating laser fields, aligned perpendicular to the atomic beam. One laser field at 5890 Å, the driving field, is circularly polarized and fixed in frequency either on-resonance or off-resonance with $3\,^2S_{1/2}$ ($F = 2$)-$3\,^2P_{3/2}$ ($F = 3$) transition. Since the light is circularly polarized, the only allowed $\Delta m = +1$ transition is to the $m_F = 3$ sublevel in the excited $3\,^2P_{3/2}$ ($F = 3$) state.[2] The second laser field at 5688 Å is tunable and is used to probe the $3\,^2P_{3/2}$ ($F = 3$, $m_F = 3$) sublevel by inducing transitions to a higher level $4\,^2D_{5/2}$ ($F = 4$, $m_F = 4$). The fluorescence from the $4\,^2D_{5/2}$ ($F = 4$) state to the $3\,^2P_{3/2}$ ($F = 3$) state is detected and used as a measure of probe field absorption.

With a weak on-resonance driving field and a weak probe field, the observed linewidth of the probed transition was very close to the natural width (3.3 MHz) of the $4\,^2D_{5/2}$ ($F = 4$) upper level even though the natural width of the $3\,^2P_{3/2}$ ($F = 3$) lower level is 10 MHz. The measured line shape was compared directly with a theoretical line shape



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based on calculations by Mollow[3] and the agreement was excellent.

With a stronger field, the probed transition became broader and for driving field intensities greater than 100 mW/cm$^2$ the splitting of the $3\,^2P_{3/2}$ (F = 3) level due to the ac Stark effect became very noticeable. The splitting consisted of two symmetrical components having equal heights and the separation between them is the Rabi nutation frequency $\Omega_R = \frac{\mu \cdot E}{h}$. The measured line shapes for different driving field intensities were found to be in very good agreement with theoretical calculations[3] which predict that the $3\,^2P_{3/2}$ (F = 3) level splits symmetrically about its unperturbed value.

With the driving field set off-resonance by a known detuning $\Delta\omega$, the splitting was asymmetric with respect to the unperturbed level. In this case, the separation between the split components is the effective Rabi frequency $\Omega'_R = \sqrt{\Omega_R^2 + \Delta\omega^2}$, the smaller component is shifted by $\delta\omega = \frac{1}{4}\left(\frac{\mu E}{h}\right)^2 \frac{1}{\Delta\omega}$ from the unperturbed level and the larger component is shifted by $\Omega' - \delta\omega$ in the opposite direction. The sign of the level shift depends on the sign of the detuning of the driving field. Again the data were in very good agreement with theory.[3]

We should point out that in the case of strong on-resonance driving field the shift in the frequency of the $3\,^2S_{1/2}$-$3\,^2P_{3/2}$ transition due to atomic recoil became more and more substantial as the atom propagated across the laser field. To overcome such a detuning effect it was necessary to compensate *for recoil shift* as discussed elsewhere.[4]

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## 2. ATOMIC ABSORPTION LINE SHAPE IN THE PRESENCE OF A STRONG FIELD

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Shaoul Ezekiel, Frederick Y. Wu

The simple Lorentzian absorption spectrum of a two-level system, as measured by a nonsaturating, tunable probe field, is greatly modified by the presence of a strong, near-resonant, fixed-frequency field.[1-5] Previous experiments with RF[6] and millimeter-

wave radiation[7] have given evidence of probe amplification by the saturated two-level system. The experiment described here is designed to measure the absorption spectrum, as it is altered by the strong field.[8]

In this measurement, prepared two-level sodium atoms[8] interact simultaneously with a "driving field" and a "probe beam." The driving field is fixed at or near resonance and can be made very intense, while the probe beam strength is kept well below saturation. The probe beam is tuned across the resonance frequency and its absorption recorded. The probe beam is focused to approximately one-tenth the diameter of the driving field at the interaction region so that only atoms in a uniform field region are probed.

When the driving field at frequency $\omega$ is exactly resonant and very intense, peak absorption is greatly reduced compared with its unsaturated value. At frequencies differing from resonance ($\omega_o$) by less than the Rabi frequency $\Omega$, the probe is amplified, but all spectral features are very small. However, when the driving field is detuned above resonance, the spectrum has one large absorption peak at $\omega_o'$ shifted down from the original resonance frequency, and one large gain peak at $2\omega - \omega_o'$. The shift $\omega_o' - \omega$ is known as the "light shift" and is caused by the strong, nonresonant field.[9]

With an atomic beam density which gives 9.4% absorption in the absence of a driving field, the measured peak amplification is 0.7%. This agrees with calculations,[5] which predict that in the limit of high intensities the peak gain occurs when the detuning $\Delta\omega$ is equal to $\Omega/3$, and is 5% of the probe field absorption in the absence of the saturating field.

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## 3. FREQUENCY STABILIZATION OF A CONTINUOUS-WAVE DYE LASER

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Shaoul Ezekiel, Frederick Y. Wu

The primary objective in this program is the development of an extremely stable, low-jitter, single-frequency cw dye laser for use in a variety of applications such as optical communication and ultrahigh-resolution spectroscopy, and for studying fundamental interactions between radiation and matter.

We have stabilized the frequency of a commercially available cw dye laser (Spectra-Physics Model 580A) for use in our experiments on the interaction of intense monochromatic radiation with atoms. The stabilization scheme required only a small modification of the laser cavity.

The free-running jitter of the laser is approximately 15 MHz and this was reduced to 20 kHz by inserting an electro-optic phase modulator inside the laser cavity. The E-O crystal enabled us to lock the laser frequency to an external Fabry-Perot interferometer with a servo bandwidth of over 1 MHz.

Two such lasers were stabilized and measurement of laser jitter was accomplished by beating the two lasers. As further evidence of the narrow laser linewidth, we performed high-resolution absorption spectroscopy of $I_2$ and Na in an atomic beam. In the case of $I_2$, the linewidth of individual hyperfine structure transitions was 800 kHz which included a natural width of 450 kHz and residual Doppler broadening due to beam geometry of approximately 400 kHz.

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## 4. PASSIVE RING RESONATOR LASER GYROSCOPE

U. S. Air Force – Office of Scientific Research (Grant AFOSR-76-3042)
Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Shaoul Ezekiel, James A. Cole, Salvatore R. Balsamo, Jack Wolosewicz

We are developing a new optical rate gyroscope using a passive ring Fabry-Perot interferometer as the rotation sensing element, based on the Sagnac effect. The clockwise and counterclockwise lengths of the cavity, which depend on inertial rotation, are measured by means of two independently controlled laser frequencies. One laser is locked to the center of the cw resonance and the other to the ccw resonance of the cavity.

To eliminate the effect of laser-frequency jitter, we use only one laser whose output is shifted by two independently controlled acousto-optic frequency shifters. For a square ring, 10 cm on a side, with 1-MHz cavity resonance width and 1-mW laser power, it should be possible to detect earth rate in an integration time of 0.5 ms and milliearth rate in several hundred seconds.

To determine the feasibility of this new optical gyroscope, a passive cavity made from solid aluminum, measuring 17.5 cm on a side, was constructed.[1] The corners of the cavity were terminated with two flat and two curved mirrors and one of the cavity mirrors was mounted on a piezoelectric transducer. The output from a linearly polarized 1-mW single frequency He-Ne laser ($f_o$) was split into two beams, each of which was upshifted by an acousto-optic crystal and then coupled into the cavity. The acousto-optic crystals were driven by two stable and independent voltage-controlled oscillators ($f_1$ and $f_2$) operating around 40 MHz.

The cw cavity resonance was locked to $f_0 + f_1$ and $f_2$ was adjusted by a second feedback loop so that $f_0 + f_2$ was held at the resonance frequency of the ccw cavity.

The entire setup was rotated on a turntable. The data, rotation rate vs $(f_1-f_2)$, were linear and free from any lock-in effects. The bias drift was also investigated by monitoring $(f_1-f_2)$ with the turntable stationary. No noticeable monotonic drift was detected in a time interval of one hour. The rms fluctuation in the output for $\tau = 1$ s corresponded to a rotation rate of 0.5 degree per hour which is close to shot-noise-limited detection in our present setup.

Another scheme under investigation uses a passive ring with an intracavity Faraday cell.[2] The possibility of a fiber optic ring is also being considered.

Aside from applications to navagation, we propose to examine the possibility of measuring earth rotation to better than one part in $10^8$, using a cavity, 3 m on a side, and a 3-W argon laser. Such measurements should give information on polar wobble, continental drift, and changes in the length of the day. The connection between earthquakes and earth wobble may also be examined. Application of such a device in experiments related to general relativity will also be considered.

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## 5. NEW TECHNIQUE FOR HIGH-SENSITIVITY AND HIGH-RESOLUTION SPECTROSCOPY

U. S. Air Force – Office of Scientific Research (Contract F44620-76-C-0079)

Shaoul Ezekiel, Richard P. Hackel, Jordin T. Kare

The measurement of absorption in a gas cell can be made more sensitive by two to three orders of magnitude if the cell is placed within a high Q cavity. It can easily be shown that for a weak absorber in a cavity, the enhancement factor is approximately $1/1-R$ where R is the reflectivity of the input and output coupling mirrors. This increase in sensitivity is essentially caused by the multipass property of the cavity.

If the gas cell is placed within a ring rather than in a linear two-mirror cavity, it becomes possible to subject the gas to two independently controlled counterpropagating beams. In this way, it is possible to perform high-resolution saturated absorption[1] and saturated dispersion[2] spectroscopy without the Doppler background with an increase in sensitivity of $1/1-R$ over the single-pass case. Moreover, this enhancement is also applicable to two-photon[3] and polarization spectroscopy.[4]

Passive ring cavities with counterpropagating excitation have been investigated recently for the measurement of inertial rotation[5] based on the Sagnac effect. The techniques developed in those studies are very applicable to the spectroscopic schemes we have outlined. Since the two counterpropagating beams are physically separate outside the ring cavity, it is convenient to select the intensity, the modulation, the polarization, and so on of the individual beams. Under optimum conditions, the minimum linear absorption that can be measured in a cavity is approximately $(1-R)/\sqrt{N\eta\tau}$, where N is the number of photons transmitted through the cavity, $\eta$ is the detector quantum efficiency, and $\tau$ is the integration time. Similar expressions can be derived for saturation or nonlinear applications.

We have conducted a preliminary experiment using a single-frequency argon ion laser at 5145 Å and an $I_2$ vapor cell in a ring cavity. In this experiment the $I_2$ cell was subjected simultaneously to a weak and a strong counterpropagating beams. The strong beam was modulated by an electro-optic intensity modulator before entering the cavity and the portion of the weak beam that is transmitted through the cavity is synchronously demodulated in a lock-in amplifier as the laser frequency is tuned over the $I_2$ absorption. (The resonance frequency of the ring cavity is locked to the laser frequency by means of a conventional frequency-stabilization scheme[5] so that the cavity resonance always tracks the laser frequency.) The data show a number of $I_2$ hyperfine structure transitions with a zero-slope background. The linewidth of the individual lines is 350 kHz at low $I_2$ pressure. The observed linewidth is at present limited by transit time effects across the laser beam within the cavity.

We are now considering this spectroscopic technique for the detection of very small

gas concentrations and for setting an upper limit on parity violation in atomic systems.[6]

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## 6. SHORT-TERM AND LONG-TERM STABILIZATION OF MULTIWATT CONTINUOUS-WAVE ARGON LASERS

U. S. Air Force – Office of Scientific Research (Contract F44620-76-C-0079)

Shaoul Ezekiel, Richard P. Hackel, Stephan C. Goldstein

This research is motivated by the need for long-term, as well as short-term, stabilized lasers for applications to earth strain seismometry, optical communication and radar, precision spectroscopy, and fundamental measurements in experimental relativity.

So far we have been stabilizing multiwatt[1] cw argon ion lasers (Spectra-Physics Model 170). We have succeeded in reducing the laser jitter to approximately 10 kHz using an intracavity electro-optic phase modulator and a wideband feedback loop, and employing a high finesse Fabry-Perot interferometer as a reference. For long-term stabilization the resonance frequency of the reference cavity was locked to a hyperfine transition in $^{127}I_2$ observed in a molecular beam. A stability of 7 parts in $10^{14}$ was achieved in an integration time of 1000 seconds. The reproducibility of the laser frequency was also investigated and 1.5 parts in $10^{12}$ was achieved.

Recently, we have improved the low-frequency performance of the wideband feedback loop. This resulted in a reduction of the laser jitter to less than 1 kHz for observation times longer than $10^{-4}$ seconds.

Many improvements are still to come. In particular, we plan to use the R(26) 62-0 transition in $I_2$, which matches the 5017 Å argon laser line, as a long-term reference. The advantage of the R(26) transition is its smaller natural width (10 kHZ). We anticipate

that, by using the R(26) and by optimizing the $I_2$ fluorescence, a stability of $10^{-14}$ for a $\tau = 1$ s can be achieved. For longer integration times, the stability is expected to be limited by second-order Doppler shifts $\approx 10^{-17}$ for a 1% change in intensity (estimated). The effect of molecular recoil in the case of a simple absorption in a beam is being investigated.

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## 7. NONRECIPROCAL PHASE SHIFTS IN OPTICAL FIBERS

Joint Services Electronics Program (Contract DAAB07-76-C-1400)
M. I. T. Sloan Fund for Basic Research

Shaoul Ezekiel, James L. Davis

Recently, there has been considerable interest in the use of optical fibers for precision measurement applications such as inertial rotation sensing by means of a Sagnac fiber interferometer,[1] an active fiber ring laser or a Sagnac passive fiber cavity.[2] Other applications include remote current measurement in high-voltage cables. In all these applications, phase changes in the fiber as a function of time or fiber environment must be very small, depending on the particular application. In the case of a Sagnac gyroscope-type application, nonreciprocal phase shifts along the fiber must be much smaller than $10^{-7}$ radian.

We plan to conduct several very basic experiments to measure nonreciprocal phase shift in a single-mode low-loss optical fiber. A Sagnac-type interferometer will be used to detect nonreciprocal phase shift under a variety of conditions. We plan to examine the case with the two counterpropagating beams having the same linear polarization and the case with the beams having orthogonal polarization.

If the results are encouraging, we shall design a large-area multiturn Sagnac interferometer for geophysics relativity-type applications.

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# VIII. QUANTUM ELECTRONICS

## B. Nonlinear Phenomena

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## 1. PICOSECOND PULSES FROM SEMICONDUCTOR LASERS

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Clifton G. Fonstad, Jr., Hermann A. Haus, Erich P. Ippen

Mode-locked dye lasers have produced subpicosecond pulses,[1,2] even though the relaxation times of the laser and absorber dye are much longer than a picosecond. The achievement of short pulses has been shown to hinge on a careful balance of the absorber and laser characteristics.[3] It appears that similar conditions may be achieved in configurations employing semiconductor diodes as the active and absorbing media.

Saturable absorber mode locking of semiconductor diodes encounters difficulties of its own. There is the dispersion of the lasing medium, the power obtainable from cw diodes is relatively small and it is difficult to couple radiation into and out of the diode if an external resonator is used. Short pulses have been observed from semiconductor laser diodes.[4] The reproducibility of these pulses has been unsatisfactory. Within the years following these experiments advances in both semiconductor diode technology and the theoretical understanding of saturable absorber mode locking[3,5] encouraged renewed attempts at mode locking of semiconductor lasers with the goal of achieving compact short-pulse, generating systems.

In order to overcome the difficulties one at a time, microwave mode locking of an A.R. coated GaAlAs/GaAs double heterojunction laser in an external resonator has been initiated, with the mode-locking modulation at 3 GHz. The signal-to-noise ratio of the two-photon fluorescence detection system is not, as yet, sufficient to measure pulses directly, yet observation of the detected modulation of the optical signal, on a microwave spectrum analyzer showed up to 20 dB enhancement of the microwave signal as the modulation frequency was tuned into coincidence with the mode separation frequency $c/2\ell$.

A new support structure of the diode will permit substantially larger amounts of optical power to be sampled from the cleaved back face of the diode so as to measure

the pulses directly by two-photon fluorescence. In the coming year the active microwave mode locking of GaAlAs/GaAs laser diodes will be pursued further to ascertain the potential of this method for short-pulse generation with semiconductor lasers.

A microwave analog of a passively mode-locked laser system was constructed and successfully operated[6] at 10 GHz. An IMPATT diode was used as the amplifier, a Schottky diode as the absorber. The system permitted an experimental investigation of combined passive and active mode locking. For this purpose, the Schottky diode was driven by a "synchronizing" signal. A theory of combined passive and active mode locking was developed which incorporates the timing jitter produced by noise perturbations.[7]

Another approach to the mode-locking problem is being taken by utilizing the relaxation oscillations observed in double-section diodes[8] to provide the basic instability initiating the laser pulsing. Feedback at the period of the relaxation oscillation will be provided by placing the diode in an external resonator. Whereas the pulse duration of the relaxation oscillation depends upon the buildup time of the laser oscillation from noise, the pulse duration of the system with feedback is limited only by the unavoidable gain and index dispersion of the laser medium.

Quaternary compound GaInAsP/InP laser double heterostructures[9] with sectioned electrodes are being constructed by graduate student L. Glasser at the Lincoln Laboratory to explore the relaxation oscillation phenomenon on these novel diodes. They will be incorporated in the external cavity design now employed for active mode locking to accomplish the pulse shortening by feedback.

In the coming year we shall investigate further the mode properties of the quaternary diode structures with the aim of accomplishing the short-pulse generation using the relaxation oscillations as the pulse-forming instability.

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# VIII. QUANTUM ELECTRONICS

## C. Distributed Feedback Structures

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### 1. FREQUENCY-STABLE, LOW-THRESHOLD INJECTION LASERS

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Clifton G. Fonstad, Jr., Hermann A. Haus

The distributed feedback (DFB) laser gets its feedback from reflection off a periodic variation of refraction, or of gain.[1] Because this variation occurs on a scale comparable to a wavelength the mode selectivity of the DFB laser is much better than that of a conventional Fabry-Perot laser. However, the usual uniform periodic structure employed in a conventional DFB laser exhibits a threshold degeneracy – two modes of equal threshold occur on either side of the Bragg frequency – and the structure is, in fact, not optimized for single-mode operation.

A DFB structure with two uniform periodic sections, and a $\lambda/4$ (or $[2n+1]\lambda/4$) phase-shifting section between them, has a lowest threshold for one single mode located at the Bragg frequency, and hence the threshold degeneracy is removed.[2]

We are involved in experimental and theoretical programs to investigate the use of these structures in lasers and as passive filters at optical wavelengths. Initially, first-order gratings at 5000 Å (≈1700 Å period) are being produced in glass substrates. Thin-film waveguides are then being sputtered on these gratings. We are assembling a dye laser for use as a probe with which we will measure the reflection spectrum of the guides, that is, of the DFB gratings. Once the uniformly periodic structures have been characterized, a phase shift will be introduced and its effects studied.

We are also studying the use of an intermediate section with variable phase shift. Such a structure would appear to offer a certain amount of tunability of the filter, or in a laser, of the emission wavelength.

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## 2. GRATING WAVEGUIDES

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Hermann A. Haus

The work on distributed feedback structures has stimulated interest in wave propagation in structures with periodic perturbations, in particular, when the transverse dimensions of the structure influence the mode structure. Whereas no such effects have been observed as yet on optical structures, surface acoustic wave (SAW) devices have exhibited mode structures[1] that are attributable to the guidance of waves by reflection off the grating boundaries. The modes of such systems exhibit unusual dispersion characteristics[2,3] that are not encountered in the analysis of simple slow-wave structures because the coupling of forward and backward waves by the grating structure leads to four transverse wave solutions within the grating structure rather than the customary solutions for two waves.

Another aspect of grating structures that promises important applications for optical systems is their use as optical filters. The technology has not yet been developed to control the grating spacings to required tolerances. In the SAW field such tolerances can be met, and promising filter designs[4] have already been realized.

We intend to pursue further the theory of grating structures as it relates to their potential use as guiding structures, to obviate the need for transverse confinement of the optical wave in a thin film.

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# IX. TIME-RESOLVED SPECTROSCOPY OF CONDENSED MATTER


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Joint Services Electronics Program (Contract DAAB07-76-C-1400)


J. David Litster

The purpose of this program is to utilize the ultrashort pulses available from passively mode-locked dye lasers to carry out time-resolved spectroscopic studies of condensed matter. The program has been sponsored by the Joint Services since July 1977 and equipment has been purchased with major assistance from the Sloan Research Fund at M.I.T.

The dye laser has been built and is now operating; it produces pulses of wavelength 600-615 nm with a peak power of ~4 kW and pulsewidth below $10^{-12}$ s as measured by second-harmonic generation autocorrelations. All necessary electronics and signal detection equipment has also been built and is operating. Figures IX-1 and IX-2 illustrate the type of information that can be obtained with this system. Figure IX-1 shows an autocorrelation measurement of the laser pulse. In Fig. IX-2 a pulse was used to bleach a solution ($10^{-4}$ moles/liter) of oxazine 4 in water. This produced a temporary dichroism which relaxed, in this case, by rotary diffusion of the molecules with a time constant of 88 ps.

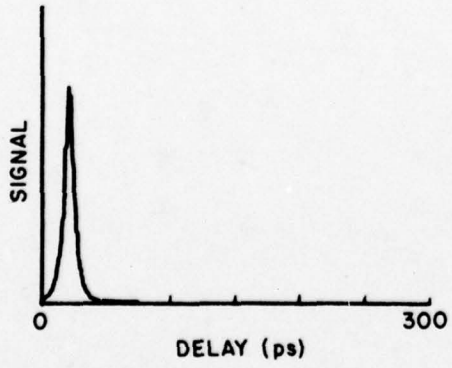



Fig. IX-1.
Dye laser pulsewidth.

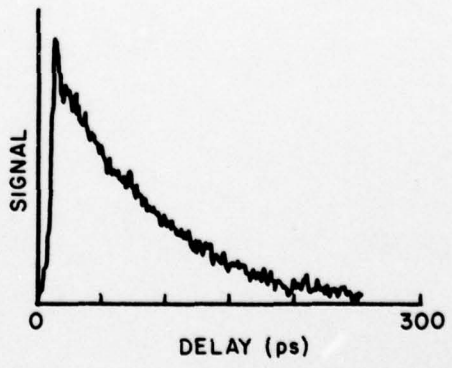



Fig. IX-2.
Decay of laser-induced dichroism.




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This type of experiment can provide detailed information on the dynamics of molecular motion and can also be used as a local probe of the solvent viscosity – as within the polymer network of a gel or within the phospholipid bilayer of a cell membrane. One may also use this method to study nonradiative intra- or inter-molecular energy transfer. We are also studying molecular motions in liquid crystal phases and hope to use the same method to study dynamical behavior near phase transitions in magnetic materials.

We are now carrying out a series of preliminary experiments to verify our theoretical predictions. The stability of the laser is not yet sufficient to permit long (>1 h) averaging to recover weak signals; we are working to improve this. Certain of our intended experiments may require more energetic pulses; a dye amplifier giving $10^3$ power gain is relatively easy to build and will be constructed when appropriate.

# X. INFRARED INSTRUMENTATION AND ASTRONOMY

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## 1. INFRARED HETERODYNE DETECTION

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Dirk J. Muehlner, Richard L. Benford, Margaret A. Frerking

A continuously tunable infrared heterodyne receiver was developed with the original intention of using it for very high spectral resolution astronomical observations. The complete detector, including a PbSnSe diode laser local oscillator, a HgCdTe photodiode mixer and associated optical components, was assembled in a small dewar. The dewar and additional transfer opticals made a compact package which could be mounted as a unit on even a small astronomical telescope.

The technology of tunable diode lasers for the mid infrared is new and we encountered considerable difficulties due to deterioration of the early lasers when they were cycled between room and liquid helium temperatures. Late in 1976 we obtained (from Laser Analytics, Inc.) a diode laser which operated at liquid nitrogen temperature, making it practical to store the instrument cold. This longest-lasting of our diode lasers was used in late 1976 to make heterodyne measurements of absorption of solar radiation by ozone in the earth's atmosphere near 1010 $cm^{-1}$. Preliminary results on this project were described in RLE Progress Report No. 119 (p. 31). The work was published[1] in essentially the same form, except that a better match of a calculated spectrum to the observed one was obtained by using the latest available line parameters[2] for ozone. The most complete description of the work, including results of high resolution laboratory absorption spectra of ozone, appears in the Ph. D. thesis[3] of Margaret Frerking.

No further experimental work was done after the ozone measurements were completed, and the project came to an end, after having demonstrated the potential of the compact heterodyne receiver, with the completion of Ms. Frerking's thesis.

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## 2. MEASUREMENTS OF THE LARGE-SCALE ANGULAR DISTRIBUTION OF THE COSMIC BACKGROUND RADIATION AT MILLIMETER AND SUBMILLIMETER WAVELENGTHS

National Aeronautics and Space Administration (Grant NGR 22-009-526)

Rainer Weiss, Dirk J. Muehlner, Richard L. Benford

For several years we have been making balloon flights with a dual-channel differential radiometer to measure the anisotropy in the angular distribution of the 3°K cosmic background radiation on angular scales of 17°. The radiometer has passbands of 3-10 $cm^{-1}$ and 10-25 $cm^{-1}$. We have established that the radiation is isotropic to a few parts in a thousand over one half of the sky. At this level of sensitivity we are observing anisotropies caused by interstellar dust clouds which exhibit a steeply increasing spectrum with frequency. The galactic plane is a major source of nonuniform width, temperature, and emissivity. Other sources have been discovered, in particular, a diffuse and extended region in the northern sky in the vicinity of W1. The analysis of the cosmic component has been complicated by these sources. Further progress requires the addition of more spectral channels in the radiometer in order to characterize the sources and allow their removal in the background measurement.

Even though isotropy measurements at smaller frequencies are less troubled by these sources and may have succeeded in measuring the anisotropy caused by the motion of the Earth against the primeval plasma, isotropy measurements must be carried out at several wavelengths so that spectra of the anisotropy can reveal the true source of the anisotropy.

This program is active and is now being administered by the Department of Physics.

## 3. SKY SURVEY AT MILLIMETER AND SUBMILLIMETER WAVELENGTHS

National Aeronautics and Space Administration (Grant NGR 22-009-526)

Rainer Weiss, Dirk J. Muehlner, Richard L. Benford

In an effort to understand the results of the isotropy experiments, we have been carrying out a sky survey from balloons in the 3-10 $cm^{-1}$ and 10-25 $cm^{-1}$ bands with an

angular resolution of 1.5°. Two flights have been made which have mapped the galactic plane $-2° < l_{II} < 120°$. The maps reveal that the galactic plane is a strong source in the 10-25 $cm^{-1}$ band, the galactic center is about 1/300 as bright as the moon in the same beam size. The galactic plane is not uniform in width but varies from a size as small as the beam size to over 8°. The spectral index varies more steeply than the frequency to the third power.

More survey flights will be made in the next year using new bolometers and two more spectral channels.

This program has been transferred to the Department of Physics.

## 4. INTEGRATED SILICON BOLOMETER

National Aeronautics and Space Administration (Grant NSG-7328)

Rainer Weiss, Patricia Downey

Broadband composite bolometers constructed entirely of silicon have been tested. The technique of manufacture is the following. A resistance thermometer is ion-implanted in a high-purity single-crystal wafer of silicon. The wafer, after masking, is etched leaving a central square 5 millimeters on a side supported by a silicon spider that makes thermal contact to a large silicon frame thermally connected to the heat bath. The central square is coated with a thin film of conductor that is the radiation absorbing surface.

At present, the best detector has had a 5-ms time constant and a radiation NEP of $3 \times 10^{-14}$ $W/Hz^{1/2}$ at 1.5°K. The observed performance is within a factor 1.2 of the calculated performance of the specific device. We expect with further refinement of present techniques to construct detectors with a NEP of a few $10^{-15}$ $W/Hz^{1/2}$ and time constants in the 10's of milliseconds.

Difficulties have been encountered in maintaining reasonable yields due to nonuniformity in the ion implants. Until this problem is solved, the initial concept of manufacturing detector arrays is unpromising. Future work will be directed toward constructing bolometers operable at 0.3°K using $He_3$ cryogen. Detectors of this style do not exhibit Kapitza resistance and should have NEP's that vary as $T^{-5/2}$.

This project has been transferred to the Department of Physics.

## 5. COSMIC BACKGROUND EXPLORER SATELLITE (COBE)

National Aeronautics and Space Administration (Contract NAS5-24096)

Rainer Weiss, Mark Halpern, David H. Shoemaker

We are participating in the phase B study of a satellite mission to be flown in 1983 to measure the spectrum and the large-scale angular distribution of the cosmic background radiation in four bands, as well as the diffuse infrared background between 2 and 300 micron wavelengths. Rainer Weiss is team leader of the study and coinvestigator on the instrument to measure the spectrum of the radiation. The phase B study will culminate in the definition, costing, and specifications of the Fourier transform spectrometer designed to measure the spectrum of the cosmic background radiation with a signal-to-noise exceeding 1000/1 at the blackbody peak in angular resolution elements between 3° and 5°. The spectral resolution of the instrument will be better than .5 $cm^{-1}$ at frequencies less than 20 $cm^{-1}$. The spectral range of the instrument extends to 100 $cm^{-1}$.

The coordinated observations of the mission should provide the most definitive measurements of the properties of the background radiation limited only by the "noise" due to the local astrophysical environment.

This project has been transferred to the Department of Physics.

# XI. INFRARED NONLINEAR OPTICS

## Academic and Research Staff

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## Graduate Students

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## 1. INFRARED NONLINEAR PROCESSES IN SEMICONDUCTORS

U. S. Air Force – Office of Scientific Research (Grant AFOSR-76-2894)

Dirk Muehlner, Peter A. Wolff, R. Andrew Wood, Lynn C. Detwiler, Kathleen Kash, Muhammad A. Khan, Roosevelt People

During the past year, a first series of experiments concerning the dispersion of the nonlinear optical susceptibility of n-type germanium was completed.[1] When pumped with two $CO_2$ lasers ($\omega_1$ and $\omega_2$), such a crystal generates radiation at frequency $\omega_3 = 2\omega_1 - \omega_2$. The power $P(\omega_3)$ is strongly enhanced (200-fold) when $\omega_1 - \omega_2$ coincides with valley-orbit splitting of the donor states. The results are in good agreement with our calculations of impurity Raman scattering and the third-order nonlinear coefficient. We plan next to use the resonant, four-photon mixing effect as a probe of other impurity levels. Experiments to detect the 1S-2S transition in n-Ge are in progress. We are also performing calculations of 2S (and higher) energy levels.

The measured cross sections imply that stimulated impurity Raman scattering should be achievable in n-Ge with $CO_2$ or far-infrared pumping. Preliminary experiments to test this idea were not successful, probably because the intense optical fields stripped the impurities. Measurements to confirm this hypothesis, and possibly obviate the problem, are planned.

We have recently observed resonant, spin-induced four-photon mixing in a ($Cd_xHg_{1-x}Te$) crystal loaned to us by Dr. Paul Kruse of the Honeywell Research Center. These experiments were performed with two $CO_2$ laser beams. The results clearly indicate that the sample contains a number of distinct regions, with slightly different g-values. Individual resonances are sharp, suggesting that there is an abrupt variation of properties from one region to the next. We plan to correlate our results with similar data obtained by the Bell Laboratories group on ($Cd_xHg_{1-x}$)Te samples grown by Cominco.

### References

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# XII. MICROWAVE AND MILLIMETER WAVE TECHNIQUES

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Dr. Alan Parrish

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Robert C. Walker

## 1. NOISE IN NONLINEAR DEVICES

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Madhu S. Gupta

The spectrum of thermal fluctuations in a physical variable, present in a linear system maintained at a given temperature in equilibrium, is given by Nyquist's theorem. An analogous, but more general, theorem has been derived for the fluctuation spectrum in a driven (i.e., nonequilibrium) nonlinear dissipative one-port system in contact with a heat reservoir at temperature T. We make the following assumptions:

The system does not store any energy so that the force and the flow variables $\beta$ and $\dot{\alpha}$ are instantaneously related.

The system is in a stationary state, driven by a steady force $\beta = \beta_o$, which is small so that the system is not very far from equilibrium.

The system is terminated in such a way that the fluctuations in the force variable $\beta$ are zero.

The transient behavior of $\alpha$, as the system relaxes toward a stationary state from a nonstationary one, is the same regardless of whether the nonequilibrium state is reached as a result of spontaneous fluctuations or because of a temporarily applied excitation.

The fluctuations are small enough to be treated under the small-signal approximation.

These assumptions allow the autocorrelation function of the random component $\dot{a}_s$ of the flow variable $\dot{\alpha}$ in steady state to be expressed as

$$\langle \dot{a}_s(t)\, \dot{a}_s(t+\tau) \rangle = 2kT \frac{\overline{\langle \dot{a}_r(t_1) \rangle\, \beta(t_1)}}{\overline{b(t_1-\tau)\, \beta(t_1)}}\, \delta(\tau), \qquad (1)$$

where $\langle \dot{a}_r(t_1) \rangle$ is the incremental part of the system response due to an incremental zero average periodic force $b(t_1)$ superimposed on the steady-state force, and the ensemble and time averages are represented by angular brackets and overbar,



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respectively. The fluctuation spectrum for positive frequencies is therefore given by

$$S_{\dot{a}\dot{a}}(f) = 4kT\, P_{ex}\overline{/b^2}, \tag{2}$$

where $P_{ex}$ is the average incremental power dissipation in the system due to $b(t_1)$.

This theorem can also be expressed in terms of the input-output characteristics of the nonlinear system. For example, identifying the variables $\alpha$ and $\beta$ with the terminal dc voltage V and current I of a nonlinear two-terminal device biased at a dc current $I_o$ leads to the following expression for the mean-square noise voltage per unit bandwidth

$$\overline{v_n^2} = 4kT\left[\frac{dV}{dI} + \frac{I}{2}\cdot\frac{d^2V}{dI^2}\right]_{I_o}. \tag{3}$$

This result yields the low-frequency noise spectra for Schottky-barrier, p-n junction, and tunnel diodes which are in agreement with those obtained from the first principles. A more detailed paper, entitled "Thermal Noise in Driven Nonlinear Resistive Systems," is being prepared for publication.

## 2. ATMOSPHERIC REFRACTION AT MILLIMETER WAVELENGTHS

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Bernard F. Burke, Alan Parrish, J. Antonio Garcia-Barreto,
Daniel D. Stancil, Barry R. Allen

The M.I.T. interferometer is now complete, and routine data taking is now in progress. During a late summer shutdown, the stepping motor drive systems were modified to provide position verification to the computer. This modification was required to insure reliable pointing in windy winter weather. The first measurements' refraction effects concentrated on high elevation angles, in order to understand the basic properties of the system.

The first observing program was designed to measure the instrumental and atmosphere stability over a period of weeks. Several quasars and the bright maser source W49N were observed. The data indicate that the long-term phase stability of the instrument is very good, that typically the observed phase on a given object and at a given sidereal time would not vary more than 30° from day to day. The data were taken with a short (813 λ) and two long (~12,000 λ) baselines, chosen so that on the strong maser source the observed phase noise will be due to the instrumental local-oscillator system on the short baseline and to the atmosphere on the long baseline, respectively. The

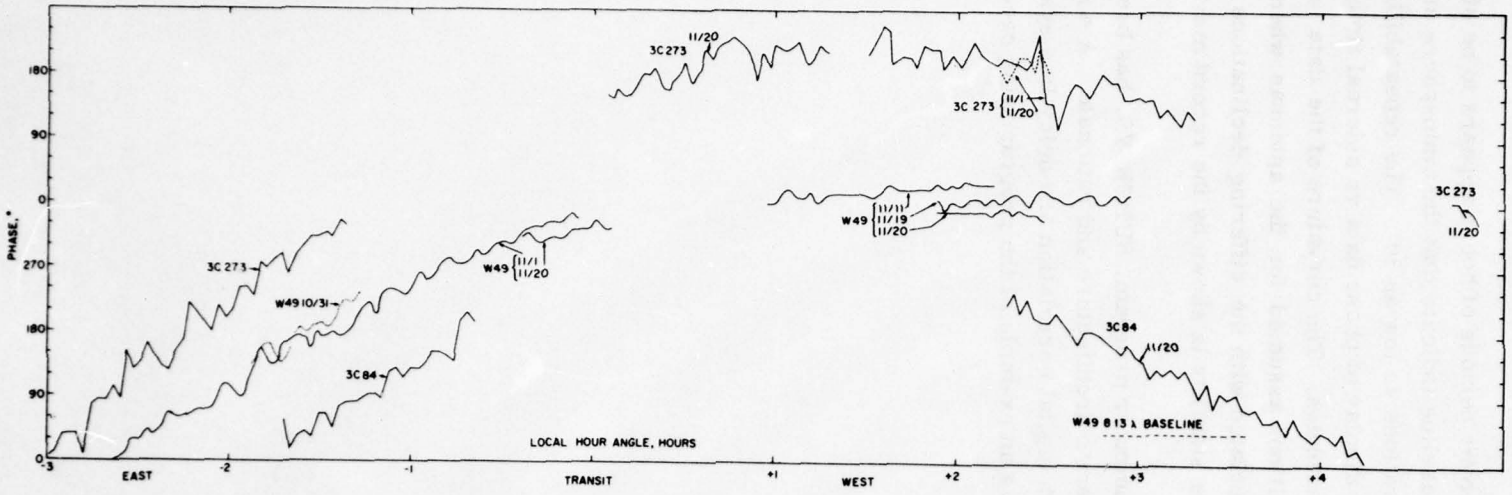



Fig. XII-1. The interferometer phase output as a function of local sidereal time. The solid and dotted lines represent the data from the long (~12,000 λ) baseline, while the dashed line represents data from the short (813 λ) baseline. The W49 source dominates the receiver noise, so any phase fluctuation on the short baseline would be instrumental, and the fluctuation on the long baseline W49 data is due to the atmosphere.

phase stability of the instrument over periods of hours appears to be of the order of 1° rms. Observations of the long baseline indicate that the atmosphere stability can be as good as 3° rms at antenna elevations as low as 30°. The repeatability of the instrument as shown in Fig. XII-1 is a display of phase data vs sidereal time taken with the long baseline averaged over 2.5 minutes. The curvature of the data is due to an error of approximately 1 cm in the positions assumed for the antennas when the data were taken, as is the phase offset associated with the differing declinations of the various sources. The instrumental phase stability is shown by the record marked "W49 813 λ Baseline" in the figure.

An overview of the on-line computer program, SUPERSYS, has been prepared with an emphasis placed on the program's architecture and rationale. A similar explanation is given for the 75-MHz bandwidth digital correlation and delay line system. The system auto load is also described as an example of the programming necessary to build a user-oriented facility.

# XIII. MICROWAVE DEVICES EMPLOYING MAGNETIC WAVES

## Academic and Research Staff

Prof. Frederic R. Morgenthaler
Prof. Robert L. Kyhl
Dr. Aryeh Platzker
Dale A. Zeskind

## Graduate Students

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## 1. GRADIENT-BOUND MAGNETOSTATIC MODES

Joint Services Electronics Program (Contract DAAB07-76-C-1400)
National Science Foundation (Grant ENG76-18359)

Frederic R. Morgenthaler, Robert L. Kyhl, Dale A. Zeskind, John J. Cooley

We have previously discussed the conditions necessary to cause magnetostatic waves to be bound or confined by dc magnetic field gradients both in rectangular slabs and solid or hollow cylinders when the wave propagation is parallel to the surfaces and perpendicular to the dc field direction. Although special field profiles were discovered that allow analytic treatment of particular waves, a more complete treatment of the eigenvalue problem has been desired.

We have now solved the eigenvalue problem governing two-dimensional magnetostatic mode propagation in thin ferrite disks when the dc magnetic field, $H_z$, is normal to the plane and varies radially as

$$H_z(r) = A + Br^{2n}$$

where n is an integer and B may be a positive or negative constant.

Although the approach taken produces a nonlinear differential equation with coefficients that may have singularities, an appropriate transformation of variables leads to a better behaved function that can be expanded without difficulty in terms of simple analytic functions. As expected, modes are found that are bound to or guided by the rim. These are similar to the surface modes found when $B = 0$, and are termed gradient-modified boundary modes. In contrast, when $|B|$ is large enough, modes are formed with peak response occurring at some interior radius. These boundary-modified gradient modes are highly localized (radially) at a "virtual surface" of discontinuity caused by the field gradient. It has been found for both types of mode that the velocity of energy circulation around the track formed by the "virtual surface" can be controlled by the magnitude of the dc gradient. All of the $B \neq 0$ modes have nonzero volume divergence of the small-signal RF magnetization. For the gradient-bound modes the divergence is very large at or near the track.

The effects of metallic boundaries placed in proximity to the ferrimagnetic disks have also been considered in the calculations. With simple modification, the theory is also applicable to disks transformed to annular rings by removal of their centers.

Experiments have been conducted on uniformly magnetized thin films of yttrium iron garnet (YIG) grown on substrates of gadolinium gallium garnet ($G^3$) by LPE techniques. Several such films approximately 5 microns in thickness have been very kindly supplied to us by Dr. Howard Glass of Rockwell International. They were grown under their Contract F44620-75-C-0045 with the Air Force Office of Scientific Research. High-Q magnetic resonances have been observed in our preliminary experiments on these films, and magnetic pole pieces designed to generate the $A + Br^{2n}$ field profiles are under construction.

An attempt will be made to study the gradient-bound modes by means of optical scattering techniques. The highly localized RF energy is expected to enhance such optical interactions.

John J. Cooley completed his study of bound modes in thick single YIG disks and on September 12, 1977 submitted a thesis entitled "Magnetostatic Modes Bound by dc H-Field Gradients" in partial fulfillment of the requirements for the degrees of Master of Science and Electrical Engineer. A summary of his thesis follows.

The study of high-Q microwave modes bound to an intentionally nonuniform dc magnetic field in a single crystal of yttrium iron garnet (YIG) was reported. The modes of a YIG disk, magnetized perpendicularly to its plane, and with internal dc field profiles either concave or convex were excited locally by fine-wire antenna structures. Modes with loaded Q's on the order of $10^3$ varied linearly with the externally applied bias field at a rate of 2.8 MHz/Oe over the frequency range 2.0 to 18.0 GHz. The internal field profiles resulted from placing the disk in either an initially uniform magnetic field (in which case the field was monotonic with the maximum at the disk edge), or a nonuniform external field shaped by high permeability magnetic pole pieces (to approximate a parabolic internal field with the maximum at the center of the disk).

The crystal used had dimensions of 1.97 mm (radius) and 0.33 mm (thickness), was cut along the (110) plane, and had both plane faces polished to optical standards. Excitation was achieved via two separate coupling structures: one in which the YIG acted as a resonant absorber and one in which the YIG coupled two nominally uncoupled antennas. Experimental results for the uniform external field configuration showed that two types of modes exist. There are well-coupled modes (10-20 dB insertion loss) which occur in a multiplet pattern (singlet, doublet, triplet, etc.) and there are poorly coupled modes (30-40 dB insertion loss) which do not follow this pattern. Experimental results for the shaped external field configuration do not show clearly defined multiplets.

Subject to the simplifying assumptions that the variation of the dc and RF fields in the direction perpendicular to the plane of the disk may be ignored, a formalism for

finding the eigenmodes of a general circularly symmetric internal field profile was discussed and a computer algorithm implemented. The computer-generated eigenmodes are $\phi$-directed and bound to circular tracks of constant radii. Families of eigenfrequencies which vary linearly with applied dc magnetic field at the rate of 2.9 MHz/Oe exhibit multiple degeneracies which suggests the possibility of multiplets. The widths of the experimentally observed mode spectra (approximately 1.5-2.0 GHz) agree qualitatively with computer-generated mode spectra.

## 2. MAGNETOSTATIC SURFACE WAVES CONTROLLED BY AN ADJUSTABLE AIR GAP

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Frederic R. Morgenthaler, Peter N. Horowitz, Dale A. Zeskind

The S.M. thesis of Peter N. Horowitz is progressing and concerns the control of magnetostatic surface wave group velocity on a sandwich structure composed of two ferrite rectangular slab crystals separated by an adjustable air gap. This geometry, suggested by Tsutsumi, appears to be a valuable one in which to study fundamental wave properties and material constants.

Both theoretical and experimental work involving mode localization by means of high magnetic flux concentration will also be conducted with special attention given to thin film geometries.

## 3. MAGNETOELASTIC YIG DELAY LINES

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Frederic R. Morgenthaler, Aryeh Platzker

The conventional magnetoelastic delay line employs input and output couplers located at the same end of a cylindrical YIG single crystal.

Improved electromagnetic input/output isolation would result from moving input and output to opposite ends of the crystal, but this requires operating with two "turning points" and two spin-elastic "crossover" surfaces. As our first attempt at producing such a structure, we have synthesized an on-axis magnetic field profile that is approximately vee-shaped, with two regions of constant gradient having opposite signs. Preliminary experiments have revealed unexpected properties and cast new light on high power saturation effects caused by too large focusing of the magnetostatic spin-wave beam.

A major study aimed at finding optimum focusing conditions is under way.

# XIV. MICROWAVE THERMOGRAPHY

## Academic and Research Staff

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## 1. MICROWAVE THERMOGRAPHY

National Institutes of Health (Grant 5 ROl GM20370-05)

Alan H. Barrett, Philip C. Myers

We have continued to develop and evaluate microwave radiometers for clinical detection of breast cancer. In collaboration with Dr. N. L. Sadowsky of Faulkner Hospital we have examined over 70 women with breast cancer confirmed by biopsy and over 4000 normal women, using a 3.3 GHz radiometer. We also examined over 25 women with breast cancer and over 1000 normal women, using a 1.3 GHz radiometer. A simple quantitative criterion of detection relies mainly on temperature asymmetry between the right and left breasts. With this criterion, observation at each frequency gives detection of about 70% of the cancers and a "false alarm" rate of about 30%. Each of these rates is similar to the corresponding detection rate of infrared thermography on the same set of patients. When the 3-GHz and infrared data are combined, the resulting cancer detection rate exceeds 90%. If microwave and infrared examinations are used as a zero-risk first-pass screen, and if mammography is used only as a follow-up of positive cases, then the resulting detection rate is about 90% and the false alarm rate can be about 15%. These results are the same as those of a program of mammography screening alone, but the number of women exposed to x rays is reduced by more than half. Thus the combined use of safe methods such as microwave and infrared examinations for breast cancer screening appears to be a distinct possibility.

Our equipment development and testing work has continued. We have completed 6-GHz tissue-matched antennas, a 6-GHz low-noise radiometer, and a microprocessor-based data handler, and expect to begin clinical evaluation of this system in the next year. We have also developed and tested higher resolution antennas. We now have two methods to evaluate the sensitivity-resolution tradeoffs involved in use of new antennas: one based on diode scattering of radiated power, and one based on the use of artificial thermal sources embedded in phantom tissue models.



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# XV. RADIO ASTRONOMY

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## 1. LONG-BASELINE ASTROMETRIC INTERFEROMETER

National Science Foundation (Grant AST77-06052)

David H. Staelin, Michael Shao

Work began this year on a new astrometric interferometer under NSF sponsorship. This is a continuation of a Sloan Fund-sponsored effort to develop a Michelson stellar optical interferometer that can track fringe positions in two colors so as to remove atmospheric effects and permit stellar separations to be measured with up to $10^{-4}$ arc-sec accuracy.[1]

The first system has one-inch optics and is designed to demonstrate the basic concept of fringe tracking. It is expected to be completed in the spring of 1978 and then moved to a western observatory site for field operations. If successful, it is hoped that an operational instrument with 4-inch optics might be developed.

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## 2. CONTROLLED THIN-FILM ANTENNA

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

David H. Staelin, James R. Melcher

Analysis of a distributed feedback control system for shaping thin-film reflector antennas began in 1977. The concept being studied involves the use of a scanning electron



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beam for depositing charge on a semirigid segmented surface parallel to a thin film or mesh that can serve as the reflecting surface for a very large microwave antenna in space. Electrostatic forces between these two surfaces shape the reflector.

Analysis of a particular 1-km diameter antenna showed that there were ~50 unstable modes in the reflector surface if it were suspended only by its rim. The growth time of these modes is sufficiently long ($\gtrsim$20 s) that a minicomputer appears to be adequate for computing the commands needed by the electron gun assembly.

A scale model is being assembled in the laboratory to test the distributed feedback concept. An assembly for measuring the secondary emission characteristics of thin films is also being constructed.

## 3. SCANNING MICROWAVE SPECTROMETER EXPERIMENT

National Aeronautics and Space Administration (Contract NAS5-21980)

David H. Staelin, Philip W. Rosenkranz

The five-channel scanning microwave spectrometer (SCAMS) yielded 10 months of almost continuous data from the Nimbus-6 satellite, launched in 1975.[1]

Analysis of Typhoon June has shown that passive microwave soundings can yield wind information in two ways: The surface wind was inferred for velocities up to ~75 m $s^{-1}$ from the enhanced surface emissivity due to foam and rough seas, and the winds aloft were deduced from the observed horizontal temperature gradients by means of the thermal wind equation.

Kalman filtering was applied to the problem of temperature profile retrievals. By simultaneously operating on data vectors for adjacent image elements, improvements in accuracy were obtained because of the systematic differences between the radiative transfer functions for different viewing angles and the correlations between adjacent atmospheric cells.

The propagation of electromagnetic waves in inhomogeneous media was analyzed for the case where the inhomogeneities can be characterized by the autocorrelation functions of the index of refraction with respect to depth and also radial separation. This model has been successfully applied to interpretation problems for snow and ice data.[2]

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2. A. D. Fisher, "A Model for Microwave Intensity Propagation in an Inhomogeneous Medium," IEEE Trans. on Antennas and Propagation, Vol. AP-25, No. 6, pp. 876-882, November 1977.

## 4. OBSERVATIONS OF CLOUDS AND ATMOSPHERIC TEMPERATURE PROFILES BY MEANS OF A 118-GHz SPECTROMETER

U.S. Air Force – Electronic Systems Division (Contract F19628-75-C-0122)

David H. Staelin, Philip W. Rosenkranz

The 118-GHz spectral region contains a strong molecular resonance of $O_2$ which can be used for atmospheric temperature sounding and, by combination with 60-GHz channels, for measurement of heavy clouds. A 7-channel 118-GHz spectrometer was developed for studying this spectral region and flown in the NASA/Ames Convair 990 aircraft in March 1977. Measurements near zenith at altitudes from zero to 35,000 ft generally confirmed the theoretical expressions for $O_2$ absorption. Recent ground-based measurements of the 118-GHz and 60-GHz spectra of clouds passing overhead are still being analyzed. The ability of 118-GHz spectrometers to sound temperature profiles has been determined theoretically to be slightly superior to 60-GHz soundings over ocean and inferior over land. The ability of combined 60-GHz and 118-GHz spectrometers to sound cloud density profiles has been found to be only moderately better than 60-GHz data alone if linear estimation methods are employed. Tsang et al.[1] analyzed theoretically the microwave emission of clouds.

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## 5. TIROS-N SATELLITE MICROWAVE SOUNDER

U.S. Department of Commerce – National Oceanic Atmospheric Administration (Grant 04-8-M01-1)

David H. Staelin, Philip W. Rosenkranz

The Tiros-N Operational Weather Satellite carries a microwave temperature-profile sounder (MSU) which has one window channel near 50 GHz, plus three channels at 52-58 GHz; these respond to the average temperatures of atmospheric layers centered near 3, 8, and 12 km altitudes, respectively. The first two such satellites will be launched in 1978. The performance of these instruments will be limited by precipitation, clouds, surface effects, and the mathematical techniques employed to estimate the atmospheric temperature field. This research program focuses on development of an improved understanding of the limits to performance and the development of high-performance estimation procedures. The problem is nonlinear and involves nonstationary, non-Gaussian statistics.

## 6. SCANNING MULTICHANNEL MICROWAVE RADIOMETER (SMMR) EXPERIMENT

National Aeronautics and Space Administration (Contract NAS5-22929)

David H. Staelin, Philip W. Rosenkranz

The SMMR instrument is scheduled for launch in 1978 on the Nimbus-G and the Seasat satellites; they will scan the Earth at a constant incidence angle at frequencies of 6.6, 10.7, 18, 21, and 37 GHz using dual linear polarization. These data will yield information about the microwave characteristics of snow, sea ice, foam, precipitation, humidity, sea surface, vegetation, soil moisture, etc., and will permit their various parameters to be mapped and monitored.

The parameter estimation problem involves nonlinear phenomena and non-Gaussian and nonstationary statistics. Kalman filtering and pattern classification techniques are being explored for retrieval of these parameters.

The estimation of snow and ice and ocean parameters also requires improved physical models that permit efficient computation of microwave emission characteristics. Such models are being developed.

## 7. METEOROLOGICAL REMOTE SENSING NEAR 2-mm WAVELENGTH

National Aeronautics and Space Administration (Contract NAS5-23677)

David H. Staelin, Philip W. Rosenkranz, William H. Ledsham

The remote sensing technology developed in the 10-60 GHz spectral region can be applied in large measure to the 100-200 GHz bands because both contain $H_2O$ and strong $O_2$ resonances, as well as spectral windows which are nearly transparent. The principal difference is that the 100-200 GHz region is 2-20 times more responsive to clouds and precipitation and that the 183-GHz $H_2O$ resonance is quite opaque below a few kilometers altitude. An important advantage of these short wavelengths is that an antenna of fixed size in synchronous orbit can have spatial resolution several times greater than that obtainable at 10-60 GHz. This feature is important for contemplated future weather satellites in geostationary orbit.

The capabilities of meteorological satellites operating at frequencies near 100, 118, 135, and 183 GHz have been analyzed and compared with systems operating below 60 GHz. In general the 100-200 GHz systems perform comparably with the lower frequency systems in clear air or light clouds, but are more easily degraded by precipitation; their performance over land is also slightly degraded for water vapor or temperature profiles at altitudes below a few kilometers. These results were based upon the use of linear estimation procedures; nonlinear estimation should significantly improve the performance of 100-200 GHz sensors in certain situations.

## 8. MICROWAVE SPECTROSCOPY OF THE INTERSTELLAR MEDIUM

National Science Foundation (Grant AST73-05042-A03)

Alan H. Barrett, Philip C. Myers

During the past year our studies of atomic and molecular interstellar gas clouds have continued, with observations of microwave transitions of H I, CO, CS, $NH_3$, $H_2CO$, and $CH_3OH$ toward Bok globules, dark clouds, molecular clouds associated with H II regions, and globular clusters. We have used radio telescopes of the National Radio Astronomy Observatory in Green Bank, West Virginia, and at Kitt Peak, Arizona; and of M. I. T. Haystack Observatory.

A search for maser emission from methanol ($CH_3OH$) in 132 sources confirmed that Orion is a unique source of methanol line emission at $\lambda \approx 1$ cm. A search for CO emission from globular clusters indicates that if mass lost from cluster stars is still trapped in the clusters, no more than ~5 $M_\odot$ is in molecular form at $T \approx 100$ K. A study of the $NH_3$ inversion lines toward molecular clouds associated with Orion A and other H II regions indicates that the gas is highly clumped on a scale of ~0.04 pc. In the Taurus dark cloud, extremely narrow $NH_3$ linewidths were observed, indicating very cold gas with $T < 28$ K. The molecular cloud CRL 437 has CO line shapes with remarkable symmetry properties, suggesting differential rotation of the cloud. A study of the ρ Ophiuchi dark cloud in several molecular lines shows scale lengths which vary from .1 pc to 6 pc. and linewidths increasing with scale length from ~1 to ~3 km $s^{-1}$. This effect suggests contracting radial motion. Observation of H I toward dark clouds with an interferometer with resolutions ~3' and ~6' indicates very strong absorption at molecular line velocities, suggesting very high H densities.

## 9. VERY LONG BASELINE INTERFEROMETER APERTURE SYNTHESIS OF MASERS

National Science Foundation (Grant AST76-20376)

Robert C. Walker, Bernard F. Burke

### a. VLBI Aperture Synthesis of Masers

Very Long Baseline Interferometer (VLBI) observations were made in an effort to study the structure of $H_2O$ masers in greater detail than has been possible in the past. A system of programs for aperture synthesis mapping of spectral line VLBI data was developed and applied to data from a five-station experiment. Synthesis maps were produced of the $H_2O$ emission in W51, CRL 2591, and ON2. The emission in many velocity

channels in these sources is spatially complex, demonstrating the value of the synthesis technique over the fringe-rate method of mapping used in most experiments. Fringe-rate maps were made of W3(C)$H_2O$ and W3(OH) which could not be synthesized due to extreme complexity in the sources and instrumental difficulties. In a separate experiment, a new map of the emission from W49N, including much of the high-velocity emission, was made using data from two stations. Intercontinental baselines were used in a third experiment to study the dependence of the apparent size of a maser spot on frequency across single, isolated lines. A dependence, in the sense that the source appears larger in the wings of the line, was found for an extraordinarily powerful line in W49N.

The observations reveal several significant scale sizes in $H_2O$ sources. The apparent size of individual maser spots is on the order of a few times $10^{13}$ cm. The dependence of source size on frequency supports the "hot spot" idea that the apparent size of maser spots can be much smaller than their real size. The separation of maser spots, which is deduced from the synthesis maps, can be taken as an indication of the actual size of masers: approximately $5 \times 10^{14}$ cm. Results from the synthesis experiment and the W49N map show that tight clusters of emission lines exist with scale sizes on the order of $4 \times 10^{15}$ cm. W49N contains several of these tight clusters. The high-velocity emission in W49N was found to be associated with the tight clusters of low-velocity emission. The scale size of the high-velocity emission about a given cluster is on the order of $10^{16}$ cm. The total extent of many sources is $10^{17}$ cm or more.

The observations have been discussed in terms of a model for the early evolution massive stars. The important feature of the model is a dust shell and associated region of shocked gas which forms about the star as it begins nuclear burning. The shell is driven away from the star by radiation pressure, and eventually fragments. The $H_2O$ masers occur in the region of shocked gas outside the shell. High-velocity features and extended regions of emission are manifestations of the fragmentation of the shell. The stage of evolution of the dust shell may be determined from the appearance of VLBI maps.

This material, in a thesis, entitled "Observations of the Detailed Structure of Interstellar $H_2O$ Masers," was submitted by R. C. Walker to the Department of Physics on August 12, 1977, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

## 10. MASER TIME VARIATIONS

National Science Foundation (Grant AST76-20376)

Aubrey D. Haschick, Thomas S. Giuffrida, Bernard F. Burke

The W3(OH)$H_2O$ maser exhibited a well-defined variation in the intensity of one component during May-June 1977. The line rose to maximum intensity over a one-week period, and declined during the following four weeks. A model for the variation has

been constructed that fits the observations accurately. The calculation assumes that the maser is saturated, the pumping mechanism is collisional, the initial source of energy occurs as a pulse localized in space and time, and that the energy is quickly thermalized. A possible geometrical model can be constructed, involving the release of energy through a brief break in the dust cocoon of a young star, which provides sufficient energy for such an event. The model suggests that there is a lack of infrared radiation from the W3(OH) maser because the phenomena are being observed at such an early stage that the infrared radiation has not yet diffused out.

## 11. FRINGE-RATE MAPPING OF W3(OH)

National Science Foundation (Grant AST76-20376)

Thomas S. Giuffrida, Aubrey D. Haschick, Bernard F. Burke

One of the principal methods of reducing spectral line Very Long Baseline Interferometer (VLBI) data is the fringe-rate map. In the current implementation, this method assumes only one source per spectral channel. This assumption is clearly incorrect for many $H_2O$ maser sources, including W3(OH). A series of programs were written avoiding this assumption to reduce VLBI data taken on W3(OH) over one year's time. The data included three experiments run during the rapid turn-on of one feature during May 1977, referred to in Section XV-10.

The resulting maps show that spot positions are repeated surprisingly during the year. Even though some spots disappear and others emerge, most remain. Those that do remain gain complexity in velocity space, something not accounted for in maser models. The maps have been discussed and the possible pump sources enumerated in a thesis, "Interferometric Observations of Astronomical Sources Emitting 1.35 cm Radiation," by T. S. Giuffrida, submitted to the Department of Physics on December 20, 1977, in partial fulfillment of the requirements for the degree of Doctor of Philosophy. The rapid turn-on implies a pump communication speed of .05 times the speed of light. This is difficult to comprehend, except in the hot-dust cold-gas pump model.

## 12. STUDIES OF HI ABSORPTION IN GALAXIES

National Science Foundation (Grant AST76-20376)

Aubrey D. Haschick, Willem A. Baan, Bernard F. Burke

Neutral hydrogen absorption-line studies of external galaxies have continued, using the 300-ft transit telescope of the NRAO.

Neutral hydrogen absorption at 21-cm wavelengths has been detected in the radio

galaxy 1506+34. The absorption feature has a halfwidth of 110 km $s^{-1}$ and midpoint radial velocity ($c\Delta\lambda/\lambda_o$) of 13,500 km $s^{-1}$ which is coincident with the optical emission line velocity of the galaxy of 13,550 km $s^{-1}$. The high optical depth of the absorbing H I cloud of $\tau = 0.4$ implies a neutral hydrogen column density of $N_H = 8.5 \times 10^{19} T_s$ H I atoms $cm^{-2}$. The absorption feature in 1506+34 is comparable both in optical depth and width to features found in the spiral galaxies NGC 253, M82, and NGC 4945.

The 300-ft transit telescope of the NRAO was used for the successful detection of neutral hydrogen absorption at 21-centimeter wavelength arising from within the radio galaxy 3C178. The radial velocity of the most prominent absorption feature of 2460 km $s^{-1}$ lies close to the median velocity of the neutral hydrogen emission profile. An estimate of the optical depth $\tau$ of 0.06 for this feature leads to a column density for the absorbing material of $3.6 \times 10^{18} T_s$ $cm^{-2}$. Three weak features appear at -34, +12, and +40 km $s^{-1}$ with respect to the central feature. The effect of the continuum radio source on the spin temperature is important, and it appears to be very difficult to locate the absorbing gas close to the nucleus. The low velocity is hard to explain dynamically, and it is possible that the main absorption arises in the galactic halo of 3C178.

# XVI. ELECTRODYNAMICS OF MEDIA

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## 1. ELECTROMAGNETIC WAVES

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Jin Au Kong

We have the following objectives in our studies of electromagnetic waves: examination of subsurface probing and communication with a dipole antenna, study of remote sensing of the earth, and investigation of integrated optics and fiber optics as applied to optical communication systems. Papers on research supported in 1977 by the Joint Services Electronics Program which have been published, accepted for publication, submitted for publication, or presented at meetings are listed in references.[1-14] The advantages of using horizontal magnetic dipole antennas were explored in detail for both isotropic- and anisotropic-layered earth.[1] We compared field calculations and experimental results for a horizontal electric dipole submerged in lake water.[2] In remote sensing we studied thermal microwave emission from random media[3-5] and from media containing spherical scatterers.[6-8] Backscattering coefficients for active sensing have also been investigated.[9-10] In applied optics we investigated electro-optical modulators and developed theories for spatially modulated periodic media.[11-14]

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## 2. PASSIVE REMOTE SENSING OF THE EARTH WITH MICROWAVES

California Institute of Technology (Contract 953524)

Jin Au Kong, David H. Staelin

In passive remote sensing of the earth we have studied microwave thermal emission from a layered random medium.[1,2] The model of a medium containing spherical scatterers has also been developed.[3,4] These theoretical models have been applied to the solid earth, as well as to clouds and rainfall.[5]

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## 3. REMOTE SENSING WITH ELECTROMAGNETIC WAVES

National Science Foundation (Grant ENG76-01654)

Jin Au Kong

Active sensing with dipole antennas has been studied with a horizontal magnetic dipole[1] and with a horizontal electric dipole.[2] Passive remote sensing of near-surface soil moistures and ice-covered land or water by using a model of a layered medium has been investigated.[3-5] The theory for thermal microwave emission from a bounded medium containing spherical scatterers has also been developed.[6,7] With a random medium model, active remote sensing techniques have been investigated.[8,9]

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## 4. ACTIVE AND PASSIVE MICROWAVE REMOTE SENSING

National Aeronautics and Space Administration (Contract NAS5-24139)

Jin Au Kong

With a random medium model, backscattering coefficients for active microwave remote sensing have been studied.[1,2] The spherical scatterer model[3] has been used to

interpret passive remote sensing data with diurnal changes. Rough surface effects are now being integrated into our theoretical models.

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# XVII. GRAVITATION RESEARCH

## Academic and Research Staff

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National Science Foundation (Grant MPS75-04033)
M. I. T. Sloan Fund for Basic Research

Rainer Weiss, Peter B. Kramer

Our research objective is to make an experimental study of the post-Newtonian effects of relativistic gravitation. At present, the major emphasis is placed on a feasibility study of gravitational radiation detectors based on the principle of the interaction between free masses and gravitational waves. Gravitational wave antennas of this type, when used with large baselines and sensed interferometrically, give some promise of being able to detect the gravitational radiation from stellar binaries. Preliminary calculations with a 1-km baseline system using 1-ton masses in space indicate that the dominant noise for periods longer than 100 s may be stochastic force attributable to high-energy protons. The antenna employing a 1-W laser would be able to detect the gravitational radiation from several short-period binary systems in several months of integration time. Because of laser amplitude noise, the limiting strain sensitivity for periods shorter than 100 s corresponds to $(\Delta\ell/\ell)^2 \sim 10^{-42}$/Hz.

A prototype interferometric antenna with a 1-m baseline is being constructed in the laboratory. The sensitivity at frequencies higher than 100 Hz is limited by laser amplitude noise and corresponds to $(\Delta\ell/\ell)^2 \sim 10^{-36}$/Hz. In the present design, at frequencies lower than 100 Hz, the noise is dominated by seismic and acoustic noise. With this antenna we should be able to set significantly lower limits on the gravitational radiation spectrum but not on a level where any reasonable astrophysical process could be measured.

Construction of the prototype is still in progress. At present the vacuum system has been assembled and tests of the optics have been carried out. Interferometry using multiple-pass delay lines was demonstrated within a factor of four of the shot-noise limit.

The program has been transferred to the Department of Physics.

# XVIII. ELECTRONIC PROPERTIES OF CHARGED CENTERS IN $SiO_2$-LIKE GLASSES


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Joint Services Electronics Program (Contract DAAB07-76-C-1400)


Marc Kastner

A vacuum-ultraviolet optical system has been constructed to examine photoluminescence from $SiO_2$. The system consists of a McPherson 218 vacuum monochromator, a McPherson Hinteregger hydrogen discharge lamp, and a high-vacuum optical system. The cost of this system (about $25,000) was furnished almost entirely by a Cottrell Grant from Research Corporation and M.I.T. funds.

A major modification of the lamp was necessary to provide stable continuous operation. This has now been completed. An improvement over previous designs allows quite long periods of stable operation.

The first measurements on Supersil fused quartz indicate that luminescence can be excited by photons with energies near the band gap even at room temperature. Many other measurements are needed to ascertain whether this photoluminescence is, as we predicted, similar to that observed at valence-alternation defects in chalcogenide glasses.

The next stage in our program is to measure the temperature dependence of the luminescence. For this a liquid He temperature cold finger must be added to our optical system. We have, so far, measured only the excitation spectrum of the luminescence. Modifications of the optical system will be made to measure the luminescence spectrum as well.




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PLASMA DYNAMICS

# XIX. PLASMA DYNAMICS

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# XIX. PLASMA DYNAMICS

## A. Basic Plasma Research

### 1. NONLINEAR WAVE INTERACTIONS

National Science Foundation (Grant ENG77-00340)

Abraham Bers, George L. Johnston, Abhijit Sen, Gérard P. Leclert, Vladimir B. Krapchev, Allan H. Reiman, Charles F. F. Karney, Nathaniel J. Fisch, Bruce E. Edwards, Stavros M. Macrakis

This continuing theoretical research concerns itself with studies of large-amplitude waves in a plasma; in particular, their time-space evolution, their relation to plasma heating, and their connection to strong turbulence phenomena. The onset of stochastic particle motion in a finite-amplitude coherent wave is a particularly striking example of a plasma heating mechanism, and may also give a possible link to strong turbulence. In addition our studies are chosen to have a direct impact on the current interest of plasma heating by means of RF power. This includes work on: parametric excitations in a magnetized, inhomogeneous plasma; their nonlinear evolution in time and space; nonlinear propagation and self-modulation of large-amplitude wave packets; and the interaction of these waves with the plasma particles.

This work has been presented in detail in journal papers and at conferences.[1-23]

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## 2. STUDIES OF NONLINEAR WAVE-PARTICLE INTERACTIONS

National Science Foundation (Grant ENG77-00340)

Peter A. Politzer, Stanley R. Shanfield, Ady Hershcovitch

We are studying the influence of turbulent electric fields on the spatial and velocity diffusion processes in a plasma. In order to do this in a controlled experiment, we use a counterstreaming electron beam facility to observe the time evolution of the particle velocity distribution function in the presence of either externally applied electric fields or the spectrum generated by instabilities of the electron beam itself. The externally applied fields have a controllable spectrum and thus we can observe the velocity-space diffusion rates as they depend on the spectral width and amplitude of this turbulence. We have modified the formalism of strong turbulence theory to include the effects of externally applied turbulence and have found that, in certain cases, it is possible to suppress plasma instabilities with a suitably chosen external spectrum.[1] This calculation has been applied to the counterstreaming electron beam configuration, and we find that there is good agreement between experiment and theory with regard both to the velocity-space diffusion coefficient and the level of turbulence required to suppress the half-cyclotron frequency instability[2] which appears in this system. This theory has also been applied to the interpretation of several RF stabilization experiments in which the drift-cone mode in magnetic mirror systems has been suppressed. Again, we find good agreement.[3] We have also considered the use of this stabilization scheme to influence trapped particle modes in Tokamaks.

The experimental facility is being modified so that we can measure the electron velocity distribution directly in two dimensions ($v_\perp$ and $v_\parallel$), rather than in only one ($v_\parallel$). We are planning to study further the effects of applied turbulence near the cyclotron frequency. We hope to be able to establish whether phase space clumps are generated in this system, and to measure their lifetime.

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### 3. COHERENT SCATTERING EXPERIMENT MEASUREMENT OF LOW-FREQUENCY TURBULENCE

National Science Foundation (Grant ENG77-00340)

Lawrence M. Lidsky

We have extensively modified and rebuilt the apparatus used to detect and resolve the high-frequency scattering from thermal level density fluctuations in our "standard" laboratory plasma source, the HCD. Calculations and preliminary measurements indicate that the source as built will have sufficient sensitivity and resolution to investigate the relatively low-frequency turbulence that plays the most important role in ion transport and heat transfer. The calculations used for this experiment are based on the low-frequency "clump" model of fluctuation phenomena in plasmas developed by T. H. Dupree, and the experimental results will be analyzed in the light of that theory.

### 4. RENORMALIZATION METHODS IN PLASMA TURBULENCE THEORY

National Science Foundation (Grant ENG77-00340)

Thomas H. Dupree

Plasma fluctuations with velocities of the order of or less than the thermal velocity are being studied. In the stationary case these fluctuations are known as B. G. K. modes. In the turbulent case, they have been referred to as clumps. A clump is an excess or deficiency in the local phase density as compared with the local average density. We can picture the deficiency case as a hole and it has the interesting property of being gravitationally bound. These structures persist on a long time scale in the plasma and have important effects on a variety of plasma phenomena. The earlier theory of these fluctuations is being improved and a more rigorous theory developed. In particular, the new theory conserves both the electric energy of the fluctuations and the kinetic energy of the particles.

## 5. INTENSE RELATIVISTIC ELECTRON BEAMS

National Science Foundation (Grant ENG77-00340)

U. S. Energy Research and Development Administration (Contracts E(11-1)-2766 and EY-76-S-02-2766)

U. S. Air Force – Office of Scientific Research (Grant AFOSR-77-3143)

George Bekefi

Two areas of research are now being studied, both of which make use of our pulsed high-voltage facility, Nereus (voltage 500 kV, current 70 kA, pulse duration 30 nsec).

### Magnetron Design

We are continuing with our studies of the relativistic electron beam magnetron. These studies include optimization of magnetron design, studies of its frequency spectra, and scaling with voltage and magnetic field. The experimental program is being supplemented by some detailed analytical studies being carried out by Masayuki Karakawa (a graduate student supervised by Dr. Kim Molvig).

### Electron Beam Pinching

The self-pinching of a relativistic electron beam in a high-voltage diode is aided by plasma formation in the anode-cathode gap. In conventional diodes the plasma is formed by a precursor of the electron beam. As a result, one has little control over the time of formation of the plasma and one has equally little control over its density, temperature, and particle species of which it is composed. In the present experiments under way the aforementioned plasma is generated independently by means of a laser. The light from a pulsed $CO_2$ laser (energy 1.5 J, pulse length 100 nsec) is focused by means of a germanium lens onto the cathode surface. A dense plasma plume of known characteristics is thus generated. As this plume expands with known velocity across the diode, the Nereus high-voltage facility is fired. The pinched beam with and without laser radiation is studied from x-ray pinhole camera pictures and from detailed time-resolved impedance measurement of the diode.

# XIX. PLASMA DYNAMICS

## B. Plasma Research Related to Fusion

### Confinement Systems

### 1. PHYSICS OF HIGH-TEMPERATURE PLASMAS

U. S. Department of Energy (Grant EG-77-G-01-4107)

Bruno Coppi

An understanding of the physics of high-temperature plasmas is of primary importance in the solution of the problem of controlled thermonuclear fusion. One of our goals is the magnetic confinement and heating of plasmas with densities in the range $10^{14}$ to $10^{15}$ particles/cm$^3$ and thermal energies in the few kiloelectronvolt range. The macroscopic transport properties (e. g., particle diffusion and thermal conductivity) of plasmas in these regimes are weakly affected by two-body collisions between particles. The relevant transport coefficients, in fact, are influenced significantly by the type of collective mode that can be excited, such as density and temperature fluctuations caused by microinstabilities.

Relevant theoretical and experimental contributions have been presented at national and international conferences or published in professional journals. The primary focus has been on the experimental effort involving the Alcator A machine. Our purpose has been to realize plasmas that can sustain very high current densities without becoming macroscopically unstable, in order to achieve the highest possible rate of resistive heating of the plasma.

Alcator's unique properties – lack of impurities ($Z \approx 1$), high current density, and large toroidal field, have made it one of the most referred to toroidal confinement devices. Specifically, we can point to the following achievements.

(i) Peak plasma densities in excess of $10^{15}$ cm$^{-3}$, with energy replacement times of ~20 ms have been attained. This yields $n\tau$ values approximately $3 \times 10^{13}$ s/cm$^3$ which exceed by a considerable factor those of any existing confinement system.

(ii) Since the particle density can be varied over two orders of magnitude, while the temperature can be independently controlled by the plasma current, and macroscopically stable plasmas can be obtained, we have continued to study a sequence of plasma regimes with a varying degree of collisionality and to derive valuable information about the nature of various transport coefficients such as electrical resistivity and energy replacement time.

(iii) By programming properly the rate of rise of the particle density and of the plasma current, it has been possible to avoid the onset of disruptive instabilities that limit, for a given value of the magnetic field, the maximum plasma current density. Therefore, record high current densities have been obtained with low values of the

so-called safety factor ($q \approx 2$). The plasma current pulse has been extended to more than 300 ms in the high-density regimes. Thus, we expect new interesting results to be produced by increasing the plasma current over the 290 kA mark achieved so far and programming its time evolution.

(iv) The anomalous transport coefficients that we had employed in a transport code developed to reproduce the main characteristics of the plasma temperature and density profiles obtained in Alcator experiments have been found to interpret a larger set of experiments produced by other machines. The same transport code has been used in the analysis of compact experiments for the study of $\alpha$-particle confinement and heating. These are generally called Ignitors. In fact, the main purpose of these experiments is to achieve the ideal ignition temperature where the electron energy loss by bremsstrahlung emission is compensated by the $\alpha$-particle heating.

The Alcator C device that we proposed in 1975 for funding to the U. S. Department of Energy has been under construction all during 1977, and its assembly is expected to be completed in early 1978. A new power supply to exploit the design parameters of this device is being installed at the Francis Bitter National Magnet Laboratory. The major aim of this experiment is to increase the value of $n\tau$ to approximately $10^{14}$ s/cm$^3$ with particle temperatures in the range $2 \div 3$ keV. The main parameters are: minor plasma radius $a \approx 17$ cm, major radius $R \approx 64$ cm, magnetic field up to 140 kG, and plasma currents up to 1 MA. This device will also complement the results that are expected from the FT machine of Frascati whose design features are: $a \approx 21$ cm, $R \approx 83$ cm, magnetic fields up to 100 kG, and plasma currents up to 1.2 MA.

Direct measurements of temperature and density profiles have been performed on the Rector experimental device with the plasma cross section elongated vertically (noncircular) by an appropriate mesh of Thomson-scattering measurements. Thus, for the first time, direct identification of the relevant magnetic surfaces has become possible. This technique will permit a detailed investigation of the confinement properties of a toroidal system with noncircular cross section. With this objective in mind, the Rector machine has been rebuilt in a more suitable experimental area, and provided with upgraded facilities for its operation and diagnostics.

We have continued to benefit from collaboration with visiting scientists from other national and foreign institutions.

## Research – Theoretical

### 2. DYNAMICS OF TOROIDAL DISCHARGES

U. S. Department of Energy (Grant EG-77-G-01-4107)

James E. McCune, Jay L. Fisher, Daniel E. Hastings, Kenneth Rubenstein, George M. Svolos

#### a. Quasi Equilibria in Rotating Toroidal Discharges at Low and Moderate Collisionalities

James E. McCune, Jay L. Fisher

Increasing interest in the effects of plasma fluid inertia on neoclassical transport and the resulting quasi equilibria in tori continues to develop as experimental evidence of plasma rotation in a variety of Tokamak experiments accumulates. The present program has led to the development of a drift-kinetic equation of sufficient generality to include significant ordered flows of the species present. The resultant inertial effects cause appreciable changes in both ion and electron behavior. Plasma ions are directly affected, while the electrons respond to the overall flows primarily through the electrostatic fields associated with the ion motion. A prominent feature associated with such motion is the development of strong radial (cross-flux) electric fields. If these fields are present, as indicated in a variety of experiments, a class of particles can develop which possesses purely circular orbits around the major diameter of the torus. The particles thus see no magnetic field modulation and can escape such orbits only through collisions. Interestingly, the presence of these particles can play a role competitive with more familiar neoclassical effects, including those of trapping, banana orbits, etc. In the case of electrons, moreover, the trapping boundaries can be altered through the electric potentials already mentioned.

Solutions of these governing equations have now been obtained in relevant parameter regimes, giving a description of quasi-steady ion and electron "equilibrium" distribution at low collisionalities with inertial effects included. As the importance of collisions increases, these results go over to those appropriate to the Pfirsch-Schlüter (MHD) regime reported earlier. At lower collisionalities, the results exhibit the physical effects described above to a varying degree.

Portions of this research are available in report form; the completed research will be submitted as the doctoral thesis of Jay L. Fisher.

b. Time Development of Rotating Toroidal Discharge at Low Collisionalities

James E. McCune, Kenneth Rubenstein

If rotating quasi equilibria in tori are to exist, it becomes important to understand their development in time during the discharge phase. This information is required both for the eventual control of such plasma devices and for a true understanding of the physical circumstances under which rotation in tori either develops or eventually dies out. In the Pfirsch-Schlüter regime, the concept of a multiple-time-scale history was successful in providing the essential features of the time development of such toroidal discharges. Recent Tokamak experimental results suggest strongly the occurrence of a similar series of events at lower (more practical) collisional rates. Various kinetic processes for the possible development of plasma rotation (or, equivalently, nonambipolar radial fields) have been put forward by various researchers in this field. Rotation can occur with or without beam injection. The current program is concerned with the analysis of the time history of ion and electron behavior during the possible development of the inertial equilibria described by Fisher. The study relies upon the time-dependent version of the drift-kinetic equation used there. Cases with and without injection can be studied in this model.

c. Drift Modes in Tori

James E. McCune, George M. Svolos

The study of the "slow" time development of inertial neoclassical equilibria which we have described is not designed to resolve instabilities or other natural oscillatory modes of such systems. As results from large Tokamak experiments (especially for those with beam injection) become available, however, an increasing need for improved understanding of drift-type instabilities in practical toroidal systems arises. The present study is focused on the analysis of drift modes in such systems. Since a straight cylinder (even with a helical field) is not a true natural limit of a Tokamak discharge, toroidal effects are included from the beginning. Insofar as the familiar model of localization of such modes on flux surfaces is a valid one, an assessment of the relative importance of such toroidal effects can be made relatively quickly. This, in turn, provides increased incentive for an improved understanding of the validity of the localization model. A systematic study of the cross-flux eigenvalue problem is under way as a central part of this research.

### d. Drift and Drift-Cyclotron Modes in Tandem Mirror Systems

James E. McCune, Daniel E. Hastings

A unique feature of the tandem mirror concept is its a priori goal of obtaining a high-beta plasma in the main confining region. This provides a challenging area for an improved understanding of plasma behavior for such devices. From the point of view of the system itself, there is a need to establish once more which instabilities, if any, can be expected to be important and what their physical effects are. The present program is, in that sense, exploratory. After appropriate assessment of the results, the most important of these is to be explored in detail; special emphasis is being placed on eventual nonlinear (or quasi-linear) effects on the tandem mirror system as a practical device.

## 3. RF HEATING AND MICROTURBULENCE

U. S. Department of Energy (Grant EG-77-G-01-4107)

Abraham Bers, George L. Johnston, Abhijit Sen, Gérard P. Leclert, Vladimir B. Krapchev, Charles F. F. Karney, Allan H. Reiman, John L. Kulp, Jr., Nathaniel J. Fisch, Miloslav S. Tekula, Kim S. Theilhaber, Bruce E. Edwards, Stavros M. Macrakis

During the past year we have continued our theoretical studies related to the supplementary heating of Tokamak plasmas, and the microturbulence due to the high-energy tail of the electron distribution function. Our interest has been to develop an understanding of all aspects of plasma heating in the lower hybrid range of frequencies (LHRF).

For parameters characteristic of Tokamak plasmas the LHRF falls in the microwave regime ($\Omega_i \ll \omega \sim \omega_{pi}$). In this regime large units of cw power ($10^6$ watt tubes) at high efficiencies (50-70%) are readily available. This power can be coupled to the plasma with phased arrays of waveguides at the plasma wall, and does not require any coupling structure inside the plasma wall. These uniquely advantageous characteristics of the LHRF have generated considerable interest in its use for supplementary heating of Tokamak plasmas. In the past two years, experiments at Princeton (ATC Tokamak) and Grenoble (WEGA Tokamak) have shown significant heating with power in the LHRF. Important experiments are now being planned on the M. I. T. Tokamaks (Alcator A and C and Versator II). Our work interacts with and impacts directly upon these and other experiments, and aims at an understanding of the scaling characteristics of heating in the LHRF. Our work has included studies of: (a) Linear and nonlinear aspects of coupling from phased arrays of waveguides at the plasma wall. (b) Nonlinear propagation of the excited fields in the plasma. (c) Heating mechanisms for the electrons

and ions in the plasma. Our studies of the high-energy tail of the electron distribution function are now becoming very relevant to understanding the details of electron mechanisms with RF power.

An important result of our recent work is a calculation that shows a new way in which RF power can be used to generate a significant current in the plasma. This offers the possibility of achieving a steady-state toroidal reactor driven by microwave power in the LHRF.

Journal and conferences publications, as well as conferences presentations, of our work in the past year are listed below.[1-33]

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## 4. NONLINEAR THEORY OF TRAPPED-PARTICLE INSTABILITIES

U. S. Department of Energy (Grant EG-77-G-01-4107)

Thomas H. Dupree, David J. Tetreault

The phenomenon of clumps is being studied in a plasma with a magnetic field. In particular, the effect of clumps on the drift and trapped particle mode instabilities is being studied. Clumps in the ion phase space density produce an enhanced ion viscosity which appears to be very effective in damping these modes and providing a nonlinear stabilization.

Concepts from strong plasma turbulence are being used to investigate magnetic islands in Tokamaks. Turbulent magnetic fluctuations induced by drift waves as well as those formed through self-consistent currents are being studied. The purpose is to determine how the resulting turbulent destruction of magnetic surfaces affects Tokamak plasma confinement.

Work is also beginning on computer simulations of the structure of clumps in plasma.

## 5. PLASMA CORRECTIONS TO THE BOHM DIFFUSION

U. S. Department of Energy (Grant EG-77-G-01-4107)

Claude Deutsch

The nodal expansion of equilibrium properties of two-component classical plasma in $2 + \epsilon$ dimensions ($0 \leq \epsilon \leq 1$) is used to investigate higher order corrections, with respect to the plasma parameter, of the transverse diffusion coefficient relevant to an arbitrarily strong and constant magnetic field. Only the short-range compact nodal graphs decaying faster than Debye contribute to the third and higher nonvanishing orders.

The usual fluid limit ($k \to 0$) procedure delivering the first-order Bohm result is shown to be consistent[1] for any dimension $2 \leq \gamma \leq 3$. These results obtained from the hydrodynamic derivation of transport (Taylor-McNamara) are now currently extended to include the microscopic derivation of transport based on conveniently renormalized kinetic equations, and also the standard Ichimaru-Rosenbluth derivation. In all three cases, the thermal spectra are rather similar, so the algebra of the nodal expansion works in the same way.

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## 6. STRONGLY COUPLED CLASSICAL PLASMAS FOR LASER FUSION

U. S. Department of Energy (Grant EG-77-G-01-4107)

Claude Deutsch

We have summarized[1] the most relevant results of the theory of strongly coupled classical plasmas which include: nodal expansions, numerical simulations, variational schemes, and integral equations for $g_r(r)$.

The applications to laser fusion and astrophysics have been emphasized. They include: lowering of the ion-ion coulomb barrier and establishing a lower bound for thermal transport in the partially degenerate electron component. They also relate to the exoenergetic behavior of Jupiter and other massive planets.

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## 7. EQUILIBRIUM PROPERTIES OF TWO-COMPONENT CLASSICAL PLASMAS

U. S. Department of Energy (Grant EG-77-G-01-4107)

Claude Deutsch

The overall two-component neutral classical coulomb gas is considered in the canonical ensemble for any value $\nu$ of the space dimension. The equilibrium properties, i. e., pair correlations and thermodynamic functions, are investigated in a two-complementary approximations approach. The first one is adequate in the low-temperature range and uses as a zero-order starting point the "molecular" approximation within a pair of unlike charges. On the other hand, the high-temperature fully ionized and translation-invariant plasma is considered within the nodal expansion with respect to the classical plasma parameter. This program is made possible through the use of effective temperature-dependent classical interactions for $\nu < 2$. As a by-product, we obtain a unified treatment of the coulomb gas thermal properties with respect to $\nu$, and also a contrasting comparison with the already known corresponding properties of the one-component plasma model. The $\nu = 2$ two-component coulomb gas appears as a landmark in this analysis. Degeneracy effects are neglected. Diffraction corrections are considered in a first-order expansion with respect to the interaction. A paper on this subject has been submitted for publication to Ann. Phys. (N. Y.).

## Research – Experimental

### 8. TOKAMAK RESEARCH

U. S. Department of Energy (Grant EG-77-G-01-4107)

George Bekefi, Miklos Porkolab

On May 1, 1977 a new device, the Versator II Tokamak, went on the air. It is a research device with a major radius of 40.5 cm and with a rectangular cross section of 30 × 30 cm. It contains 20 diagnostic portholes 5 cm wide and 28 cm long.

The machine is running reliably, with good equilibrium at a toroidal magnetic field not exceeding 8 kG. Typical discharge currents are 25-30 kA with current pulses lasting up to 16 ms.

An upgraded version of the Versator II device is under construction. Its principal purpose is to permit operation at 15 kG rather than at 8 kG. It is expected that the upgraded version will be in operation by January 1978.

The major purpose of the research to be carried out on the Versator II Tokamak is the study of various RF heating mechanisms. The first series of experiments to begin in February 1978 are concerned with RF heating at the lower hybrid frequency, which in our case occurs at approximately 800 MHz. Some 200 kW of RF power will be injected into the torus by means of a specially constructed 4-waveguide (grill) antenna. This work will be carried out in cooperation with the Princeton Plasma Physics Laboratory which is going to provide the requisite RF power and plumbing.

In the second series of experiments to begin in the Fall of 1978 microwave power will be injected into the torus at a frequency corresponding to the electron cyclotron frequency. For this purpose a novel gyrotron microwave generator is being developed by the Naval Research Laboratory. It will be capable of supplying approximately 200 kW of microwave radiation at a frequency of 35 GHz.

These RF heating studies will be accompanied by detailed plasma diagnostics including Thomson laser scattering measurements, neutral charge-exchange experiments, synchrotron radiation measurements, and RF fluctuation measurements.

### 9. EXPERIMENTAL MIRROR STUDIES

U. S. Department of Energy (Grant EG-77-G-01-4107)

Louis D. Smullin, Robert E. Klinkowstein, Michael E. Mauel

The purpose of this study is to investigate the stabilization of DCLC (drift-cyclotron loss-cone) instabilities by hot electrons. Last year (1977), in the apparatus described in Progress Report No. 119, January 1977 (p. 83), we demonstrated the stabilization of the DCLC by the action of an axially injected electron beam (~50 kW). The stabilization

is believed to be due to the trapped hot electrons produced by the beam-plasma instability.

During this year (1978) we plan to continue our detailed studies of this stabilizing mechanism. We have proposed the construction of a somewhat larger mirror system to the Department of Energy. This would permit the direct comparison of stabilization by electron beam-plasma interaction, and ECRH (electron cyclotron resonance heating) used by Joffe' in the USSR.

## 10. NEUTRAL BEAM STUDIES

U. S. Department of Energy (Grant EG-77-G-01-4107)

Louis D. Smullin, Peter T. Kenyon, Barry N. Breen

We have essentially completed the work on our "Magarc" high-current positive ion source, and are shifting our attention to the problem of generating high-current, high-voltage negative ion ($H^-$ or $D^-$) beams for ultimate transformation to neutral beams.

The Magarc source has achieved the following results: Collected positive ion current = 200 amps, arc power = 40 kW, cathode heater power = 150 W, gas pressure ≈ 2 mT. Beam-line tests are scheduled to be made in January 1978 at the Oak Ridge National Laboratory.

## Fusion Technology Studies

### 11. THE FUSION TECHNOLOGY PROGRAM

U. S. Department of Energy (Grant EG-77-G-01-4107)

Lawrence M. Lidsky

The Fusion Technology Program is an interdepartmental effort supported by the Development and Technology branch of the Division of Magnetic Fusion Engineering. The program's goal is to investigate various engineering problems of controlled fusion reactors with particular emphasis this year on reactor fueling, reactor blanket analysis, safety and environmental studies, and "new concepts development." The program is centered in the Department of Nuclear Engineering, M. I. T., but a substantial portion of the work is carried out under the auspices of the Research Laboratory of Electronics. In addition to the work order on pellet fueling the following tasks were completed:

a. The consequence code for the Wash-1400 Fission Reactor Safety Study was modified to include the appropriate isotopes for fusion reactor applications.
b. A numerical model of lithium spill phenomena was developed.
c. A methodology was developed for generic analysis of fusion reactor blanket design and applied to the case of a gas-cooled solid breeder design for operation with isolated failed modules.
d. The effect of fuel cycle costs on hybrid and symbiotic fissile breeders was analyzed and used to guide the design of an optimized 233 U breeding hybrid blanket.
e. A system cost analysis of a commercial EBT reactor was completed and conjoined with a similar study performed at ORNL.
f. A liquid-metal flow loop was constructed and used to measure the effect on right-angle bends on MHD pressure drops with interaction parameters in the proposed reactor regime.

We are currently engaged in:

a. The establishment of design windows for lithium-cooled fusion reactor blankets;
b. Continued development of the methodology required for safety and environmental analysis of proposed fusion power plants and generation of the physical models needed for this analysis;
c. A large-scale study of the economic and technical feasibility of the stellarator-torsatron confinement geometry as the basis of a steady-state commercial reactor.

The torsatron reactor design study is being carried out in close collaboration with the University of Wisconsin group directed by Professor J. L. Shohet. We have completed

the preliminary design of a large-scale torsatron experiment suitable for construction at the National Magnet Laboratory in the near future. A full-scale design program has been proposed to the U. S. Department of Energy and presumably will be initiated in the near future.

## 12. PELLET FUELING OF FUSION REACTORS

U.S. Department of Energy (Grant EG-77-G-01-4107)

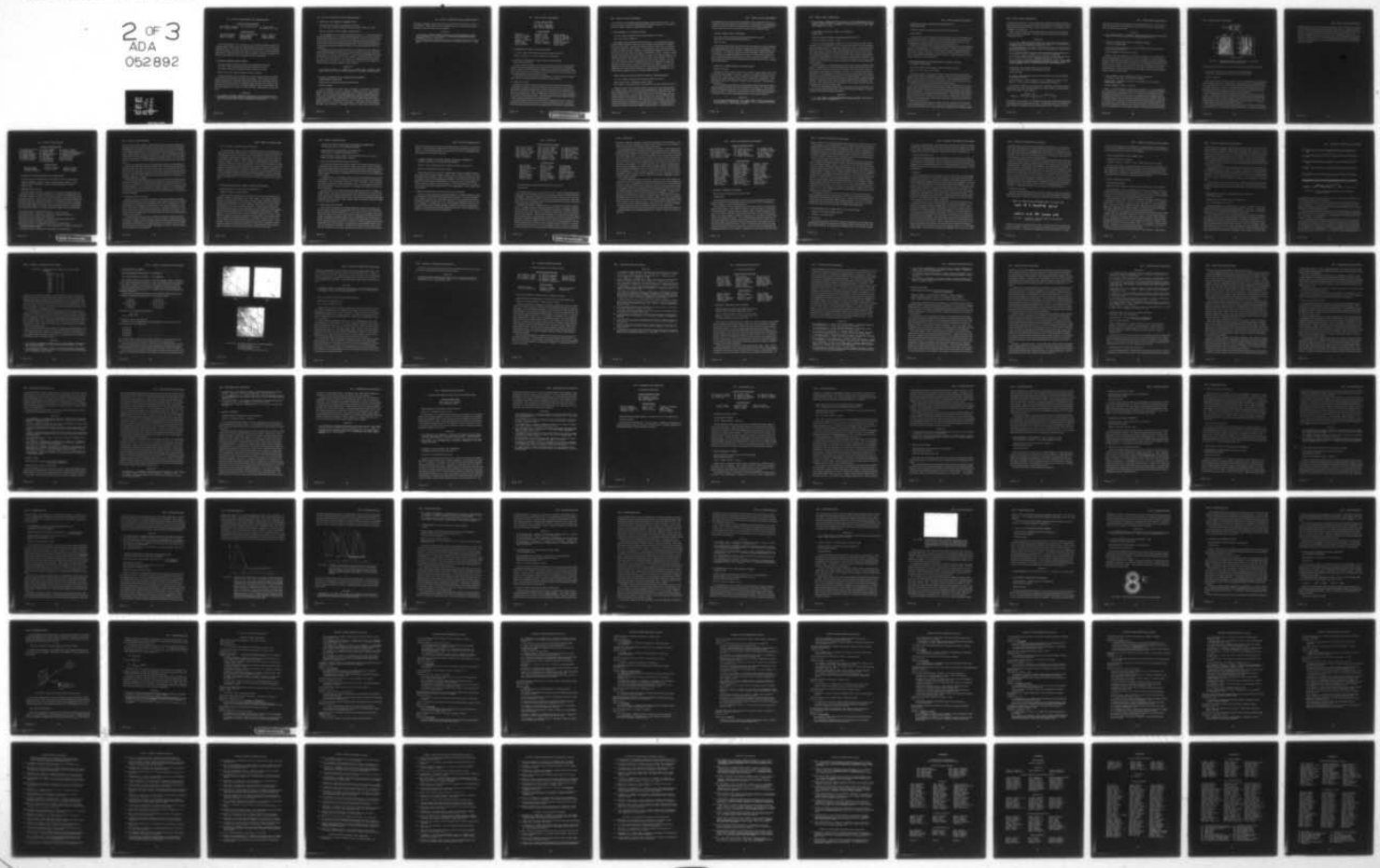
Peter A. Politzer, Mark L. McKinstry, Clarence E. Thomas

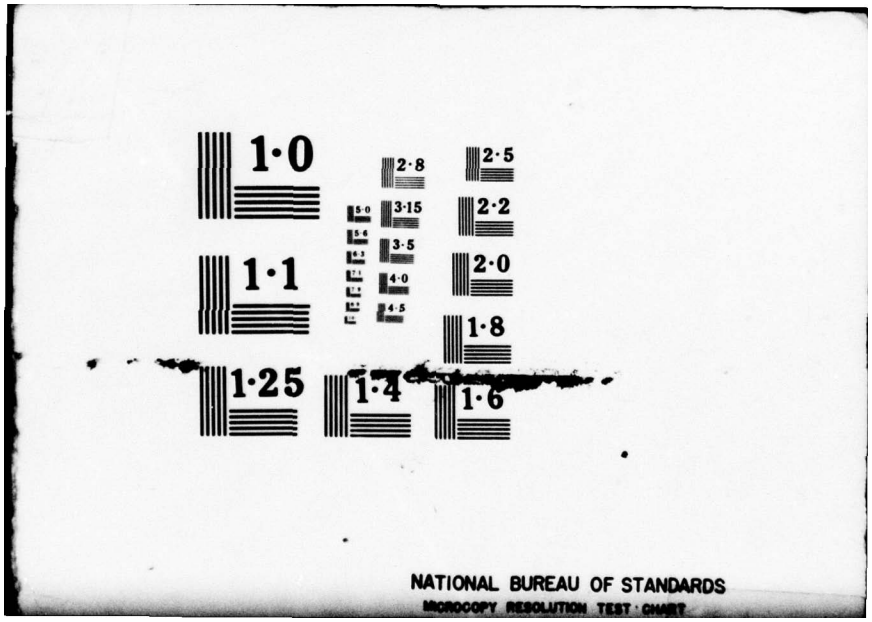
In order to operate a quasi-steady-state fusion reactor, a source of deuterium and tritium fuel must be provided that is distributed throughout the reactor plasma cross section. The most promising scheme for introducing this fuel is the injection into the plasma of solid D-T pellets at high velocity. In order to determine the velocity required, we need to know the ablation rate of a solid D-T surface in the presence of a hot, dense plasma. We are approaching this problem in a number of ways. We have constructed a Z-pinch discharge facility which can sustain reactorlike conditions of plasma energy density and flux for several microseconds. We are now diagnosing this plasma in order to determine the appropriate operating regime. We plan next to insert solid pellets into this plasma in order to obtain an experimental measure of ablation rates under reactor-like conditions. In addition, we have undertaken a cooperative experiment with the Oak Ridge National Laboratory to measure the ablation rates of pellets injected into the ISX Tokamak. We are designing a holographic and spectroscopic diagnostic system for this experiment. Our third effort has been to develop an analytic model for the ablation process and, particularly, for the self-shielding mechanisms involved. The dominant shielding process under reactor conditions is the exclusion of the magnetic field from the region surrounding the pellet by the high-pressure blow-off plasma cloud. A computer code has been written to model this effect and we find significant reduction of the ablation rate and, consequently, of the pellet-injection velocity required.

# COMMUNICATION SCIENCES
# AND
# ENGINEERING

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# XX. OPTICAL PROPAGATION AND COMMUNICATION

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Prof. Cardinal Warde
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The broad objectives of our program are to (i) formulate propagation models for important optical channels from the underlying physical processes, (ii) determine the fundamental limits on detection and communication performance that can be realized with these channels, (iii) develop techniques for optical detection and communication which achieve or approach these limits, and (iv) establish, by means of experiment, the validity of the theoretical results and guide their further development.

## 1. QUANTUM COMMUNICATION THEORY

National Aeronautics and Space Administration (Grant NGL 22-009-013)
U.S. Navy – Office of Naval Research (Contract N00014-76-C-0605)
Joint Services Electronics Program (Contract DAAB07-76-C-1400)

Horace P. H. Yuen, Jeffrey H. Shapiro, Robert S. Kennedy

The long-range goal of this investigation is to realize improved optical communication, detection, and estimation in the space environment. Such improvement may be possible through the use of quantum measurements (optical receivers) that are superior to those now considered and the use of quantum states other than coherent states.[1] Our major goal during the next year is to design an experiment which will demonstrate that the desired quantum states, which are called two-photon coherent states, can be produced.

### References

1. R. S. Kennedy, "Problems in Quantum Communication and Information Theory," presented at the 1975 IEEE-USSR Joint Workshop on Information Theory, Moscow, 1975 (Proceedings published by IEEE, 75CH1167-61T), pp. 105-110.

## 2. IMPROVED LOW-VISIBILITY COMMUNICATION

National Science Foundation (Grant ENG74-00131-A03)
U.S. Air Force – Electronic Systems Division (Contract F19628-76-C-0054)

Robert S. Kennedy, Jeffrey H. Shapiro, Cardinal Warde

This investigation, which is carried out jointly with the M.I.T. Center for Materials Science and Engineering, is concerned with the performance of terrestrial line-of-sight communication systems under conditions of low visibility. Our aim is to determine the extent to which performance can be improved through appropriate system design, and to develop the devices for achieving this improvement. The potential for improvement resides in the energy and information contained in the scattered component of the received field.

The collection of data to establish the frequency, variability, and the regularity of the key channel parameters has been a major concern during the past year. Measurements taken on a 13-km line-of-sight path at 0.69 μm and 2 μm wavelengths have shown little dispersion of the field, either in time or angle, for optical thicknesses as large as ten. Up to that optical thickness, the results are well approximated by the predicted unscattered field.[1] Recently we have installed new 1.06 μm and 0.54 μm lasers with which we expect to be able to operate at lower visibilities.

### References

1. W. H. Paik, M. Tebyani, D. J. Epstein, R. S. Kennedy, and J. H. Shapiro, "Propagation Experiments in Low-Visibility Atmospheres" (to appear in Applied Optics).

## 3. OPTICAL PROPAGATION AND COMMUNICATION THROUGH ATMOSPHERIC TURBULENCE

National Science Foundation (Grant ENG74-03996-A01)

Jeffrey H. Shapiro

In this investigation, we have sought to quantify the performance limitations imposed by atmospheric turbulence on specific imaging and optical communication systems, and to develop system configurations that are immune to atmospheric fluctuations. Our work in previous years has established a rigorous analytical framework for parametric performance comparisons among various imaging and communication system alternatives.[1] During the past year, we have focused our attention on channel/signal estimation structures and their performance. In particular, we have examined the design and performance of focal-plane detection arrays using a state-variable

atmospheric propagation model that includes both drift and evolution terms in its temporal behavior. These results, which will appear in Marcel F. Coderch's S.M. thesis,[2] comprise the final work done under this program.

References

1. J. H. Shapiro, "Imaging and Optical Communication through Atmospheric Turbulence" (to appear in J. W. Strohbehn (Ed.), Laser Beam Propagation through the Atmosphere, Springer Verlag, Berlin).

2. M. F. Coderch, "Focal Plane Optical Detection for Turbulent Channels," S.M. thesis proposal, Department of Electrical Engineering and Computer Science, M.I.T., May 1977.

# XXI. DIGITAL SIGNAL PROCESSING

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Syed H. Nawab
Robert W. Patterson
Michael R. Portnoff
Thomas F. Quatieri, Jr.
Antonio Ruiz
Kenneth B. Theriault
José M. Tribolet
Pirooz Vatan

## 1. HOMOMORPHIC SPEECH ANALYSIS-SYNTHESIS

U. S. Navy – Office of Naval Research (Contract N00014-75-C-0951)

Thomas F. Quatieri, Jr., Alan V. Oppenheim, Antonio Ruiz

### a. Simulation of a Homomorphic Vocoder Based on Charged Coupled Device (CCD) Technology

We have completed simulations of various speech analysis-synthesis configurations based on both the conventional chirp-z-transform (CZT) realization of the discrete Fourier transform and the sliding CZT realization of the discrete sliding Fourier transform. These realizations are amenable to CCD technology and allow for real-time, low-cost implementation of the homomorphic vocoder.

A comparative study was performed, illustrating the tradeoffs between synthetic speech quality and implementational complexity for the two schemes.

### b. Quality Improvement

Techniques for synthetic speech quality improvement were tested and evaluated in collaboration with studies of the Speech Group at Lincoln Laboratory. Issues such as interpolation, amplitude measurements, buzziness, hoarseness, and coding were explored. For male speech, formal listening tests indicate that for low bit rates (2400 to 3600 bps) the homomorphic system is comparable in quality to more established schemes such as LPC and the channel vocoder. For high bit rates (8000 to 9600 bps), the homomorphic system was judged to have the highest quality.

The female synthetic speech, on the other hand, unlike that of the male, tends in general to be degraded by a "hoarseness." We are investigating ways of rigorously characterizing this degradation and are exploring adaptive techniques for improvement.



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We shall soon be completing a pitch-synchronous complex cepstral vocoder. This scheme, we hope, will yield an understanding of the effects of phase of the estimated vocal tract impulse response on synthetic speech quality.

## 2. ENHANCEMENT OF DEGRADED SPEECH

U. S. Navy – Office of Naval Research (Contract N00014-75-C-0951)

Jae S. Lim, Alan V. Oppenheim

Continuing our work on enhancing degraded speech, we have attempted to develop a complete analysis/synthesis system in which the synthesis parameters are estimated from noisy speech data. The particular analysis/synthesis system we have considered is based on an all-pole model of speech. Our approach has been to apply a Maximum A Posteriori (MAP) estimation procedure in estimating the coefficient vector of an all-pole system from noisy speech accounting for the presence of noise. In general, a MAP estimation procedure for noisy speech leads to solving a set of nonlinear equations. Two suboptimal procedures which require solving only sets of linear equations have, however, been developed. These methods have been applied to both synthetic and real speech data with white Gaussian background noise, and our preliminary listening test indicates that both systems are capable of significant noise reduction. We are now engaged in a more formal subjective test which is directed toward evaluating the two linear systems in terms of their performance in enhancing speech intelligibility and quality when the background noise is of various different spectra.

## 3. TIME-VARYING LINEAR PREDICTIVE CODING OF SPEECH SIGNALS

U. S. Navy – Office of Naval Research (Contract N00014-75-C-0951)

Mark G. Hall, Alan V. Oppenheim, Alan S. Willsky
[Prof. Willsky is Assistant Director of the Electronic Systems Laboratory, M. I. T.]

During this year we have completed a project involved with time-varying predictive coding of speech. The project involved a generalization of linear prediction using time-varying coefficients. By representing each time-varying coefficient, either in terms of a power series, or in terms of a Fourier series, a set of equations to determine the coefficients was obtained. These coefficients are reminiscent of those in the time-invariant case in that they are block-symmetric or block-Toeplitz. The basic problem can either be formulated in a covariance form or in a correlation form and the relative characteristics of these two approaches were explored. Through a study of a number of synthetic examples and examples using real data, we concluded that the

covariance form with a power series representation for the coefficients was the most preferable and that this approach has the potential for representing a long nonstationary segment of speech with fewer total coefficients than would be required through the use of time-invariant LPC in which an analysis window is moved through the data.

## 4. DIGITAL SEISMIC SIGNAL PROCESSING

U. S. Navy – Office of Naval Research (Contract N00014-75-C-0951)
National Science Foundation (Grant ENG76-24117)

David B. Harris

A seismic surveying technique called wave equation migration is being investigated for possible applications of two-dimensional digital signal processing algorithms. The key component of the migration algorithm is a difference equation approximation to the wave equation. This difference equation is used to extrapolate a wave field recorded on the boundary of a region backwards into the region. An ideal transfer function for the two-dimensional difference equation can be derived from the wave equation. Currently, methods are being sought to approximate this transfer function which is all-pass with a specified phase.

## 5. TIME SCALE MODIFICATIONS OF SPEECH SIGNALS

Michael R. Portnoff

The objective of our research in this area is to modify a speech signal in such a manner that the resulting signal is perceived as identical to the original except for its rate of articulation. In particular, we seek to preserve such qualities as naturalness, intelligibility, and speaker-dependent features, while avoiding the introduction of such objectionable artifacts as "glitches," "burbles," and reverberation often present in vocoded speech.

We have developed and demonstrated a high-quality system for time-scale compression and expansion of speech based on short-time Fourier analysis.[1,2] This system is capable of compressing speech by ratios as large as 3:1 and expanding speech by arbitrarily large ratios. Furthermore, the performance of this system does not appear to be sensitive to the presence of broadband noise in the speech source material.

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1. M. R. Portnoff, "Implementation of the Digital Phase Vocoder Using the Fast Fourier Transform," IEEE Trans. on Acoustics, Speech and Signal Processing, Vol. ASSP-24, No. 3, pp. 245-248, June 1976.

2. M. R. Portnoff, "A Mathematical Framework for Time-Scale Modification of Speech Signals," Ninety-third Meeting, Acoustical Society of America, State College, Pennsylvania, June 7-10, 1977. (Abstract in J. Acoust. Soc. Am., Vol. 61, Suppl. No. 1, Spring 1977, p. S68.)

## 6. ALGORITHMS FOR HIGHLY PARALLEL COMPUTER STRUCTURES

National Aeronautics and Space Administration (Grant NSG-5157)

James H. McClellan, David C. LeDoux

In order to process photographic images from Earth observation satellites rapidly, computers with a very high degree of parallel processing capability are being designed. One such machine[1] would be composed of a minimum of 16, 384 very simple processors arranged in a 128 × 128 array. Each processing element contains a bit-serial adder with a small amount of memory and is able to transfer data, one bit at a time, to any of its four nearest neighbors. A central control unit issues an instruction to the entire array and the individual processors decide whether or not to execute it, depending on a mask bit in each processor. In use, each processor operates on one pixel in a sampled photo and the parallel processing allows great time savings over more traditional serial computers.

A frequent operation in satellite image processing is that of image registration which involves computing the cross-correlation between two images of the same scene. Correlations may be computed indirectly and sometimes more efficiently by using two-dimensional transforms such as the Fourier transform or the Fermat number transform (FNT). The computation of the FNT does not involve multiplications or complex numbers, and is well suited to the simplicity of the small processors. We have investigated the use of the FNT to perform correlation on a highly parallel computer developed by NASA. Programs have been writen and timing estimates have been obtained. The FNT can be more efficient than direct computation of the correlation (on this machine), depending on the sizes of the images used.

We are now investigating the applicability of the parallel computer structure to several new image restoration algorithms, particularly those which attempt to correct for the effects of the Earth's turbulent atmosphere.

### References

1. L. W. Fung, MPPC: A Massively Parallel Processing Computer, NASA Goddard Space Flight Center, September 1976.

## 7. WINOGRAD FOURIER TRANSFORM ALGORITHM (WFTA) IMPLEMENTATION

National Aeronautics and Space Administration (Grant NSG-5157)

Syed H. Nawab

This research is concerned with some implementation issues for the Winograd Fourier Transform Algorithm. Although this DFT computation algorithm has fewer multiplies than the FFT, speed comparisons between these algorithms requires a further investigation of computation structures used in the implementations.

Attention has been focused on two-address general register machines and computation structures with parallelism. For the register machines, a register allocation study has been carried out to determine the relationship between algorithm speed and execution times for the machine instructions. In the parallelism study, existing FFT structures have been generalized to yield WFTA parallel structures. Speed comparisons for these parallel structures are now being made.

## 8. IMPLEMENTATION OF MULTIDIMENSIONAL DISCRETE SYSTEMS FOR SIGNAL PROCESSING

Joint Services Electronics Program (Contract DAAB07-76-C-1400)

David S. K. Chan, James H. McClellan

This research seeks to develop understanding of the implementation of multidimensional discrete systems by studying the properties of these systems and developing techniques for the synthesis of efficient implementations. Such understanding will lead to more systematic methods of analysis and synthesis of these systems and better utilization of modern resources for multidimensional signal processing.

Our research has established a framework for studying the implementation of a very general class of multidimensional discrete systems, called oriented discrete systems,[1] which is much broader than the class of first-quadrant causal systems that have generally been considered. It constitutes the practical, rather than analytical, generalization of one-dimensional causal systems to multidimensions. We have shown that, by broadening our perspective to include this class of systems, realizations having smaller dimension and requiring less overall memory than under first-quadrant causality can be obtained in certain cases.[1]

Our research has also dealt with structures for the realization of linear shift-invariant multidimensional systems, not only in the first-quadrant causal case,[2,3] but also in the more general case. Using a framework we developed for the characterization

of realization structures,[4,5] we have extended the technique of continuously equivalent analog networks to the minimization of coefficient sensitivity and roundoff noise in multidimensional digital networks under structure transformation. The refinement of these techniques is now under way.

Finally, we have looked into block implementations of multidimensional systems using fast convolution algorithms, and implementation using simple interconnections of multiple processors.

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1. D. S. K. Chan, "Multidimensional Oriented Discrete Systems – Characterization and Realization," Eleventh Annual Asilomar Conference on Circuits, Systems, and Computers, Monterey, California, November 7-9, 1977.
2. J. H. McClellan and D. S. K. Chan, "A 2-D FIR Filter Structure Derived from the Chebyshev Recursion," IEEE Trans. on Circuits and Systems, Vol. CAS-24, No. 7, pp. 372-378, July 1977.
3. D. S. K. Chan, "A Simple Derivation of Minimal and Near-Minimal Realization of 2-D Transfer Functions," to appear in Proc. IEEE (Correspondence).
4. D. S. K. Chan, "A Novel Framework for the Description of Realization Structures for 1-D and 2-D Digital Filters," EASCON '76 Record, pp. 157-A-157-H.
5. D. S. K. Chan, "A Unified Framework for the Realization Problem in Linear Digital Filtering," Record of the 1977 International Conference on Acoustics, Speech, and Signal Processing, Hartford, Connecticut, May 9-11, 1977, pp. 543-547.

## 9. ALGORITHM FOR COMPUTATION OF THE ACOUSTIC PLANE-WAVE REFLECTION COEFFICIENT OF THE OCEAN BOTTOM

U.S. Navy – Office of Naval Research (Contract N00014-77-C-0196), Woods Hole Oceanographic Institution

David R. Martinez, Arthur B. Baggeroer, Alan V. Oppenheim, George V. Frisk
[George V. Frisk is with the Woods Hole Oceanographic Institution.]

For a spherical acoustic wave incident on the ocean bottom, the reflected pressure field and the plane-wave reflection coefficient are related through a two-dimensional spatial-wave number Fourier transform.

$$R(k_x, k_y) = -\frac{i\beta\, e^{-i\beta_1(z+z_o)}}{2\pi} \iint_{-\infty}^{\infty} \Phi_n(x, y, z)\, e^{-i[k_x x + k_y y]}\, dxdy.$$

The objective of this project is to calculate the plane-wave reflection coefficient R(k) from samples of the reflected pressure field. An algorithm based on the "projection-slice" theorem[1] associated with the two-dimensional Fourier transform has been

implemented on an HP 2100 at Woods Hole Oceanographic Institution. We have investigated the effectiveness of the algorithm for the perfectly reflecting hard bottom R(k) = 1, and it has yielded accurate results.

References

1. R. M. Mersereau and A. V. Oppenheim, "Digital Reconstruction of Multidimensional Signals from Their Projections," Proc. IEEE 62, 1319-1338 (1974).

## 10. ACCURACY BOUNDS FOR NORMAL INCIDENCE ACOUSTIC STRUCTURE ESTIMATION

U.S. Navy – Office of Naval Research (Contract N00014-75-C-0852), Department of Ocean Engineering, M.I.T.

Arthur B. Baggeroer, Kenneth B. Theriault

Kenneth B. Theriault submitted a doctoral thesis in August, 1977 in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Electrical Engineering and Computer Science, M.I.T., and the Woods Hole Oceanographic Institution. The thesis analyzed how accurately one can estimate acoustic structure with signals at normal incidence in the presence of noise. Several specific models and acoustic structures were analyzed which indicated the effects of reverberation and source energy distribution. Results indicate that very high signal-to-noise ratios (>40 dB) are required to obtain accurate results.

## 11. DATA ADAPTIVE VELOCITY/DEPTH SPECTRA ESTIMATION IN SEISMIC WIDE-ANGLE REFLECTION ANALYSIS

National Science Foundation subcontract to Grant GX 41962 to Woods Hole Oceanographic Institution

Arthur B. Baggeroer, Steven J. Leverette

Steven J. Leverette submitted a doctoral thesis in August, 1977 in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Electrical Engineering and Computer Science, M.I.T., awarded jointly with the Woods Hole Oceanographic Institution. His thesis dealt with the application of the Maximum Likelihood Method (MLM) of spectral analysis to estimating the velocity structure of the earth in wide-angle seismic reflection. The effects of the data windowing and the statistics of the estimator for a small number of observations were studied. The algorithm was applied to both simulated and field data, which demonstrated the superiority of the method over more conventional ones. Figure XXI-1 indicates a comparison of spectra estimated

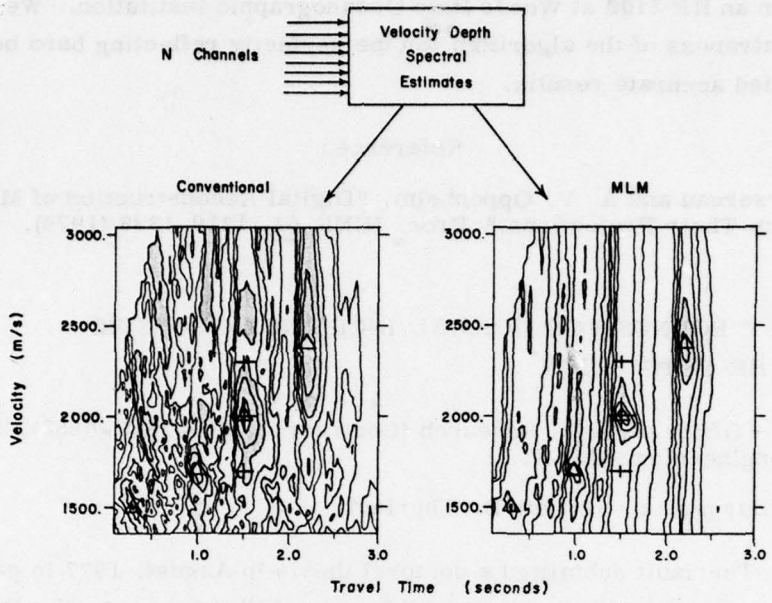



Fig. XXI-1. Comparison of velocity depth spectra for conventional and maximum-likelihood processing.

by using a conventional coherence criterion with spectra using the MLM algorithm.

## 12. A LINEAR PREDICTIVE APPROACH TO TWO-DIMENSIONAL SPECTRAL FACTORIZATION AND SPECTRAL ESTIMATION

Thomas L. Marzetta

Some recent results in the theory of time-series linear prediction have been extended to the two-dimensional case. In particular, an equivalence has been established among three separate domains: a class of two-dimensional analytic and positive-definite autocorrelation sequences, the class of two-dimensional minimum-phase prediction error filters and positive prediction error variances, and a class of two-dimensional reflection coefficient sequences and positive prediction error variances.

The two-dimensional reflection coefficient representation is the basis of a new approach to two-dimensional spectral factorization and autoregressive model fitting in which the prediction error filter is designed in the reflection coefficient domain. By constraining the reflection coefficient magnitudes to be less than one, the difficult minimum-phase requirement is automatically satisfied.

The remaining practical question concerns how to choose the reflection coefficients in an "optimal" way. For the spectral factorization problem a convenient (but generally

suboptimal) method involves sequentially choosing the reflection coefficients to minimize the mean-square prediction error at each stage of the procedure. A program has been written to implement this algorithm and has been tested for two examples. In the first example, the spectrum was relatively smooth, and the algorithm performed well. In the second example, the spectrum was discontinuous, and the performance of the algorithm was less satisfactory. It is believed that the full potential of this new approach can only be realized by using a more sophisticated gradient algorithm for choosing the reflection coefficients.

# XXII. SPEECH COMMUNICATION

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## 1. STUDIES OF SPEECH PRODUCTION AND PERCEPTION

National Institutes of Health (Grants 5 RO1 NS04332-15 and 5 T32 NS07040-03)

Sheila E. Blumstein, Marcia A. Bush, Bertrand Delgutte, William L. Henke, Dennis H. Klatt, Colin Painter, Joseph S. Perkell, Kenneth N. Stevens, Victor W. Zue

### a. Segmental Aspects of Speech

One of our research objectives continues to be to develop a theoretical basis for the phonetic categories or features that appear to be universal in language and to begin to delineate in detail the inventory of these phonetic features and their articulatory and perceptual correlates. During the past year, we have been concerned particularly with the features that describe place of articulation for consonants and vowels, and the features that specify tonal contrasts for vowels. Our recent work with the consonants has been acoustic analyses of a number of stop and nasal consonants in syllable-initial and syllable-final positions. Our data have provided support for earlier observations

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that short-time spectra sampled at consonantal release have invariant properties that distinguish fairly reliably between labial, alveolar, and velar places of articulation independent of vowel context or voicing and nasality characteristics of the consonant. These findings suggest that the auditory system is somehow predisposed to classify auditory inputs in terms of these acoustic properties. These observations have indicated that further research is needed to describe how auditory signals with these characteristics are processed in peripheral stages of the auditory system, and work along these lines is in progress, using the techniques of both psychophysics and electrophysiology.

We have been exploring various ways of describing articulatory configurations for vowels, the objective being to determine whether there are procedures for specifying articulatory states for vowels that are related in some simple, quantal fashion to the vowel features. In particular, we have been attempting, through palatography and radiography, to determine whether patterns of contact on the tongue or on the palate for the production of different vowels might provide an invariant articulatory specification of the features high, low, and back.

Research on the laryngeal features has in the past year been directed toward establishing a perceptual basis for the fundamental-frequency ($F_0$) contour shapes that are observed in tone languages. Through acoustic analyses of contour shapes that are used in different languages, and through experiments that examine listener responses to contour shapes that are varied systematically in synthetic syllables, we are attempting to determine how the predispositions of the auditory system constrain the $F_0$ contours that are used in language.

b. Physiology of Speech Production

Progress has been made toward establishing a capability to perform experiments in which cineradiographic and electromyographic data on speech production are obtained simultaneously. Data from these experiments will be used in conjunction with a model of the tongue for the exploration of the properties of the tongue musculature as they influence articulatory configurations and movements. Preliminary EMG records have been obtained, and methods of reducing radiographic dosage have been explored. Our computer facility is being updated to provide an interactive multichannel (physiological) data processing capability.

An experiment has been performed in collaboration with Dr. Thomas Gay (of the University of Connecticut Health Sciences Center and Haskins Laboratories) on the short-latency feedback effects of unexpected reductions in intraoral air pressure during the production of bilabial stops. In apparent conflict with a previous result, no short-latency changes in the timing of laryngeal EMG signals were found. We plan to repeat this experiment in our own laboratory.

c. Word-, Phrase-, and Sentence-Level Phenomena

The speech signal contains acoustical manifestations not only of segments and features but also of larger syntactic units. A complete theory of the speech production and perception process must account for these acoustical influences that are the result of concatenation of segments into words, phrases, and sentences. Our work in this area has included studies of speech timing in sentences, characterization of fundamental-frequency contours in sentences, and the study of certain phonological phenomena that occur when syllables and words are concatenated. This research is leading to the implementation of a model of sentence production that includes a phonological component (providing a transformation from an abstract representation in terms of segments and features, syntactic marking, and semantic information, to a detailed phonetic and prosodic representation) and a phonetic-to-acoustic transformation. Plans for improving the model include systematic evaluations of the intelligibility and naturalness of the output, and modification of the rules in areas where these evaluations show deficiencies.

## 2. SYNTACTIC-TO-PHONETIC CODING IN SPEECH PRODUCTION

National Institutes of Health (Grant 5 RO1 NS13028-02)

William E. Cooper, John M. Sorensen

A model of speech production has been designed to describe the translation from a speaker's syntactic representation to a phonetic output. The model is designed to account for such phenomena as (a) clause- and phrase-final lengthening, (b) optional pausing at the beginning and end of main clauses, (c) blocking of cross-word phonetic conditioning at the boundaries of major constituents, and (d) fall-rise contours of fundamental frequency at major constituent boundaries. Formal linguistic studies have been conducted to develop rules for syntactically determined pausing, and experimental studies have been conducted on each of the four phenomena mentioned above. Taken together, the experimental studies provide substantial support for the notion that a speaker's syntactic code exerts a systematic and direct influence on the phonetic properties of duration and fundamental frequency. In addition, the results of such work have permitted new inferences about the precise form of the speaker's syntactic representation. By using a controlled experimental technique which is applicable to direct hypothesis-testing, we have been able to obtain more information about the speaker's syntactic code than has previously been possible on the basis of other data.

## 3. STUDIES OF SPEECH PRODUCTION AND SPEECH DISCRIMINATION BY CHILDREN AND BY THE HEARING-IMPAIRED

National Institutes of Health (Grant 5 T32 NS07040-03)
National Science Foundation (Grant BNS76-80278)

Jared Bernstein, Marcia A. Bush, Ursula G. Goldstein, Howard L. Golub, William L. Henke, Margaret Kahn, Lise Menn

### a. Speech and Sound Production by Infants and Children

A review of the literature has led to descriptions of the anatomical growth of the various parts of the vocal tract of children. Based on these data, a static vocal-tract model representing various levels of anatomical development is being implemented. This model will be used to explore the phonetic capabilities of children and the relationship between children's articulatory configurations for different vowels and the configurations used by adults.

In another project, we are applying modern signal-processing techniques to an analysis of infant cries, with a view toward developing improved methods of classifying the attributes of cries and individual differences in these attributes. We have obtained recordings of cries from a number of newborns, and we are collecting data on the temporal characteristics, formant frequencies, and fundamental-frequency contours for these vocalizations.

In another study, we have been gathering and analyzing speech from recordings of a number of two-to-five year olds in conversation with their parents in a structured laboratory setting. These data are being used to uncover certain principles governing the use of pitch contours in parent-child discourse, particularly the semantically-determined conditions under which the pitch range remains similar or undergoes significant changes from one clause to the next.

### b. Speech Production by the Deaf

This research is concerned with identifying differences between the speech of the deaf and normal speech while attempting to isolate the causes of these differences. Speech timing and segmental patterns of a small number of deaf children have been described in detail, and one child's speech has been modeled and manipulated so that the relative contributions of different speech errors to intelligibility can be measured. An analysis of syllable and word concatenation among a larger population of deaf children during reading and spontaneous speech is being started. Another ongoing project involves transcription and acoustic analysis of segmental and suprasegmental aspects of the speech of adventitiously deaf adults. The data from this group of adults seems to indicate that, following the onset of post-lingual profound deafness, those aspects of speech

which can be monitored by rich afferent information may be less likely to deteriorate. Finally, a refined computer program has been developed for marking fundamental pitch periods. We hope that this program will be useful in the analysis of pathological phonation qualities in both children and adults.

## 4. ACOUSTIC STUDIES OF SPEECH SOUNDS: INVARIANT ATTRIBUTES, CONTEXT EFFECTS, AND SPEAKER DIFFERENCES

William L. Henke, Martha Laferriere, Kenneth N. Stevens, Victor W. Zue

### a. Study of the Phonological Processes in English

The goal of this work is to provide, through acoustic studies, quantitative information on the variations of the properties of speech sounds in context. Whenever the variations appear to be systematic, either for all speakers or a subset of the speakers, rules are proposed to describe such phonological variations. Over the past year we have completed a study of the acoustic characteristics of medial [t, d], and we have initiated a study of the acoustic effect of vowel nasalization. In the forthcoming year, we expect to move on to other phonological processes, such as palatalization, vowel reduction, and schwa deletion.

### b. Statistics of Fundamental-Frequency ($F_0$) Contours in Sentences

We have been collecting long-term statistical data on $F_0$ contours produced by a number of speakers during reading and during spontaneous speech. Three kinds of analysis of the contours are under way, representing successively more sophisticated attempts to uncover the underlying differences in the control of $F_0$ by different speakers: (i) long-term distribution of fundamental periods; (ii) statistical properties describing an "average" breath group (a breath group being a segment of an utterance produced without pauses, and separated from adjacent segments by pauses); and (iii) statistical properties of each of several classes of breath groups.

# XXIII. LINGUISTICS

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National Institute of Mental Health (Grant 5 PO1 MH13390-11)

Morris Halle

The ultimate objective of our research is to gain a better understanding of man's mental capacities by studying the ways in which these capacities manifest themselves in language. Language is a particularly promising avenue because, on the one hand, it is an intellectual achievement that is accessible to all normal humans and, on the other hand, we have more detailed knowledge about language than about any other human activity involving man's mental capacities.

Scientific descriptions of languages have for a very long time followed a standard format. A number of topics are almost invariably discussed; for example, pronunciation, the inflection of words, word formation, the expression of syntactic relations, word order, and so forth. Moreover, the manner in which these have been treated has also been quite standard. While traditional grammars have many shortcomings, their great practical utility is beyond question; generations of students have acquired adequate command of innumerable languages with the help of grammars of the standard type. A plausible inference that might be drawn from this fact is that languages are somehow not very different from one another and the traditional standard format has succeeded in capturing essential aspects of what all languages share in common. Accordingly, much of the research of our group has been devoted to studying the common framework



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that underlies different languages, the general principles that are exemplified in the grammar of different languages. Results strongly indicate that this assumption is indeed correct as far as the linguistic evidence is concerned.

The preceding discussion leads quite naturally to the question, "What evidence from outside of linguistics might one adduce in favor of the hypothesis that all languages are constructed in accordance with a single plan, a single framework?" It seems to us that the most striking evidence in favor of the hypothesis is, on the one hand, the rapidity with which children master their mother tongue, and, on the other hand, the fact that even a young child's command of his mother tongue encompasses not only phrases and utterances he has heard but also an unlimited number of phrases and utterances he has not previously encountered. To account for these two sets of facts, we must assume that in learning a language a child makes correct inferences about the structural principles that govern his language on the basis of very limited exposure to the actual sentences and utterances. In other words, we must assume that with regard to matters of language a child is uniquely capable of jumping to the correct conclusions in the overwhelming majority of instances, and it is the task of the student of language to explain how this might be possible.

A possible explanation might run as follows. Assume that the human organism is constructed so that man is capable of discovering only selected facts about language and, moreover, that he is constrained to represent his discoveries in a very specific fashion from which certain fairly far-reaching inferences about the organization of other parts of the language would follow automatically. If this assumption is accepted, the next task is to advance specific proposals concerning the devices that might be actually at play. The obvious candidate is the theoretical framework of linguistics, for while it is logically conceivable that the structure of language might be quite distinct from that of the organism that is known to possess the ability to speak, it is much more plausible that this is not the case, that the structures that appear to underlie all languages reflect quite directly features of the human mind. To the extent that this hypothesis is correct – and there is considerable empirical evidence in its favor – the study of language is rightly regarded as an effort at mapping the mysteries of the human mind.

Additional detailed information on various projects connected with this research is available through inquiry to the department head, Dr. Samuel J. Keyser, Room 20D-105, Ext. 4141.

# XXIV. COGNITIVE INFORMATION PROCESSING

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## 1. NATURAL LANGUAGE PROCESSING

National Science Foundation (Grant SED76-81985)

Jonathan Allen

The overall objective of this project continues to be the development of both a comprehensive model for converting English text to speech and a practical implementation of these techniques in special-purpose hardware.

The entire model is a set of algorithms (currently coded in BCPL) with well-defined input-output interfaces. Each of these is devoted to a particular aspect of text analysis or speech synthesis, including morphemic analysis, parts-of-speech computation, parsing, letter-to-sound conversion, lexical stress determination, pitch and timing computations, and, finally, phonemic synthesis of speech by rule. Our efforts are now focused on the last two parts of the system. We have implemented preliminary versions of timing and pitch algorithms, but these areas continue to require further research. There are a large number of determinants of pitch and timing, based on all aspects of the initial text and derived phonetic string. Thus it is a difficult task to determine an algorithmic specification for pitch and timing, but even more difficult to determine the perceptual necessity of these correlates. Furthermore, it has become clear that certain

linguistic features, such as stress, have multiple correlates that trade among each other in a way which is not currently understood. This complex relationship is probably an important factor in determining the naturalness of synthetic speech. Since the level of intelligibility of our synthetic speech is already high, the provision of naturalness for satisfactory long-term use becomes important. For these reasons, a major effort is being made to determine the relation between linguistic structures and these prosodic correlates, and also to express these relations in a well-structured algorithm appropriate to the needs of practical synthesis of speech by rule.

As a research vehicle, the model for text-to-speech conversion that we have developed is flexible, easy to understand and modify, and relatively machine-independent. On a conventional computer, however, it will not work in real time, and such an implementation would be too costly and bulky for most applications. For this reason, attention has now been directed to the development of custom-integrated circuits for practical implementations. Starting in 1978, we shall undertake the design of the entire phonemic synthesis part of the system in custom MOS technology. This project will require the design of custom architectures for these procedures, as well as complete logical design and layout. At present, the terminal analog synthesizer used to generate the output speech waveform requires approximately 150 dual-in-line circuit packages. Our expectation is that this task can be accomplished using 6 or fewer custom packages, with corresponding savings in space, power, and cost. We are also examining the possibility of custom devices for conversion of the phonetic transcription to parameters for the synthesizer circuit. The computational load for this task has been assessed, and an initial architecture is being devised.

The eventual goal of our work is to provide practical means for the generation of highly intelligible and natural-sounding speech from text in a fundamental way based on sound results from linguistics and speech science. This aim has led to parallel efforts in both basic research and custom implementation techniques. Our belief is that this strategy will lead to high-quality, practical implementations within the next few years, which will be attractive for a broad range of computer-based applications.

## 2. CONSTRUCTION AND GRAPHIC DISPLAY OF GUJARATI TEXT

Graphic Arts Research Foundation (Grant)

Francis F. Lee, Firoz Dosani

### a. Introduction

This report describes the work done to design and implement a set of computer algorithms that would permit the construction and graphic display of Gujarati text on a relatively simple keyboard. By typing keys on a keyboard such as an ordinary teletype

connected to a computer system, one would produce as output, text (words) in the Gujarati language. One approach to producing an integrated system has actually been implemented. This includes techniques for constructing, sorting, and selectively retrieving for display the characters of Gujarati. The procedure used is described below.

b. The Gujarati Writing Form

Gujarati is an Indian language whose writing form and structure is very typical of most other Indian languages such as Hindi. The basic unit of the Gujarati writing form is the "aksara" or open syllable. Also included as an essential and inherent part of the language are vowel and diphthong markers. These generally occur with every consonant to denote its pronunciation. Gujarati is further enhanced by the great number of consonant conjuncts.

c. Approach

One very significant idea in the approach used was to take what is typically thought of as the basic structure or element of the writing form – the aksara or open syllable – and break it into finer units. Thus the first task was to determine these finer units or basic building blocks (graphemes) from which the aksaras of the language are constructed, and define combining rules to form the aksaras from these graphemes. One of the reasons for this breaking down is the consonant conjuncts feature of the language. Most of the consonant clusters are constructed by taking a part of the first consonant and combining it with the second consonant in the cluster. This part of the first consonant would be one of the graphemes or finer units used to represent that consonant. Also, many of the syllables have a common subunit, so that the use of basic building blocks to construct the syllables would result in considerable savings of the time and storage space required to define all the clusters graphically.

The next step was to write computer programs to construct and display the basic building blocks for the aksaras, to combine these to form the actual aksaras, and to construct and display the vowels and diphthongs. This was done in PL/1 on Multics, primarily because Multics supports a good graphics system that is highly terminal-independent. In writing programs to define the graphemes, an important design criterion was that the aesthetic quality of the output text would have to be of a sufficiently high standard to be acceptable to the Asian peoples, most of whom have a highly developed taste for good calligraphy. This consideration led, after some experimentation, to the decision to define the graphic elements using a dot matrix representation rather than a vector matrix representation. Further experimentation showed that an 8 * 8 dot matrix representation did not produce the fineness that was desirable to distinguish clearly between any two similar characters in the language, and so a 16 * 16 dot matrix was preferable. The extra cost of storing all the graphemes (up to four times as much

memory) seems to be worth the resulting elegance and naturalness of the characters. Also, since some aksaras are much wider than others (even by more than a factor of two), rather than using a 16 * 16 square matrix representation, it was decided to keep the width of the aksaras variable, going from as little as 8 up to a maximum of 32 units. In addition, there would be a variable but maximum of 12 units above, and 8 units beneath an aksara, for the vowel and diphthong markers.

The third and final major step involved determining and defining rules by which text (words) is constructed from the aksaras, the consonant clusters, and the vowel signs. This includes a fairly complex computer program for the selection and correct positioning of the vowels. Although most of the aksaras are internally stored in two distinct parts, externally, on the teletype, only one key is used to denote the full aksara; so that typing a key denoting a particular syllable will cause both parts of the syllable to be output and correctly positioned, whereas typing a key for a consonant cluster may cause only one of the internal parts of the first consonant to be output. This was done because there are far too few keys on an ordinary teletype to allow the use of separate keys to denote the different parts of an aksara. Separate keys are used to denote the vowel and diphthong markers. These markers have to be positioned correctly by the program, to the right of, to the left of, above, beneath, or partly overlapping an aksara or a consonant adjunct. Other special features of the writing form are also taken care of.

d. Results and Conclusion

The user-visible program will take in a string of characters, and output in Gujarati the aksaras, the consonant conjuncts, and the vowel and diphthong markers that the character string denotes. Moreover, spacing of the output text – for instance, the spacing

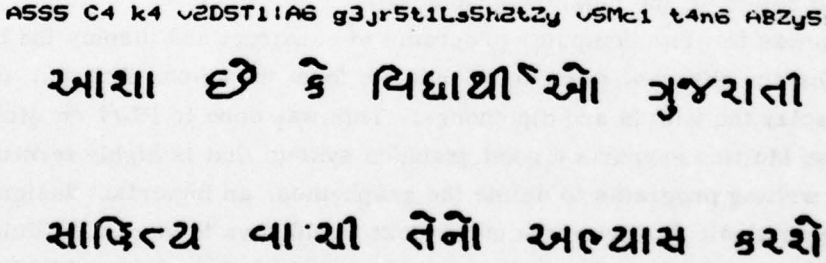


Fig. XXIV-1. Translation: I hope that students will read Gujarati literature and study it.

between lines, between words and between letters – as well as the size of the output characters, are parameters that the user can specify and change from one invocation of the program to another. A sample two-line output text is shown in Fig. XXIV-1. Further

work in this area could lead to a development of a computerized type-setting system to be used by the newspaper and other printing industries of the third-world countries, for the printing of Gujarati and of other similar languages.

### 3. DATA PROCESSING FOR THE GRAPHIC ARTS

Providence Gravure, Inc. (Grant)

William F. Schreiber, Donald E. Troxel, Leonard Picard, Peter V. Dolan

The aim of this project is to explore the feasibility of digital processing and computer manipulation of graphic arts quality images which are intended to be duplicated on printing presses. Specific areas of investigation include data compression, tone-scale reproduction, enhancement, input/output hardware and software, and the economical storage and retrieval of very large amounts of pictorial data.

### 4. DIGITAL WIREPHOTO SYSTEM

Associated Press (Grant)

Donald E. Troxel, William F. Schreiber, Samuel M. Goldwasser, John N. Ratzel

Since August 1970, we have been developing a news picture (Wirephoto) distribution system that is entirely new for the Associated Press. It is to be introduced in stages, in such a way that at least the present standard of quality and service will be maintained everywhere, with improvements spreading gradually to all locations.

The ultimate system as now envisioned will operate as follows. Pictures will be stored under computer control. An editor can then view any picture on a TV display in order to select, discard, edit, transmit, or store that image for later automatic dispatch. Editing may include cropping, enlarging, reducing, tone-scale enhancement, sharpening, combining, and addition of captions. No additional chemical photographic work will be required for any of these picture-processing operations.

Transmission over the "backbone" system linking AP bureaus and large metropolitan newspapers that have substantial computer facilities will be via high-speed digital links and will originate and terminate generally at computer-controlled digital storage devices. Transmission to subscribers will be analog or digital and at speeds and scanning standards appropriate to the existing transmission facilities. Complete control will be exercised by the New York network monitor. In the absence of manual interventions, transmission to all points among the bureaus, from point to point, and to regional networks, will be accomplished automatically.

We have implemented some of these procedures in the laboratory, using a PDP-11

computer (80k core, 38 megabit disk). The input may be a picture from the AP network, from a local analog transmitter, magnetic tape or Dectape, and is stored on a disk. Pictures may be transmitted from the disk to comparable receiving points. Pictures stored on the disk may be viewed on a TV display utilizing a full-frame semiconductor storage system. Editing facilities already in operation include cropping, enlarging or reducing, combining several pictures into one, addition of captions, and sharpening.

The multitask software operating system permits new picture-processing operations to be integrated easily, and we plan to keep incorporating additional picture-processing routines into the system.

We are particularly interested in picture-processing operations in which the processing depends on the local content of the picture. That is, the detailed parameters of a coding or enhancement scheme vary for different local areas. In this type of processing it is of prime importance to avoid artifacts such as contours outlining these local areas. We are also accelerating our interest in color picture processing, both from the viewpoint of coding for bandwidth compression and enhancement or manipulation.

The Associated Press is now in the process of installing the computer-based image processing system in New York City. When operational, it will initially be used to coordinate the newsphoto transmissions between the domestic and international Wirephoto networks.

## 5. SIMULATION OF PARTIAL DENATURATION MAPS (PDM) OF BACTERIAL PHAGE

National Institutes of Health (Grant 1 RO1 GM22547-01)

Ian T. Young, Donald S. Levinstone

In studying the PDM of long DNA molecules we have made extensive use of the PDM histogram generated by algorithmic procedures.[1,2] In order to determine the significance of the histogram prototypical maps isolated in this manner, the alignment procedure was run on several sets of randomly generated data.

The histogram T6056 (Fig. XXIV-2a) is generated from 63 artificial denaturation maps each of which has the identical number and lengths of denaturation bubbles as a corresponding curve of the original P22 data, but a randomly chosen position – i.e., these data have essentially identical statistics to the real data, except that the postulated regional dependence of denaturation is lacking. The three histograms T0066, T1856, and T0876 (Fig. XXIV-2b, c, d) were generated from artificial PDM with the number of denatured regions per curve selected by a Poisson distribution having the same measured statistics as the original P22 ensemble, with the length of the region chosen

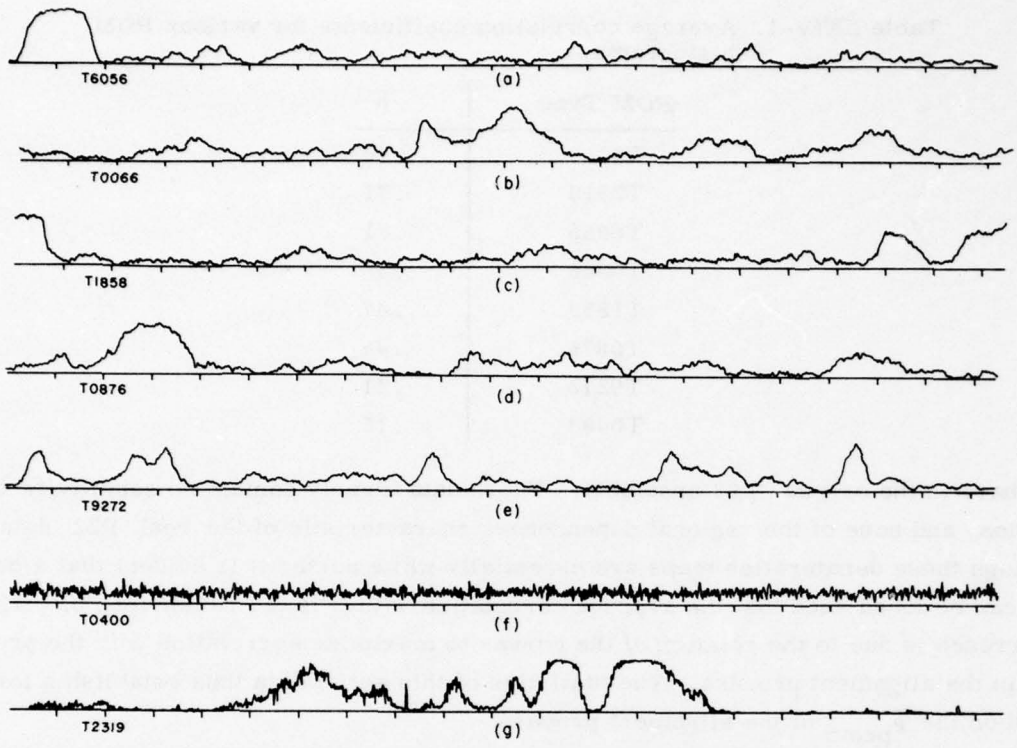



Fig. XXIV-2. Partial denaturation map histograms of stochastically generated molecules.

via a probability mass function accumulated over the original P22 data ensemble, and with uniformly random points of denaturation.

The histogram T9272 (Fig. XXIV-2e) was generated from artificial PDM with two Poisson distributions, for the number of bubbles per curve and the lengths of these regions (with parameters chosen to agree with the measured parameters of the original P22 data), and random region positioning.

It can be seen that while the histograms converge to a peaked pattern, the average correlation coefficient ($\bar{\rho}$), a measure of the extent to which the computer faithfully models its components, is in general quite low, as contrasted with the results on the real P22 data, as shown in Table XXIV-1.

The conclusion that may be drawn from these simulations is that relatively consistent position information (with respect to denaturation) among the curves comprising the ensemble is an important factor in convergence to a pattern which correlates well with its substituents. The data set corresponding to histogram T0400 (Fig. XXIV-2f) was generated by a coin-flipping process. The probability that any individual point of the 1024 comprising a curve will be a 1 is .21, the same as the average probability of a 1

Table XXIV-1. Average correlation coefficients for various PDM histograms.

| PDM Type | $\bar{\rho}$ |
|---|---|
| P22 | .72 |
| T2319 | .71 |
| T6056 | .51 |
| T0066 | .46 |
| T1858 | .47 |
| T0876 | .48 |
| T9272 | .41 |
| T0400 | .15 |

anywhere in the original P22 ensemble. These data clearly contain no sensitivity to position, and none of the regional dependences characteristic of the real P22 data. Although these denaturation maps are essentially white noise, it is evident that a pattern can be found such that the average correlation with it is .15 rather than 0. This occurrence is due to the rotation of the curves to maximize correlation with the prototype in the alignment process. The statistics of this set of data thus establish a lower bound on the $\bar{\rho}_{proto}$ of the alignment process.

The final simulation with P22 statistics is represented by the histogram denoted T2319. In this experiment a similar coin-flipping procedure was utilized, but with the probability of 1 at any position equal to the fraction of the curves denatured at that position in the histogram of P22 data (used as a representation of the true position dependence of denaturation in P22). Thus, denaturation "bubbles" are not generated, but the overall regional nature of the denaturation process in the P22 data is mirrored in Fig. XXIV-2f. It may be noted here that the $\bar{\rho}_{proto}$ for these data is almost identical to that of the real P22 data set.

The conclusion drawn from these simulations is that the principal information recognized by our pattern-isolation scheme is the position dependence of the denaturation.

Our alignment procedure appears to be dependent on relatively consistent data, with the significant denatured regions of similar extent, for good construction of a pattern clearly different from an alignment of noise.

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## 6. ANALYSIS OF CELL AGING

National Institutes of Health (Grant 1 PO1 AG00354-01)

Ian T. Young, Donald S. Levinstone, Irvin S. Englander

This report describes an initial study toward the automatic location of fibroblast cells in a field under Hoffman contrast microscopy. Figure XXIV-3a shows an example of such a field. The goal is a set of contours outlining the cells present in the field.

The study was performed on the Cognitive Information Processing Group's PDP-9 Biological Image Processing Computer using the PIXIE interactive picture experimentor, developed by Englander.[1]

As a first step, we generated the gradient picture from the original picture by convolving the original with the following directional derivative masks:

$$\vec{H} = \begin{array}{|c|c|c|}\hline -1 & 0 & 1 \\ \hline -2 & 0 & 2 \\ \hline -1 & 0 & 1 \\ \hline \end{array} * \vec{P} \qquad \vec{V} = \begin{array}{|c|c|c|}\hline -1 & -2 & -1 \\ \hline 0 & 0 & 0 \\ \hline 1 & 2 & 1 \\ \hline \end{array} * \vec{P}$$

The gradient is the point-by-point calculation

$$g_{xy} = \sqrt{H_{xy}^2 + V_{xy}^2}.$$

The gradient is shown in Fig. XXIV-3b.

A threshold operation was performed on the gradient; the resulting binary picture was filtered using the following mask,

| | | |
|---|---|---|
| 1 | 1 | 1 |
| 1 | 1 | 1 |
| 1 | 1 | 1 |

and a threshold which accepts points for which at least four of the points are in the binary picture. This new picture was "inclusive-ored" with the binary picture.

The resulting picture was contoured. Small regions were eliminated from the result, as were interior exclusions. The trace lines were smoothed in regions where a short potential perimeter enclosed a large exclusion. The final result is shown in Fig. XXIV-3c.

It can be seen that the results of the initial study are promising. All of the cells in the picture have been located and outlined. Two sections of the cell at center right have been

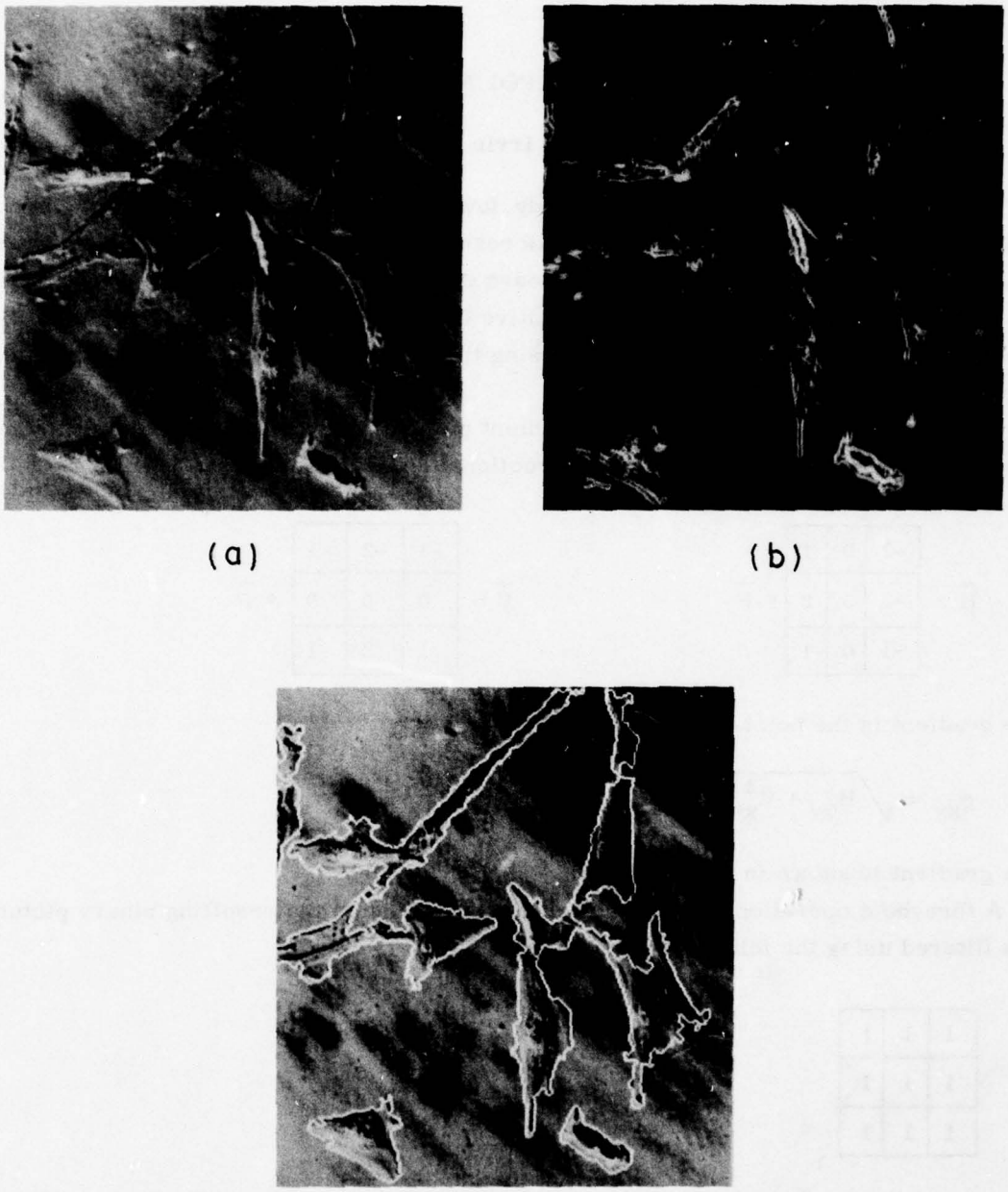



Fig. XXIV-3. Fibroblasts observed under Hoffman modulation contrast microscopy.
(a) Original (digitized) image.
(b) Gradient image.
(c) Final contours superimposed on cells.

eliminated; although pieces of these regions existed in the original contour trace, there was not sufficient evidence under our criteria to attach them to the cell. Further research is needed in this area. Additionally, no effort was made to deal with the problem of overlapping cells, although the intermediate picture data give some indicators as to an approach to the problem. Considerable future research will be required in this area.

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## 7. TEST FOR DONOR-RECIPIENT HISTOCOMPATIBILITY

Health Sciences Fund (Grant 76-11)

Ian T. Young, Stephanie E. Sher

The major thrust of our work on mixed lymphocyte cultures from June 1976 to January 1977 was in image analysis. A system was developed to enter a selected area of photographs of MLC wells into the PDP-9 computer. The pictures were read in through a video camera attached to the Tempo computer. The Tempo coded the pictures into levels of brightness between white and black, and transmitted the information in digital form to the PDP-9.

A student, Mark Alan Shalloway, analyzed six sets of photographs, one set from cells compatible at the LD and HLA loci, one set compatible at LHA, but not LD locus, and four incompatible at both loci. He identified two kinds of textural features which differed between wells. One consisted of large clusters of cells, some with smooth, well-defined edges and others with rough, diffuse edges. He termed this texture macrostructure and concluded from the data that it represented a response of the cultured lymphocytes to the serum in the culture medium. The other texture consisted of individual cells and the spaces between them. He termed this microstructure.

He developed an image-processing system based on analysis of the distance between adjacent dark points. This corresponded to information on cell size and distribution. Using this analysis of microstructure, the ability to predict the compatibility on the six plates was inconclusive. We attribute this to two areas: Our inability to understand how humans can successfully predict the compatibility based upon textural features[1] and the heterogeneity in the cell population from use of the human model when we are trying to determine the controlling variables.

The work will be continued under a grant from the Leukemia Foundation using a different type of image analysis and a different animal model.

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# XXV. COMMUNICATIONS BIOPHYSICS

## A. Signal Transmission in the Auditory System

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### 1. BASIC AND CLINICAL STUDIES OF THE AUDITORY SYSTEM

National Institutes of Health (Grants 5 PO1 NS13126-02 and 5 KO4 NS00113-03)

Nelson Y. S. Kiang, William T. Peake, Thomas F. Weiss

Members of the Research Laboratory of Electronics participate in basic and clinical studies of the auditory system conducted by the Eaton-Peabody Laboratory of Auditory Physiology. The Eaton-Peabody Laboratory, which is housed at the Massachusetts Eye and Ear Infirmary, also includes investigators from the Eye and Ear Infirmary, Harvard Medical School, and Massachusetts General Hospital, as well as from M. I. T. The goal of the Eaton-Peabody Laboratory is to investigate the physiological and anatomical bases of hearing and to apply results of fundamental research to clinical problems. Active areas of basic research include studies of sound transmission in the middle and inner ear, mechano-electric transduction in the inner ear, coding of sound stimuli into neural signals in normal and abnormal inner ears, processing of neural signals in the central nervous system, and the relation of gross population responses to the underlying cellular activity. Active areas of clinical research include the measurement of evoked electric response to sound for diagnostic purposes in patients with hearing or neurological pathology.

This work has been reported at meetings of the Acoustical Society of America,[1-5] and at other symposia.[6,7] Journal papers have been accepted for publication.[8-11] One Master of Science thesis[12] and one Doctor of Philosophy thesis[13] have also been awarded this year to graduate students in the Research Laboratory of Electronics for their research in this area.

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# XXV. COMMUNICATIONS BIOPHYSICS

## B. Auditory Psychophysics

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## 1. INTENSITY PERCEPTION AND LOUDNESS

National Institutes of Health (Grant 2 ROl NS11153-02A1)
National Science Foundation (Grant BNS77-16861)

Louis D. Braida, Sheila M. Chase, H. Steven Colburn, Nathaniel I. Durlach, Adrian J. M. Houtsma, Jae S. Lim, William M. Rabinowitz, Charlotte M. Reed

This research is oriented toward the creation of a coherent, quantitative, and unified theory of intensity perception and loudness, and involves the construction and integration of models of decision making, sensory processes, short-term memory, and perceptual context effects, as well as extensive psychophysical experimentation.[1-10] We expect the results to provide greater insight into basic phenomena of intensity perception and loudness, and to be of value in the study of equivalent problems involving other stimulus dimensions and subjective attributes and other senses. Also, we expect the results to be of use in the study of memory processes involving more complex stimuli or more complex tasks, and in various applications such as the evaluation of annoyance in noise pollution and the interpretation of abnormal intensity perception and loudness in subjects with hearing impairments.

During the past year, research has been conducted in five areas. First, we have extended our theoretical work on a perceptual-anchor model of context-coding designed to explain the resolution edge effect[7] and the effect of standards in identification.[9] This effort has been directed primarily toward deriving closed-form approximations to

exact formulations that cannot be expressed in closed form, and computing sets of curves to describe the dependence of the model's predictions on the various parameters of the model. The results of this effort are now being prepared for publication. Second, we have performed further experiments to evaluate our theoretical predictions[8] concerning the relation of discrimination to loudness matching. According to these predictions, two stimuli are matched in loudness when they divide their respective dynamic ranges proportionately in terms of number of just-noticeable differences in intensity. The experiments are designed to test these predictions for stimuli consisting of tones, noise, and tones partially masked by noise. The results of these experiments are now being analyzed. Third, we have initiated a new series of experiments to determine the effect of frequency-of-presentation and stimulus spacing on resolution in identification. In most of our past work, the frequency of presentation has been the same for all stimuli and the spacing has been uniform in dB. In the specific experiment now under way, we are examining how resolution is affected by increasing the frequency of presentation of the extreme stimuli or of a stimulus in the center of the stimulus range. Fourth, we have begun to explore how the dependence of intensity resolution on overall level[6] relates to physiological results on auditory nerve firing patterns. This work will make extensive use of data obtained at the Eaton-Peabody Laboratory of Auditory Physiology. Finally, we have started a new experimental program to determine whether the theoretical models and experimental techniques that we have developed to aid us in understanding intensity perception and loudness in normal-hearing subjects can be used to increase our understanding of the same topics in hearing-impaired subjects. All of these projects will be continued during the coming year.

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## 2. BINAURAL HEARING

National Institutes of Health (Grant 5 RO1 NS10916-03 and
Fellowship 1 F32 NS05327)

Edward M. Burns, H. Steven Colburn, Nathaniel I. Durlach, Kaigham J. Gabriel, Rudolph G. Hausler, Adrian J. M. Houtsma, Allen W. Mills, Peter J. Moss, William M. Siebert, Ronald A. Siegel, Richard M. Stern, Jr.

The primary objective of this research continues to be the development of a unified quantitative theory of binaural interaction that is applicable to a wide variety of binaural phenomena and is consistent with neurophysiological data on the auditory system.[1-5] A secondary objective is to apply our understanding of binaural interaction to the problems of the hearing-impaired. During the past year, significant progress has been made in a variety of areas.

In one project, we are examining more closely our assumption that the variability of the decision variable in binaural detection tasks with a noise masker can be ascribed primarily to the stochastic nature of the peripheral transduction from the acoustic stimulus to firing patterns on the auditory nerve and that the variability arising from the stochastic nature of the acoustic stimulus is negligible. So far, the results of this examination, which are based both on theoretical computations and experiments involving repeated noise bursts having fixed waveforms, are consistent with our assumption.

In a second project, we have explored further the ability to discriminate between interaural time delays and interaural amplitude differences. Earphone listening experiments were conducted in which the subject's task was to discriminate between two tones that were identical except for interaural parameters and were adjusted to have the same mean lateral position.[6] An inability to perform better than chance in this task for some combination of interaural parameters would imply that interaural time and interaural amplitude are completely tradable for this combination. These experiments differed from previous studies directed toward the same question in that acoustic monitoring was used to precisely control the stimulus conditions and that stimulus pairs with symmetric interaural differences were included. The results of these experiments indicate that

subjects who can focus their attention on aspects of the binaural image other than mean lateral position can perform well above chance for all ratios of interaural differences. Our results differ from those previously reported in the quantitative results obtained, the subjective reports of the listeners, and the dependence of the perceptions on training and listening technique. In general, these results support the idea that interaural time and intensity are not tradable (provided the subjects are given an ample amount of appropriate training) and have important implications for the further development of our theory.[5]

In a third project, concerned with binaural adaptation, a series of experiments was conducted to determine the effects that unbalanced interaural parameters have on lateralization judgments.[7] Two types of adaptation were considered: adaptation to interaural amplitude differences and adaptation to interaural time differences. In both cases, the amount of adaptation was measured by using a cancelling interaural time delay to move the binaural image to perceived center. Also, the amount of adaptation was measured over time (from onset of the adaptation period to the point at which the adaptation effect stabilized) so that time constants could be estimated. The results of these experiments indicate that substantial adaptation effects do indeed exist (changes by a factor of two in the time-intensity trading ratio are not uncommon), that the amount of adaptation is influenced by the initial position of the image, and that adaptation effects should be seriously considered in future work on lateralization.

In a fourth project, concerned with the binaural system's ability to extract envelope information, a series of experiments was conducted to investigate the binaural interaction of sinusoidally-amplitude-modulated-Gaussian-noise signals.[8] For conditions in which wideband noise carriers were interaurally incoherent, listeners were able to discriminate interaural differences in modulation phase or modulation rate for modulation rates less than approximately 400 Hz, presumably reflecting the listener's ability to utilize information from the temporal envelope of the stimuli at these modulation rates. The effects on performance of highpass and lowpass filtering of these stimuli implies that this envelope information can be mediated by either high-characteristic-frequency or low-characteristic-frequency neurons, but that interaural comparisons are made only between neurons with similar characteristic frequencies. For conditions in which the noise carriers are interaurally coherent, interpretation of the results is more difficult because of interactions associated with the fine structure of the waveforms.

In addition to the above projects, we have initiated two further projects: an investigation of lateralization "cue-reversal points" as a function of frequency[4] and an investigation of spatial resolution in impaired listeners. The latter project is being conducted in collaboration with the Eaton-Peabody Laboratory of Auditory Physiology. Work on most of these projects will be continued during the coming year.

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## 3. COMMUNICATION AIDS FOR THE HEARING-IMPAIRED, THE DEAF, AND THE DEAF-BLIND

National Institutes of Health (Grant 5 RO1 NS12846-02 and Fellowship 1 F32 NS05266)
Edith E. Sturgis Foundation

Louis D. Braida, Mark A. Clements, Michael C. Coln, H. Steven Colburn, Stephen V. DeGennaro, Leonard C. Dowdy, Nathaniel I. Durlach, Bruce L. Hicks, Richard P. Lippmann, Douglas R. Mook, Susan J. Norton, Patrick M. Peterson, Michael A. Picheny, Charlotte M. Reed, Martin C. Schultz, Edgar Villchur

The general goal of our research on aids is to develop aids that provide substantially improved speech communication for persons suffering from hearing loss or to understand the fundamental reasons why such aids cannot be developed. During the past year, our research in this area has focused on two main topics: matching speech to residual auditory function, and tactile communication of speech.

### a. Matching Speech to Residual Auditory Function

Work on matching speech to residual auditory function continues to focus on multiband amplitude compression for listeners with reduced dynamic range and on frequency

lowering for listeners with negligible hearing at high frequencies.

We have completed an initial study of the effects of multiband amplitude compression on speech intelligibility for persons with sensorineural losses.[1] Experiments were conducted on five listeners with sensorineural impairments and reduced dynamic ranges using 16-channel computer-controlled, amplitude-compression systems. Each subject was tested with two compression systems and, for reference purposes, four linear systems. One of the compression systems was chosen to restore normal equal-loudness contours; the other employed reduced high-frequency emphasis and reduced compression ratios. The four linear systems differed only in the frequency-gain characteristic (orthotelephonic plus three characteristics with high-frequency emphasis that were expected to produce better results than orthotelephonic). The six systems were compared on each of the five subjects using nonsense CVC monosyllables and sentence material spoken by male and female talkers and presented in quiet/anechoic and noisy/reverberant environments at the most comfortable level for each listener.

The principal results of these tests were: first, the linear systems with high-frequency emphasis produced substantially better performance than the orthotelephonic system, and second, neither of the two compression systems led to significantly better performance than the best linear system. In considering these results, it should be noted that (i) the long-term level of the speech material was held constant before processing, (ii) the subjects suffered from only moderate losses, and (iii) only two compression systems were tested. If we take account of the differences in the linear systems to which the compression systems were compared, these results are roughly consistent with those of Villchur[2] and of Barfo[3,4]

Work on frequency lowering is directed toward evaluating a number of pitch-synchronous time-dilation processing techniques (including both lowering and warping[5]), as well as pitch-asynchronous techniques that have been studied by others. In initial studies we are employing listeners with normal hearing and using lowpass filtering and additive noise to simulate hearing loss. Three projects are now under way: (i) a study of the basic resolution for materials processed by frequency lowering, (ii) a study of the perception of frequency-lowered vowels, and (iii) a study of the perception of frequency-lowered consonants.

(i) Work on basic resolution is directed at exploring a wide variety of lowering schemes. By examining pairwise discriminations using test procedures which impose relatively little memory load, resolution can be studied without the need for extensive training with processed materials. We are testing schemes having different amounts of lowering and different degrees of warping. In addition, we are varying the amount of lowpass filtering for a given lowering-warping combination.

(ii) Work on the perception of frequency-lowered vowels has made use of a number of frequency-lowering schemes and has been concerned mainly with the performance of

relatively naive listeners on vowel identification tasks. These data will provide a baseline for studies involving extensive training and will also be used in interpreting results obtained by other investigators.

(iii) Work on the perception of frequency-lowered consonants has focused on the ability of listeners to learn (with extensive laboratory training) to recognize CV monosyllables processed by a specific pitch-synchronous lowering-warping scheme that alters high-frequency components to a greater extent than low-frequency components (and that appeared, on the basis of informal listening, to be more promising than some of the other schemes tested).

Substantial experimental work has been completed in each of these three project areas and the results are now being analyzed.

In conjunction with this research, we have also completed a comprehensive review of past work on matching speech to residual auditory function.[6] Work on both amplitude compression and frequency lowering will continue during the coming year.

b. Tactile Communication of Speech

The goal of this research is to increase our knowledge of the capabilities and limitations of various tactile display schemes for communicating speech signals. We are now involved in research with two types of display schemes: (i) spectral displays using the Optacon transducer system and (ii) articulatory displays using the Tadoma method (in which the "reader" monitors the articulatory features of speech directly by placing his hand on the talker's face).

(i) Current experiments with the spectral display have focused on discrimination and identification of consonants and vowels. In one experiment, in which frequency and amplitude information is displayed in the rows and columns of the Optacon, we are exploring subjects' abilities to identify a set of 12 consonants, recorded by four different speakers. In another experiment, we are exploring the discriminability of pairs of vowels using two different spectral displays: the frequency-amplitude displays used in the consonant study and a time-swept frequency display. Based on the results of these experiments, as well as further experiments involving other types of speech material and/or other spectral display schemes, we hope to determine the relative merits of a variety of spectral display schemes.

(ii) Experiments on the Tadoma method have been conducted both with a highly experienced Tadoma user[7] and with subjects with normal hearing and sight[8] (for whom deafness and blindness is simulated). Our recent work with the experienced Tadoma user has concentrated primarily on a study of vowel and consonant perception to determine the types of errors that are made and the perceptual cues that are used. Work with normal subjects has consisted of two projects: a study in which subjects were trained to recognize consonants and vowels; and a study in which subjects were trained

to understand connected speech through Tadoma. Preliminary results from the first study indicate that with several hundred hours of training, subjects are able to identify 24 consonants and 15 vowels with an accuracy comparable to that demonstrated by the experienced Tadoma user. In the study of the perception of connected speech through Tadoma, subjects began training with a small set of words that were first learned in isolation and then combined to form sentences. The number of words in the vocabulary was increased gradually over the training period to about 50 words. The data from this study are now being analyzed.

The direction and level of our future work on the tactile communication of speech will depend on the funds available for this research.

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## 4. MUSICAL PITCH

National Institutes of Health (Grant 1 RO1 NS11680-01 and
Fellowship 1 F32 NS05327)

Edward M. Burns, Adrian J. M. Houtsma

The overall objective of this research is to obtain a better understanding of the auditory processes that underlie the transformation of a complex sound into a sensation of musical pitch. In connection with this objective, two studies have been carried out.

In one study, concerned with the pitch of harmonic two-tone complexes, musical-

interval identification experiments were conducted using a pulse train for the first note (the reference) and a dichotically presented two-tone complex of nonsuccessive harmonic numbers (n and n+2, n and n+3, or n and n+4) for the second note (the target). The results of these experiments were compared with theoretical upper and lower bounds on performance predicted from a general template processing model.[1] The theoretical upper bound is formed by allowing a fundamental scan over the range of fundamental frequencies used in the stimulus set; the theoretical lower bound is formed by allowing an unrestricted fundamental scan. Generally speaking, the experimental data were found to be between these bounds, but, some notable exceptions were observed. For example, when the third and seventh harmonics of 200 Hz were used, performance fell significantly below the lower bound. A study of these results, as well as previous data[2-4] which demonstrate that information about a fundamental can be extracted from even one harmonic under the right conditions, suggested that for the present paradigm a sufficient condition for correct interval identification is that at least one of the two tones in the target complex bear an octave relationship to the target pitch (fundamental). This hypothesis was successfully tested by a control experiment in which only one of the two tones in the target complex was presented. In general, our results are consistent with the idea that a two-tone complex $nf_o$ and $(n+m)f_o$ evokes a pitch corresponding to the fundamental $f_o$ (synthetic listening mode) and pitches corresponding to $nf_o$ and $(n+m)f_o$ (analytic listening mode), and that the strength of the former mode relative to the latter decreases with increasing m.

In a second study, we explored further the pitchlike quantities of the sinusoidally amplitude-modulated noise signals used in the interaural discrimination experiments described in Sec. XXV-2. The results of these interaural discrimination experiments provide indirect evidence that the pitchlike qualities of these stimuli are based on temporal information contained in the envelope of the modulated waveform. In particular, it was observed that the region of modulation rates in which listeners can discriminate interaural differences in the modulation phase (discrimination that is almost certainly based on temporal information) is very similar to the region of modulation rates in which listeners can identify musical intervals for these stimuli.[5,6] In a separate experiment designed to study the effect of interaural phase of the modulation waveform on the identification of musical intervals, it was found that performance was independent of whether the two ears were in phase (subjective image centered in the head) or out of phase (subjective image diffuse or lateralized in the two ears).

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## 5. MUSICAL ACOUSTICS

National Institutes of Health (Grant 1 ROl NS11680-01)

Adrian J. M. Houtsma, Ernest J. Perevoski

The overall purpose of this program is to gain insight into the processes involved in the production and perception of music. Work during the past year has continued to focus on electronic pickup systems for the classical guitar and pitch tracking of recorded vocal music.

When an acoustically weak instrument such as the classical guitar is played in a large symphony hall, electronic amplification becomes a necessity. Furthermore, the conventional technique of amplifying a near-field microphone recording seems likely to produce a less than optimal representation of the far-field acoustic spectrum of the instrument. Thus, attempts were made to match the frequency response of a mechanically driven guitar body, measured through an acoustic microphone in the far field in a reverberant chamber, to a linear mix of signals obtained from contact microphones on the guitar body.[1] It was found that the closest match is obtained when the signal from an acoustic microphone in the sound hole is mixed with the integrated signal from a single accelerometer-type contact microphone placed on the bridge, the overall signal thus representing the sound pressure in the sound hole (principally the Helmholtz resonance of the body cavity) and the velocity of antinodes of the sound board (all higher characteristic modes). This "optimal" array was then compared with the conventional near-field microphone recording in a comparative listening test.[1] Listeners were exposed to various sounds from the guitar, such as mechanically driven white noise, pure tones, pulse trains, and string-driven open notes, fretted notes and chords, all recorded in the far field. Each sound was immediately followed by three "pickup versions" of that sound: one from a near-field acoustic microphone, a second from our "optimal array," and a third from another, less-than-optimal array. Listeners were asked to indicate which of the three versions was closest to the target (far-field) sound. The third array was never chosen, but in more than half the cases the near-field microphone

was chosen over the "optimal array." Presumably, this result reflects a significant discrepancy in the physical and subjective criteria used to match spectra.

Research on pitch tracking of recorded music has resulted in the construction of a "melograph" (based on a previous device[2]) which plots pitch vs time on a continuous strip chart. The melograph has an amplitude compressor to eliminate dynamic changes, a rectifying circuit to introduce energy at the fundamental in case there is no energy at the fundamental in the original signal, a bandpass filter tuned to the expected fundamental range, and a Schmit-trigger circuit. A second lowpass filter measures the dc value of the triggered pulse train, proportional to the pitch of the fundamental, and controls the vertical input of the strip chart. This system was found to handle a large variety of instrumental and vocal sounds, and, unlike most commercially available pitch-tracking devices, showed little sensitivity to timbre changes (e.g., singing an /*a*/, /eI/, /i/, /o/, /u/ sound with a given pitch does not change the pitch reading).

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# XXV. COMMUNICATIONS BIOPHYSICS

## C. Transduction Mechanisms in Lateral Line and Vestibular Organs

### Academic Research Staff

Prof. Lawrence S. Frishkopf
Prof. Charles M. Oman

National Institutes of Health (Grant 2 ROl NS11080-04)

Lawrence S. Frishkopf, Charles M. Oman

Our broad goal is to understand the mechanisms of transduction in the receptor organs of the acoustico-lateralis system of vertebrates by studying the mechanical, electrical and synaptic events in hair cell organs, and their relation to nerve activity. During the past year we have: (i) completed an analysis of inner-ear fluid composition in representative vertebrate species;[1] (ii) completed a study of cupula motion in the semicircular canal of the skate;[2] and (iii) continued our efforts to identify the afferent transmitter substance in hair cells.

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## 1. EVIDENCE OF THE PRESENCE OF MONOAMINE CONTAINING STRUCTURES IN HAIR CELLS

Lawrence S. Frishkopf, Richard D. Kunin

A number of recent studies provide evidence relating to the identity of the afferent transmitter substance in hair cells. Proposed candidates include glutamate and aspartate,[1-3] monoamines,[4,5] and GABA.[6] Our results indicate that monoamine-containing structures are present in hair cells. Specifically, we have observed in the crista of the skate semicircular canal numerous small inclusions which fluoresce when the tissue is treated by a histochemical technique that demonstrates by fluorescence the presence of biogenic monoamines.[7,8] We are attempting to localize and identify these inclusions, using techniques of fluorescence, phase, and electron microscopy. We have found that the inclusions are confined to the apical portion of the sensory epithelium, where hair cells are located; many are clearly within hair cells. It is not yet possible to say

whether they occur only in hair cells or may also be found in apical portions of supporting cells and nerve terminals. Earlier studies[4,5] have shown that drugs (reserpine, guanethidine, and FLA-63) that deplete monoamine stores cause significant alterations in synaptic bar and synaptic vesicle morphology in hair cells. The possibility is therefore suggested that the fluorescent inclusions that we have seen in hair cells may be synaptic bars. This interpretation is consistent with both the locations and sizes of the inclusions: like synaptic bars, they are found in hair cells, often close to the cell membrane, and most are less than 0.5 μm in diameter.

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# XXV. COMMUNICATIONS BIOPHYSICS

## D. Biomedical Engineering

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National Institutes of Health (Grants 5 T32 GM07301-03 and 5 TOl GM01555-10)

William M. Siebert

Included under this heading are a variety of topics in biophysics, physiology, and medical engineering. Many of these are individual projects of students supported by training grants from the National Institutes of Health.

# XXVI. NEUROPHYSIOLOGY

## Academic and Research Staff

Prof. Jerome Y. Lettvin
Prof. Stephen G. Waxman
Dr. Isabelle Alter
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## 1. THRESHOLD HUNTER DEVICE

Bell Laboratories (Grant)

Louis L. Odette, Stephen A. Raymond

The threshold hunter device places the nerve in a feedback loop so that changes in threshold can be tracked. Where traditional methods for measuring threshold require a series of trial stimuli, to which the responses yield a measure of the response probability for each stimulus level, the threshold hunter forces the stimulus to a level which will produce a response 50% of the time. As this level varies with, for example, temperature or other variables, the hunter follows the variation in accordance with its frequency response. Strictly speaking, the nonlinearity introduced into the feedback loop by the threshold element does not allow determination of the transient response directly from the frequency response, but simulations can be used to choose the "optimal hunting strategy" for a particular situation. The term "optimal hunting strategy" refers to the discrete time filter which is placed in the feedback loop with the threshold element.

## 2. NERVE MEMBRANE MODELS

National Institutes of Health (Grant 5 ROi EY01149-03S2)
Bell Laboratories (Grant)

Louis L. Odette, Jerome Y. Lettvin

Kinetic reaction sequences for both the sodium and potassium conductance systems have been under investigation. Each sequence involves calcium ion adsorption-desorption on the ion channels, each channel being in one of two conditions, open or closed, depending on the state of the channel sites which bind calcium.

Several types of sequence yield both the steady-state distribution of channel states, in terms of the Hodgkin-Huxley parameters m, n, and h, and the relaxation time

constants, as a function of transmembrane voltage. The models also reproduce the experimental observations of the effects of altered calcium ion concentration on the electrical properties of the axon. With this background, we shall explore the relationship between the models and physical representations of the membrane.

## 3. RELATION OF THE E-WAVE TO THE DELAYED GANGLION CELL RESPONSE AND THE PROLONGED ROD RESPONSE

National Institutes of Health (Grants 5 TO1 EY00090-04 and 5 RO1 EY01149-03S2)
Bell Laboratories (Grant)

Eric A. Newman, Jerome Y. Lettvin

The e-wave is a delayed component of the electroretinogram which can be recorded from the dark-adapted vertebrate retina. It was first described ten years ago by Crescitelli and Sickel,[1] who recorded e-waves from the isolated retina of the frog. A delayed response can also be recorded from retinal ganglion cells. This activity has been termed the 'delayed ganglion cell response' by Varjú and Pickering.[2]

We have recorded the e-wave and the delayed ganglion cell response simultaneously in order to study the relation between these two delayed responses. A dark-adapted eyecup preparation of the frog (Rana pipiens) was used. The preparation was cooled to 15°C and maintained in a moist 95% $O_2$-5% $CO_2$ atmosphere.

Bright flashes (100 ms) of diffuse white light evoked a prominent e-wave which was recorded with an intraretinal electrode referred to the vitreous. The e-wave appeared as a negative notch, or dip (lasting 5 to 15 seconds), superimposed on a slow, positive intraretinal voltage, the slow PIII. Latency to the onset of the e-wave was roughly proportional to the log of stimulus intensity, varying from 2 seconds to over 60 seconds. Simultaneous recordings of ganglion cell activity and the e-wave showed that the two are closely related. Bright stimulus flashes produced a long silent period followed by a prolonged burst of ganglion cell activity which began concurrently with the e-wave. In addition, the length of the delayed ganglion cell response corresponded to the duration of the e-wave response. Bursty ganglion cell activity was associated with an (abnormal) oscillatory e-wave response. These temporal correlations suggest that the two delayed responses represent closely linked retinal phenomena.

The role of the rod receptor response in the generation of delayed retinal responses was investigated. The rod response was recorded differentially between two intraretinal electrodes positioned on either side of the receptor layer in aspartate-treated eyecups. Bright stimulus flashes evoked rod responses consisting of a prolonged (saturated) plateau phase followed by a decay phase. Brighter flashes produced longer delays to the onset of decay. The latency vs log intensity relation of the e-wave response

determined before aspartate treatment was found to match closely the latency vs log intensity relation of the decay phase of the rod receptor response. The onset of the decay phase of the rod response was determined in normal, untreated preparations by measuring the intraretinal b-wave threshold following stimulus flashes. A precipitous drop in the rod phase of retinal threshold, indicating decay of the rod response from a saturated level, always occurred concurrently with the onset of the e-wave.

These experiments demonstrate that the onset of the e-wave (and thus the delayed ganglion cell response) occurs as the plateau phase of the produced rod response begins to decay. This correspondence strongly implies that the latencies at the two delayed responses are determined by the rods.

Preliminary experiments have been conducted in order to localize the origin of the e-wave. Experiments utilizing tetrodotoxin have demonstrated that a normal e-wave can be generated in the absence of ganglion cell spike activity. A source density analysis of the e-wave has shown that the response is primarily generated by a current source near the ganglion cell layer and a current sink near the border between the inner plexiform and inner nuclear layers. This source-sink distribution suggests that the e-wave is mainly generated by proximal elements in the retina.

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## 4. NUCLEUS AND ISTHMI

National Institutes of Health (Grant 5 TO1 EY00090-04)

Bell Laboratories (Grant)

Edward R. Gruberg, Susan B. Udin

In the past year we have completed study of the connections between the nucleus isthmi and the tectum in the frog. These were determined by several anatomical techniques.

The connections between the nucleus isthmi and the tectum in the frog have been determined by several anatomical techniques: iontophoresis of horseradish peroxidase into the tectum, iontophoresis of $^{3}$H-proline into the nucleus isthmi and the tectum, and Fink-Heimer degeneration staining after lesions of the nucleus isthmi. The results show that the nucleus isthmi projects bilaterally to the tectal lobes. The ipsilateral

isthmio-tectal fibers are distributed in the superficial layers of the tectum, coincident with the retinotectal terminals. The contralateral isthmio-tectal fibers travel anteriorly adjacent to the lateral optic tract and across the midline in the supraoptic ventral decussation, where they turn dorsally and caudally; upon reaching the tectum, the fibers end in two discrete layers, layers 8 and A of Potter. The tectum projects to the ipsilateral nucleus isthmi, and there is a reciprocal topographic relationship between the two structures. Thus, a retino-tecto-isthmio-tectal route exists which may contribute to the indirect ipsilateral retinotectal projection which is observed electrophysiologically. The connections between the nucleus isthmi and the tectum in the frog are strikingly similar to the connections between the parabigeminal nucleus and the superior colliculus of mammals.

A report of this work has been accepted by the Journal of Comparative Neurology.

This anatomical work has spurred our interest as to what physiological role the nucleus may play. The connections are shown to be both open-loop and closed-loop. We have begun single-unit recording from the nucleus. Preliminary work has revealed that there are at least two types of cells that are akin, to a first approximation, to types 2 and 4 ganglion cell fibers. The units are very susceptible to curare block, and we are developing a preparation which does not need any immobilizing drugs. We have also begun injecting HRP into the nucleus isthmi of a series of animals, and, to our surprise, both superficial and deep tectal cells are stained via retrograde transport.

## 5. SOMATOSENSORY PROJECTIONS IN THE TECTUM OF THE SALAMANDER IN RELATION TO A MONOAMINERGIC SYSTEM

National Institutes of Health (Grant 5 TO1 EY00090-04)
Bell Laboratories (Grant)

Edward R. Gruberg

After hemisection of the spinal cord or medulla oblongata, a projection has been traced to the inner half of the tectal white of the tiger salamander, using Fink-Heimer degeneration staining. By microelectrode recording it was found that the tectal projection forms a topographic somatosensory map of the contralateral half of the body. This map is in register with the overlying retinotectal visual projection. Using the Falck-Hillarp technique, it was found that the somatosensory tectal input is associated with yellow-fluorescing 5-hydroxytryptamine fibers.

A report of this work has been submitted for publication.

## 6. ORIGIN OF SPINOTECTAL TRACT

National Institutes of Health (Grant 5 TOl EY00090-04)
Bell Laboratories (Grant)

Edward R. Gruberg

We have recently completed studies on the distribution of the spinal cord cells which project to the salamander tectum. By HRP tectal injection, we have found that most stained spinal cord cells are in a thin, bilateral, mostly medial lamina at the ventral border of the spinal gray. These results very closely match the distribution of fluorescing cells (by the Falck-Hillarp method) which are almost exclusively in this same lamina. We are currently writing a paper containing these results.

## 7. THRESHOLD OF NERVE MEMBRANE

National Institutes of Health (Grant 5 ROl EY01149-03S2)
Bell Laboratories (Grant)

Stephen A. Raymond, Larry R. Carley

Activity-dependent connectivity among neuronal elements appears to be a basic substrate for information handling. The concept that informational consequences would follow failed invasion of axon branches was first suggested years ago by Walter Pitts, and evidence in accord with that notion has been accumulating since. We have been concerned with activity-dependent variables that will modulate conduction into branches. A major influence is the threshold of the branch, which we have continued to study through the past year. The following are our main observations:

### a. Effect of Depression on Refractory Period

Activity rates greater than one impulse every two seconds lead to a progressive increase in threshold called "depression." At higher activities (e.g., 10/s), the depression builds up to an equilibrium level that is 25% -100% greater than resting threshold level. The refractory period of impulses conducted while the nerve is in the depressed phase is extended. The absolute refractory period, during which even the strongest stimuli are ineffective, is prolonged from 2 ms to 3 or 3.5 ms, depending on the severity of the depression. The relative refractory period, during which impulses may conduct but require more intense stimuli than rested nerve requires, is also prolonged. If the depression is strong enough, the threshold never crosses the resting level, indicating that even the maximum period of superexcitability may be above resting threshold following impulses in depressed fibers.

b. Effects of Lithium Ion on Threshold

When 30 mg of LiCl is added to 100 ml of normal Ringer's solution, the resting threshold rises to a level that depends on lithium concentration. This effect was investigated and found to stem from the increased osmolarity of the solution. The effect is a predictable consequence of the change in resistivity of the Ringer's. The observations suggested that alterations in axonal conduction could arise from shifts of osmolarity, but we had been hoping to find a lithium-specific effect. Such an effect was observed on the equilibrium level of activity-induced depression. Even as little as 5 mM LiCl in the Ringer's surrounding an active nerve leads to a gradual reduction of the depression. NaCl and choline chloride result in increased threshold during the depressed phase, probably due to the osmolarity change. These studies form the preliminary observations on which we have designed a plan of study and investigation during 1978, concerning the question of the physiological site and mechanism of the clinical action of lithium ion.

c. Nerve Threshold Chemograph

This device is an extension of the operations involved in tracking thresholds. The activity-dependent threshold curves of axon membrane are used as an index of the effects of neuropharmaceuticals and other chemical agents. In essence, the notion is the same as the case of looking for changes in transistors by watching for shifts in the performance curves. We are seeking to establish a set of operations and procedures that will allow detection and identification of a broad variety of compounds having effects on nerve membrane. Additional experiments are needed, but await the delivery of a programmable threshold hunter. This work will continue into 1978.

## 8. CONDUCTION VELOCITY VARIATION WITH THRESHOLD

National Institutes of Health (Grant 5 RO1 EY01149-03S2)
Bell Laboratories (Grant)

Stephen A. Raymond

Swadlow and Waxman,[1] S. A. George,[2] and a number of other workers have been studying the aftereffects of impulse activity on conduction velocity. Although a correlation between threshold change and velocity shifts is expected, I studied the extent of this correlation throughout each of the phases of the threshold oscillations following activity. Threshold at the point of stimulation and conduction time over a 6-8 cm distance of axon are well correlated, suggesting that both the changes in threshold and those in conduction velocity may arise in the same processes. Those fibers with largest

threshold variation during activity also showed the largest conduction velocity changes. Changing the concentration of dissolved $CO_2$ (and hence pH and $HCO_3^-$) also produced covariation of threshold and conduction velocity.

The strength of the correlation suggests that conduction velocity can be used as an indication of threshold changes in situations where the direct measurement of threshold is difficult. I monitored the conduction velocity during intermittent responsiveness of frog axons exposed to continuous stimulation at levels fixed slightly above threshold. Since stimuli were fixed, my usual means of tracking threshold by changing the duration of each stimulus could not be used. Conduction velocities proved revealing, since at the beginnings of periods of continuous response, they became slower rapidly as the periods of response got longer. Just before failure, the conduction latencies were 20% - 30% longer and the noise in conduction velocity was high. After a period of block, or rest, the next period of responsiveness began with fast conduction velocities. This is in accord with the explanation of intermittent conduction based on threshold changes proposed in 1970. These observations were reported at the Seventh Annual Meeting of the Society for Neurosciences, November 5-10, 1977.[3]

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## 9. DESIGN AND CONSTRUCTION OF AN ARTIFICIAL LARYNX

National Institutes of Health (Grant 5 ROl EY01149-03S2)
Bell Laboratories (Grant)

Donald W. Schoendorfer, Stephen A. Raymond

We have concluded this project this year. A working, internal larynx has been worn successfully by two patients at the Roswell Park Memorial Hospital in Buffalo. Speech restoration was tested using intelligibility tests developed by Professor Kenneth Stevens, of the RLE Speech Communication Group. A natural voice from an unoperated control scored 100, and the M. I. T. Artificial Larynx scored 60. A very commonly used alternative prosthesis, the electrolarynx, scored 4. The spectral quality of the voice is pleasing; it is loud (124 dB vs 127 dB for a normal voice on the same test); dependable,

free from leakage, and acceptable to the small sample of patients so far introduced to it. We are hopeful that the publication of this work will bring the possibility of successful rehabilitation of laryngectomized patients to the attention of surgeons and speech therapists.

## 10. CYTOCHEMICAL STUDIES ON DIFFERENTIATION OF THE NEURONAL PLASMA MEMBRANE

National Institutes of Health (Grants 5 ROl NS12307-03, 5 TOl EY00090-04, and KO4 NS00010)
National Multiple Sclerosis Society (Grant RG-1133-A-1)
Health Sciences Fund (Grant 78-10)

Stephen G. Waxman, Donald C. Quick

A major interest of this laboratory over the past two years has been the differentiation of the neuronal surface in both the normal state and under various pathological conditions. Our previous studies[1, 2] had shown that there are distinct structural differences between the axon membrane at nodes of Ranvier and beneath the myelin in the internodes. Studies on the specialized electrocyte axons in the gymnotic Sternarchus indicated that normally excitable nodes of Ranvier stain intensely on the cytoplasmic surface with ferric ion and ferrocyanide following fixation in cacodylate-buffered aldehydes, while inexcitable nodes along the same axons, despite equal access to the staining solutions, are not stained by this procedure. Comparison of our results with freeze-fracture, pharmacological and physiological data suggested that the ferric ion-ferrocyanide technique might provide a cytochemical marker for regions of the axon membrane with a high sodium-channel density.[3] In order to test this hypothesis, we examined the initial segments of spinal motor neurons following staining with this technique.

On the basis of computer simulation studies on the generation of motor neuron action potentials, Dodge and Cooley[4] predicted that there should be sharp spatial gradients of sodium-channel density over the surface of motor neurons, ranging from low channel density values in the dendrites to high values at the spike initiation region in the initial segment. Their data suggested that in order for the initial segment trigger zone to excite the axon reliably in spite of the electrical load imposed by the soma and dendrites, sodium-channel density at the initial segment should approach that at the node of Ranvier.

Our electron microscopic studies, carried out on rat spinal motor neurons, have demonstrated that following fixation in cacodylate-buffered aldehydes and osmium tetroxide, a subsequent staining with ferric ion and ferrocyanide, aggregates of stain are

localized specifically on the cytoplasmic surface of the initial segment which is deeply stained, in contrast to the cell body and dendrites which do not stain. These results, which provide evidence for a structural differentiation of the neuronal plasma membrane at the initial segment, are consistent with the hypothesis that the ferric ion-ferrocyanide staining procedure may provide a cytochemical marker for regions of high ionic channel density. We are now using this technique to study membrane organization in abnormally myelinated axons (see Sec. XXVI-12) and to study the structure of excitable dendrites.

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## 11. COMPUTER SIMULATION STUDIES ON PREREQUISITES FOR IMPULSE CONDUCTION IN MULTIPLE SCLEROSIS

National Institutes of Health (Grants 5 ROl NS12307-03, 5 TOl EY00090-04, and KO4 NS00010)

Bell Laboratories (Grant)

National Multiple Sclerosis Society (Grant RG-1133-A-1)

Health Sciences Fund (Grant 78-10)

Stephen G. Waxman, Michael H. Brill

Clinical and laboratory observations suggest that it should be possible for action potentials to traverse, in a continuous manner and without interruption, demyelinated zones along some axons. The observation of demyelinated plaques in some asymptomatic patients indicates that at least some demyelinated axons have the capability to conduct impulses. One of the factors which will tend to prevent such conduction is the impedance mismatch at sites of focal demyelination, which may result in a reduction in current density sufficient to cause conduction failure. As part of an effort to examine the pathophysiology and possible modes of symptomatic therapy in multiple sclerosis, we have examined, using computer simulations, the prerequisites, in terms of membrane properties and fiber geometry, for conduction into and beyond a demyelinated region. The present studies of conduction were initiated with a hybrid integration method (implicit internode, explicit node) utilizing a modification of the Crank-Nicholson method of implicit solution of cable equations.[1] Computational parameters and values have been

published previously.[2] Our results are summarized in Figs. XXVI-1 and XXVI-2. As shown in Fig. XXVI-1, at a focally demyelinated fiber with either normal nodal membrane (sodium-channel density = 5000/square micron, based on a conductance of 2.5 pmho/channel) or with Hodgkin-Huxley membrane (500 sodium channels/square micron) in the demyelinated region, presence of sodium channels in the demyelinated region does not insure conduction past this region. Conduction failure may occur at the demyelinated zone, despite normal membrane excitability as a result of impedance mismatch, i.e., due to insufficient current density. However, as shown in Fig. XXVI-2, our simulations indicate that reduction in length of the two internodes closest to the demyelinated region, to approximately one-third of normal length or less, will facilitate conduction into and beyond the demyelinated plaque. We also examined the prerequisites in terms of channel density necessary to sustain conduction through the plaque

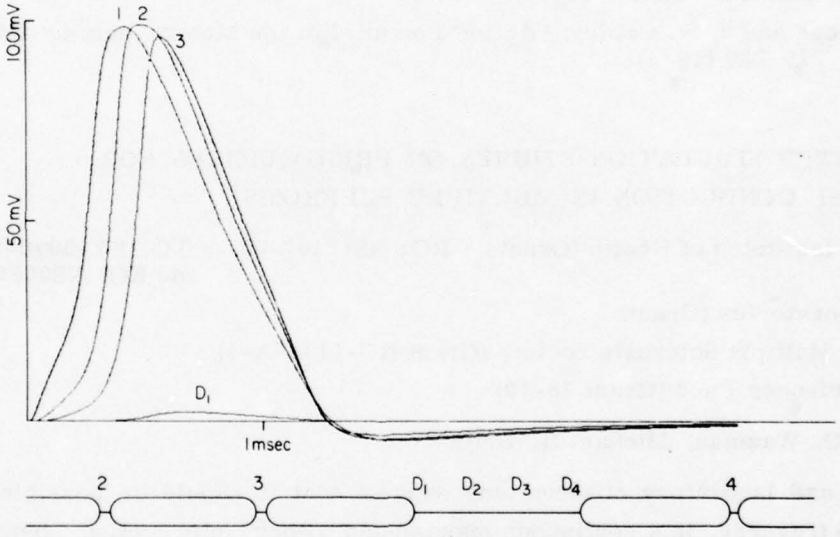



Fig. XXVI-1. Computed action potentials for a fiber focally demyelinated in the region from $D_1$ to $D_4$. The axon membrane in the demyelinated region has the same specific membrane properties as normal nodal axolemma. For the fiber shown in this figure, the internode proximal to the demyelinated region ($3\text{-}D_1$) is of normal (2000 μm) length. Despite the assumption of excitable membrane in the demyelinated region, conduction fails at point $D_1$ as a result of inadequate current density. In this and Fig. XXVI-2, potentials from nodes 1-6 and in the demyelinated region ($D_1\text{-}D_4$) are shown; potentials at nodes 7-11 were computed but are omitted for clarity. Schematic diagrams below the traces show fiber geometry in the vicinity of the demyelinated region; internode 1-2 and all internodes distal to node 4 are of normal length.

and found that a channel density of 200 channels/square micron or greater would suffice to support conduction through the demyelinated region, although again the presence of reduced internode distances proximal to the demyelinated zone was necessary. The present results thus show that reduction in internode distance proximal to a demyelinated region may play a role in permitting action potentials to invade and pass the demyelinated area. In this context it should be noted that histological studies have shown the

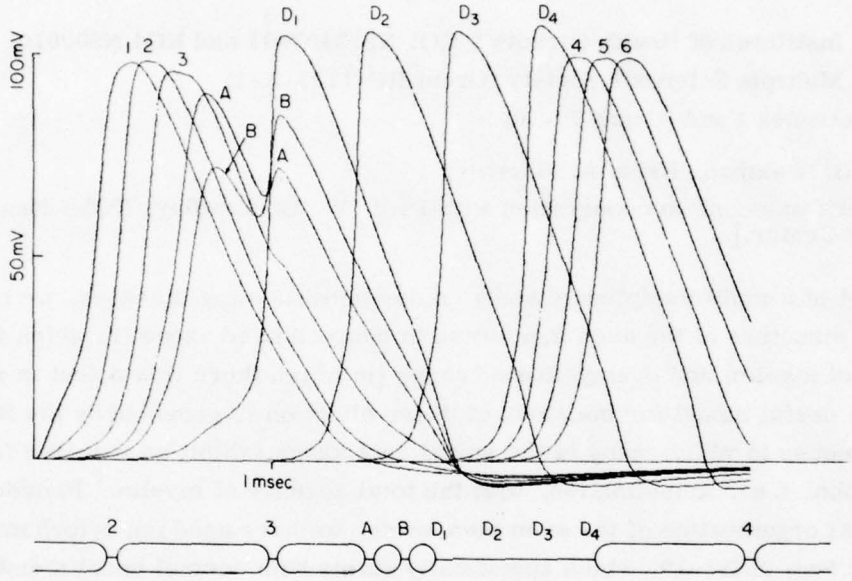



Fig. XXVI-2. Computed action potentials for a fiber similar to that shown in Fig. XXVI-1 with two short internodes (A-B, B-$D_1$; 400 μm) interposed proximal to the demyelinated region. Under these conditions, the impulse invades the demyelinated region, and passes without interruption into the distal part (e.g., nodes 4, 5, 6) of the fiber.

presence of reduced internode distances along remyelinated fibers. We are led to conclude that, in remyelinated axons, matching of internode distances to functional requirements may be of considerable importance, and that reductions in the internode length may have functional significance in terms of facilitating conduction past focally demyelinated areas.[3]

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## 12. ORGANIZATION OF THE AXOLEMMA IN DYSMYELINATED AXONS

National Institutes of Health (Grants 5 ROI NS12307-03 and KO4 NS00010)

National Multiple Sclerosis Society (Grant RG-1133-A-1)

Health Sciences Fund (Grant 78-10)

Stephen G. Waxman, Erika A. Hartwieg

[This work was done in cooperation with Prof. W. G. Bradley, Tufts New England Medical Center.]

As a part of a multidisciplinary study on the demyelinating diseases, we have begun to study the structure of the axon membrane in demyelinated axons (in which there is destruction of myelin) and dysmyelinated axons (in which there is a defect in myelinogenesis). A useful model for the study of dysmyelination is provided by the ReJ dy/dy dystrophic mouse in which many of the spinal root axons exhibit an extreme form of dysmyelination, i.e., amyelination, with the total absence of myelin.[1] In order to study the structural organization of the axon membrane, we have used the cytochemical method described in Sec. XXVI-10, which specifically stains both normal nodal membrane and the membrane at the initial segment, and which we believe may allow visualization of regions of high sodium-channel density membrane.

We examined the lumbar ventral roots of 46-day old, litter mate dy/dy and +/? female mice, following fixation in cacodylate-buffered aldehydes and staining with ferric ion and ferrocyanide as described previously.[2] In both normal roots (from +/? mice) and at the occasional normally myelinated fibers in dystrophic (dy/dy) roots, dense precipitates of stain were present on the cytoplasmic surface of the nodal axolemma. In contrast to this, the amyelinated axons exhibited no dense staining. In some cases a fuzzy undercoating was present subjacent to the axolemma, as has been described following conventional staining at normal nodes of Ranvier. Observations of heminodes, at the junction between myelinated and amyelinated regions, showed thin extensions of the paranodal Schwann cell cytoplasm, in some cases extending for several microns over the initial portion of the amyelinated axon.

The present data show clear structural differences between the axon membrane of the amyelinated axons in dystrophic mice and the axon membrane at normal nodes of Ranvier (as judged by staining with ferric ion and ferrocyanide in both normal and

dystrophic animals). On the basis of results we are tempted to speculate that sodium-channel density may be substantially lower in the amyelinated axon membrane than at normal nodes of Ranvier. It is interesting, in this regard, that Rasminsky et al.[3] have demonstrated continuous conduction along the dysmyelinated parts of some spinal root axons in dystrophic mice. As noted in Sec. XXVI-13, we have examined, using computer simulations, the prerequisites in terms of membrane properties and fiber geometry for such continuous conduction.

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## 13. NEUROPHYSIOLOGY OF CONDUCTION ALONG AXONS IN THE NORMAL CNS

National Institutes of Health (Grants 5 RO1 NS12307-03 and KO4 NS00010)
National Multiple Sclerosis Society (Grant RG-1133-A-1)
Health Sciences Fund (Grant 78-10)

Harvey A. Swadlow, Stephen G. Waxman

Our previous studies on conduction along axons in the corpus callosum of the rabbit indicated that conduction properties of these axons are not invariant in the temporal domain, but, on the contrary, vary with the history of previous impulse activity along the axon. In particular, the conduction properties of each axon are determined by the sequence: action potential → refractory period → supernormal period → subnormal period. (This is described elsewhere in greater detail.[1]) During the past year we have addressed two additional problems: impulse conduction along axons within the primate brain; and development of a modified criterion of latency invariability for the identification of antidromically activated neurons.

### a. Impulse Conduction along Axons within the Primate Brain

For these studies, extracellular recordings were obtained from single neurons in the prelunate gyrus of the Rhesus monkey, Macaca mulatta. These studies utilized methods similar to those which we have described previously.[2] Impulse conduction along callosal axons was studied by measuring latency to antidromic activation of cell

bodies following constant current stimulation via chronically implanted electrodes. Stimulating electrodes were placed intracortically in the contralateral prelunate gyrus and also under visual control into the posterior portion of the corpus callosum. Antidromically activated neurons were identified by collision techniques. For neurons which were shown to be antidromically activated, latency to a test stimulus was determined at various intervals following a single suprathreshold conditioning delivered through the same stimulating electrode or following a spontaneous impulse. As had previously been found in callosal axons in the rabbit, variations in both threshold and latency of the response to a test stimulus occur following a single conditioning stimulus. Threshold was therefore determined at each conditioning stimulus/test stimulus interval, and intensity of the test stimulus was always adjusted to 1.2 × this threshold value.

Each of more than 40 neurons tested showed a period of supernormal impulse conduction following the relative refractory period of a single prior impulse. Peak magnitude of the decrease in latency occurred at intervals of 4-12 ms and was generally from 5% to 10% of controlling antidromic latency. Duration of the supernormal period ranged from 30 ms to more than 150 ms. If a train of conditioning pulses was presented instead of a single conditioning pulse, a subnormal period of decreased conduction velocity and excitability was observed to follow the initial increase in conduction velocity and excitability. Duration and magnitude of the subnormal period were both dependent upon the number and duration of the conditioning pulses. Many neurons were shown to take several seconds to return to control levels after a conditioning train of 10 or 20 pulses. Some callosal axons could be antidromically activated from both midline callosal and contralateral cortical stimulation sites. For such axons the magnitude of the variations in antidromic conduction latency was approximately proportional to the control latency at each stimulation site. These results indicate that variations in antidromic latency reflect variations in the conduction velocity distributed along the axon under study. The results of the present study, as in those of previous studies, indicate that variations in conduction velocity and excitability to the test stimulus are a function of prior activity in the axon under study rather than the result of ephaptic interactions between axons or some other artifact of prior electrical stimulation. Thus, variations in latency occur following spontaneous as well as electrically elicited prior impulses.

In addition, control experiments showed that while no decrease in latency occurred to a test stimulus that followed a conditioning stimulus which is just subthreshold, decreases in latency of similar magnitude and time course occur to a test stimulus that follows a conditioning stimulus presented at either 1.1 or 2.0 × threshold. Finally, additional control procedures have shown that when the intensity of a conditioning stimulus is just at threshold, a decrease in latency to the test stimulus only occurs when the initial conditioning stimulus results in a spike.

The present results extend our observations on activity-dependent variations in

conduction velocity and excitability to axons within the brain of the primate. Similar observations have been made within the past year by Kocsis et al.[3] in the axons of caudate nucleus neurons, and Renaud and Hopkins[4] in the axons of hypothalamic neurons. The results of Raymond and Lettvin[5] address the question of the mechanisms underlying these aftereffects of activity.

In the rhesus monkey, where interhemispheric conduction distances are less than 60 mm, we have observed variations in interhemispheric conduction time of more than 6 milliseconds. In the human, where interhemispheric distances may exceed 100 mm, we would anticipate variations in axonal conduction time of an even greater magnitude. Such variations in conduction time may significantly affect the temporal summation and coding of neural information.

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## 14. NEUROPHYSIOLOGY OF DEMYELINATED CENTRAL AXONS IN SITU

National Institutes of Health (Grants 5 RO1 NS12307-03 and KO4 NS00010)
National Multiple Sclerosis Society (Grant RG-1133-A-1)
Health Sciences Fund (Grant 78-10)

Stephen G. Waxman, Jeffery D. Kocsis

We are beginning a series of studies on the neurophysiology of impulse conduction along demyelinated axons within the mammalian brain. The studies will utilize our previous data on impulse conduction along normal central axons within rabbit corpus callosum for normative data.[1] We now intend to study impulse conduction in this same system following the production of focal demyelinating lesions. We are at present investigating various methods for producing such lesions. We intend to produce focal lesions

in such a manner that it will be possible to study impulse conduction along demyelinated and normally myelinated regions of the same fiber, so that each fiber will act as its own control. We then intend to compare the physiology of conduction in demyelinated and normally myelinated regions of these fibers and to study their pharmacology. As in our previous studies on impulse conduction in the CNS, we are doing correlative ultrastructure and cytochemistry on the affected axons. Our ultimate goal in this research is the development of appropriate models with which to screen pharmacological agents of possible use in multiple sclerosis.

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## 15. NOVEL FORM OF LETTER CHART FOR EYE TESTIN

National Institutes of Health (Grant 5 TO1 EY00090-04)
Bell Laboratories (Grant)

Bradford Howland

The familiar Snellen eye-testing chart uses large, black, serifed letters on a white background, and is the universal standard by which visual resolution is compared. A disadvantage of the Snellen chart is the fact that defocused letters can still be partially recognized by their blur patterns; much time is thus wasted as the patient attempts to guess the letter. The layout of this chart is further complicated by the fact that each letter has a different degree of recognizability.

Analysis of the spatial frequency content of the Snellen letters reveals that they contain high and low spatial frequencies in generous measure. We have recently experimented with charts in which the low spatial frequency components have been filtered out, or are absent by design.

Figure XXVI-3 shows such a chart, using superimposed transfer letters of the same type font. The basic letter stroke is a black line with a white stripe down the middle and is placed on a neutral gray background having the same average luminosity as the stripe. When viewed from a distance, the letters of the new chart behave as follows: (a) When the letters are too small to be recognized, they disappear from view, rather than being unrecognizable blurs. (b) The distance at which disappearance occurs is determined by width of the letter stroke, and each of the letters has very nearly the same visibility. Thus, the choice of letters, or the particular choice of type font is largely immaterial to the design of the new chart, as long as the stroke of the letter is uniform in width.

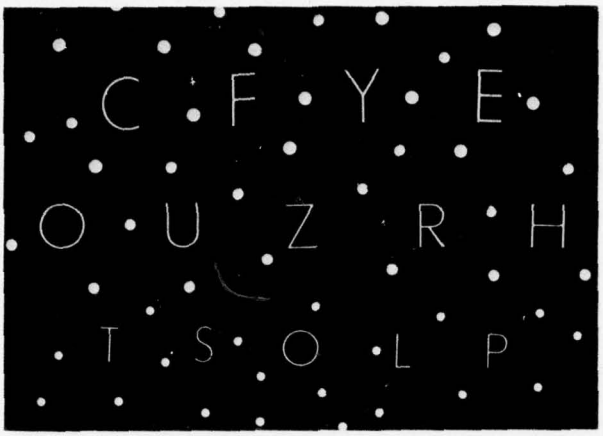



Fig. XXVI-3. Photograph of new letter chart with superimposed array of dots. Letters were formed by superimposed black (futura inline) and white (futura demi-bold) transfer lettering (chartpak) on a 25% reflecting neutral gray surface. (The shade of gray in this offset print may differ appreciably.)

For these effects to occur, the photometric balance of the letter-stroke versus the gray background must be accurate to a few percent, and the shade of gray must be chromatically neutral since defocused letters against a warm (brownish) gray appear as blue outlines. The requirement of accurate photometric balance effectively rules out hand-drafting of the letters; we have therefore made use of available transfer letters, in outline, and solid forms of the same type font.

Achievement of photometric balance in the symmetrical triphasic letter-stroke goes a long way toward minimizing the low spatial frequency content of the letter. The ideal lowpass filtered letter stroke would be a thin white line (a delta function) with a gray surround, modulated by the sin x/x function. Since such a letter stroke is impractical at present, we are investigating the Fourier transform functions for three- and five-element solid black and white strokes of various proportions.

More recently, we have added to the new letter chart a galaxy of randomly placed stars, dots, or asterisks having a diameter equal to the stroke width, with approximately three to five stars per letter. This refinement greatly inhibits the recognition of letters of marginal visibility. This is evidently due to the fact that the solid white or black stars which have appreciable low-spatial-frequency content retain their visibility, when defocused, more than do the letters, thus functioning as an effective "noise" background. When, however, the letters are in focus, the background of stars is easily ignored. With the addition of the stars or dots photographic reproductions of the charts, which were unsatisfactory because of uneven gray scale, functioned as well as the originals.

An obvious extension of the method is to use a set of outline drawings of simple

objects, in which each picture would have a different stripe width on the same gray background. These could be used for the testing of very young children and other illiterates.

We wish to thank Dr. Jerome Rosner, formerly at the New England College of Optometry, for helpful discussions and suggestions.

## 16. NEW TYPE OF SUBJECTIVE PUPILLOMETER

National Institutes of Health (Grant 5 TO1 EY00090-04)
Bell Laboratories (Grant)

Bradford Howland

We have constructed an instrument that permits a subject to measure the diameter of his/her pupil to an accuracy of approximately 0.2 mm in light or dark-adapted condition. The optical design of this instrument, which utilizes a strong, crossed-cylinder lens, is such that it does not exhibit the large errors, due to uncertain refraction or subject accommodation, of previously described instruments, such as the entoptic pupillometer of Allen, described by I. M. Borish.[1] The instrument presents a set of four circular blur patterns with sharp outlines: the subject turns a knob that adjusts the spacing until the patterns are tangent. The instrument is simple to operate but is subject to the usual uncertainties, due to the ease with which pupil diameter varies with subjective and psychological factors. The instrument uses light-emitting diodes and a simple mechanism, and could perhaps prove useful in the monitoring of therapy with drugs such as the tricyclid antidepressants, that noticeably affect pupil size.

### References

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## 17. ELECTRONIC ABERRATION SYNTHESIZER

National Institutes of Health (Grant 5 TO1 EY00090-04)
Bell Laboratories (Grant)

Bradford Howland

The electronic aberration synthesizer is a device with which a subject can determine the first nine coefficients in the polynomial describing the aberrations of the lens of his eye. The subject adjusts the controls of the aberration generator, until the elements of a perceived grid pattern are linear and parallel. The apparatus has been built,

calibrated, and tested, using the designer as subject, and tests with a group of subjects will shortly commence. An aim of our study will be to test whether the statistical averages of aberration coefficients obtained with an entirely subjective method, using analysis of the drawings of 55 subjects, are repeatable with the new method.[1] Furthermore, we hope to determine correlations of the new aberration data with the subject's performance on letter-test charts, of traditional and newer designs.

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## 18. A FIGURE SHOWING BLUE-BLACK REVERSAL WITH INCREASED VIEWING DISTANCE

National Institutes of Health (Grant 5 TO1 EY00090-04)

Michael Brill, Bradford Howland

In our efforts to understand the special role of the blue receptor in color vision, we constructed a display of blue and black felt marker lines on white construction paper partly painted with yellow tempera, such that the blue and black appearances reversed when viewing distance was increased.

A reduced facsimile of the display is shown in Fig. XXVI-4. The entire figure was originally 12 inches high. The black lines (width 1/16 inch) were separated from the yellow areas by 1/4 inch of white. The dark blue line (width 1/8 inch) was between the two yellow areas (width 1 inch).

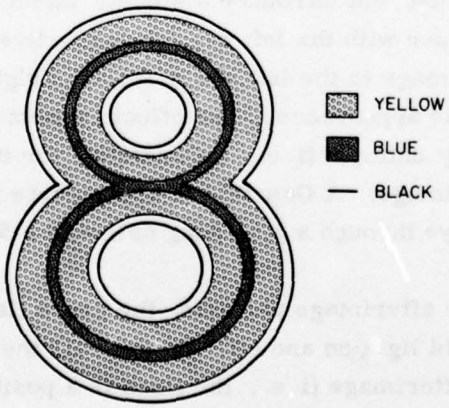



Fig. XXVI-4. Blue-black reversal with increased viewing distance.

When viewed under incandescent light from a distance of 3 feet, the blue and black lines were readily identified in accordance with the pigment names. From 10-15 feet, however, most observers saw the black lines change to blue and the blue line to black.

The change of blue to black can be attributed to the rather low spatial resolution of the blue-sensitive visual mechanism compared to that responsible for assessing contrasts of brightness. Hence the blue and the adjacent complementary yellow cancel as seen by the blue mechanism, leaving a sensation of no hue at the site of the dark line.

The change of black to blue is more difficult to explain by such conventional arguments. It is not easy to understand why the complementary blue induced at the edge of each yellow field (partly by eye movements across the boundary into the white region) is ascribed to the black line by the perceiver.

## 19. BINOCULAR AFTERIMAGE EFFECT

National Institutes of Health (Grant 5 TOl EY00090-04)

Michael Brill

We have recently observed a striking binocular afterimage effect: Illuminating one eye can cause the polarity of an afterimage already present in the other eye to change (transiently) from negative to positive.

One can easily observe the effect as follows:

Look briefly with the left eye at an intense green light, and then look with the same eye at a piece of white paper under incandescent light. The long negative (dark) afterimage occasioned by the green light will look magenta at first and then turn bluish-purple. This happens whether or not the right eye is open. Closing the left eye or dimming the light on the white paper makes the afterimage turn bright green (positive).

Now repeat the procedure, but introduce a steady, intense light into the right eye as you look at the white paper with the left eye. Irrespective of the color of the light in the right eye, the afterimage in the left eye will flash bright green for a second and then return to a dark purple appearance. The effect is most pronounced when the light in the right eye is spatially uniform (i. e., a Ganzfeld), for then there can be no binocular rivalry with the afterimage. A Ganzfeld of appropriate intensity can also be made by illuminating the right eye through a ping pong ball with a 500-watt projector from 3 feet away.

As long as the negative afterimage persists, the green flash can be elicited repeatedly by turning the Ganzfeld light on and off. In general, the flash is the same color as the light occasioning the afterimage (i. e., the flash is a positive homochromatic afterimage).

The green (homochromatic) flash cannot be attributed to stray light entering the left

eye from the illuminant producing Ganzfeld on the right eye: More light in the left eye just makes the afterimage appear darker and more purple. On the contrary, the flash effect is similar to the polarity reversal that happens when light is dimmed in the left eye.

One can demonstrate that the green flash is the result of dimming of the light in the left eye caused by sympathetic iris contraction in the left eye from the Ganzfeld in the right eye. Repeat the above experiment, but replace the white piece of paper with a moderate white light in Maxwellian view. This can be done by interposing a lens between the eye and a distant light source, such that the near focal point of the lens is in the plane of the pupil and at its center. When all the light passes through the center of the pupil, it will not be affected by iris contraction. Now look at an intense Ganzfeld light with the right eye, and the green flash will not appear.

The time course of the green flash may be the combined effect of the transience of the pupil reflex and the adaptation of receptors to the dimmed light. It is interesting to note that the perceptual effect of the afterimage reversal is far greater than that of the general dimming of the visual field caused by the sympathetic iris contraction.

## 20. DEVICE FOR ILLUMINANT-INVARIANT ASSESSMENT OF CHROMATIC RELATIONS

National Institutes of Health (Grant 5 TO1 EY00090-04)

Michael Brill

For a large class of illuminant spectra and object spectral reflectances, we have designed a trichromatic photosensing device that compares the light reflected from several objects in its visual field, and computes quantities characteristic of the compared reflectance spectra of these objects, independent of the illuminant spectrum. Although the design makes no direct suggestions for human color vision, such an invariance could be helpful in color constancy.

The design[1] follows the approach of H. Yilmaz.[2] Over a visible wavelength range $\phi \in [0, 2\pi]$, define three photoreceptor spectral sensitivities

$$q_1(\phi) = 1, \qquad q_2(\phi) = 1 + \sin(\phi), \qquad q_3(\phi) = 1 + \cos(\phi).$$

Suppose the energy spectrum of the illuminant is uniform in space and time, and varies slowly enough in wavelength so that it is adequately represented by the first three terms in its Fourier expansion in $\phi$. Then, for some $a_1, a_2, a_3$, the illuminant spectrum $I(\phi)$ is given by

$$I(\phi) = a_1 + a_2 \sin(\phi) + a_3 \cos(\phi).$$

Let each (nonfluorescent) reflecting object i have a reflectance spectrum constrained only by the stipulation that it has no Fourier components in $\cos(2\phi)$ or $\sin(2\phi)$. (We exclude these components in order to insure the invariance that follows.) Then the reflectance spectrum $r_i(\phi)$ for the $i^{th}$ object is

$$r_i(\phi) = b_{i1} + b_{i2} \sin(\phi) + b_{i3} \cos(\phi) + \sum_{k=3}^{\infty} [c_{ik} \cos(k\phi) + d_{ik} \sin(k\phi)].$$

Note that we have allowed a tremendous freedom in the possible spectra of reflectance, which can be very jagged. Chlorophyll is one example of a natural pigment with this property.

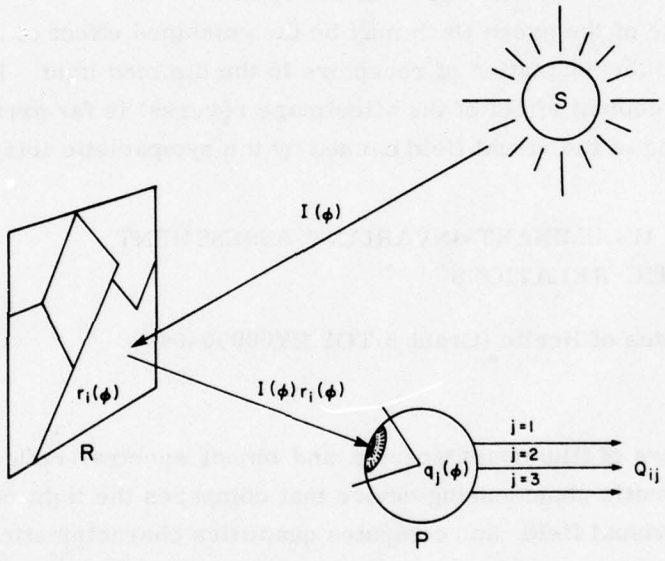



Fig. XXVI-5. Reception of reflected light by the photosensor.

If a triad of photoreceptors, each with a different spectral sensitivity, receives light from object i, three linear filtrates (tristimulus values) $Q_{ij}$ are obtained (see Fig. XXVI-5), given by the integrated products of the illuminant spectrum, the $i^{th}$ reflectance spectrum, and the spectral sensitivity of the $j^{th}$ photopigment ($j = 1, 2, 3$):

$$Q_{ij} = \int_0^{2\pi} r_i(\phi)\, I(\phi)\, q_j(\phi)\, d\phi.$$

From these assumptions, it follows that the tristimulus vector $(Q_{i1}, Q_{i2}, Q_{i3})$ of an object i is an invertible linear transformation of the object color 3-vector $(b_{i1}, b_{i2}, b_{i3})$, with the coefficients depending only on the illuminant parameters $a_j$. Thus a ratio of

tristimulus volumes is independent of illuminant, and is an assessable measure of relationships among the object spectral reflectances. Implications for experiments such as those of Land[3] are discussed elsewhere.[1]

The design may be generalized as follows: over a visible wavelength region $\lambda \in [\lambda_1, \lambda_2]$, define $n^{th}$ degree polynomials $P_n(\lambda)$ $(n = 0, 1, 2, \ldots)$ orthogonal with respect to a weighting function $w(\lambda)$. For $j = 0, 1, 2$, define $q_j(\lambda) = P_j(\lambda)\, w(\lambda)$. Over the visible range, approximate the illuminant spectrum by

$$I(\lambda) = \sum_{k=0}^{2} a_k P_k(\lambda)$$

and the reflectances by

$$r_i(\lambda) = \sum_{\ell=0,\, \ell \neq 3,\, 4}^{\infty} b_{i\ell} P_\ell(\lambda).$$

Then once more the illuminant incurs a linear transformation on the object color 3-vectors $(b_{i1}, b_{i2}, b_{i3})$ to make the tristimulus vectors $(Q_{i1}, Q_{i2}, Q_{i3})$, and hence tristimulus volume ratios are once again illuminant-invariant.

It should be noted that when an illuminant change shows up as an invertible linear transformation on object tristimulus vectors, the inverse of the transformation can be constructed if three of these vectors are known before and after the change. Thus, under the above assumptions, a device with prior information about three object colors can reconstruct all the others in its visual field, thereby attaining invariance in the appearance of each individual object as well as in their relationships.

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# PUBLICATIONS AND REPORTS

## MEETING PAPERS PRESENTED

SPIE 20th Annual Technical Symposium, San Diego, California

August 23-27, 1976

Paper in SPIE Vol. 84

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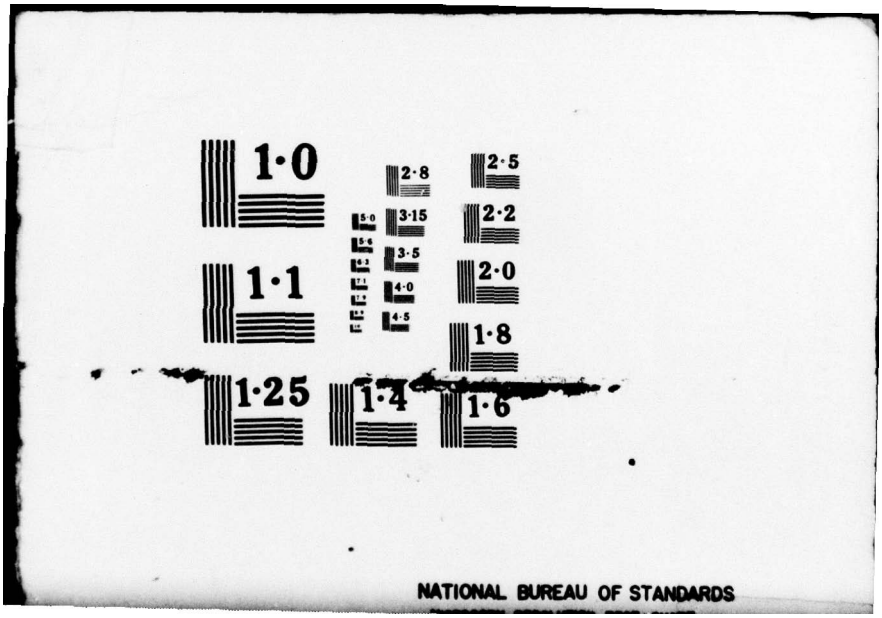
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