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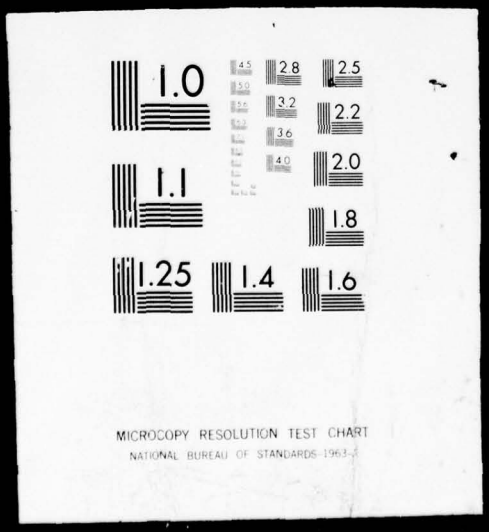

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RLE PROGRESS REPORT

No. 119

JANUARY 1977

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

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
RESEARCH LABORATORY OF ELECTRONICS

RLE PROGRESS REPORT NO. 119

January 1977

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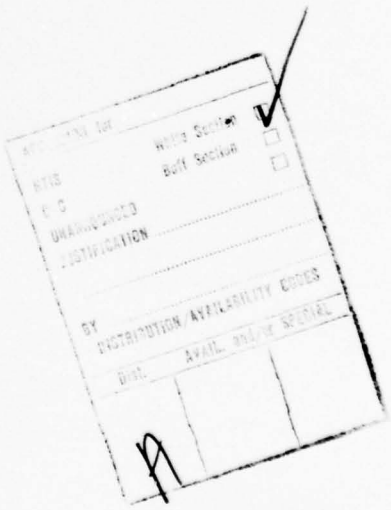
J. Allen



FOREWORD

This report, No. 119 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. Emphasis is on research progress for the half-year period ending December 31, 1976, and the source of support is indicated for each project.

Detailed reports of progress for individual projects will no longer be included in RLE Progress Reports. They may, at the discretion of the research supervisor, be issued individually as part of a new numbered series of RLE Research Reports. Persons interested in receiving reports in a particular field of research should write the research supervisor or the Document Room, Research Laboratory of Electronics, M. I. T., Room 36-412.

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GENERAL PHYSICS

I. MOLECULE MICROSCOPY

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Dusan G. Lysy
Allen M. Razdow
Bruce R. Silver
Peter W. Stephens

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John G. King, James C. Weaver

We have been developing instruments called molecule microscopes based on the simple idea that neutral molecules travel in straight lines between collisions. We are interested in producing magnified images (micrographs) of samples that emit neutral molecules as a result of various stimuli.

The contrast in a molecule micrograph arises from spatial variations in properties of the sample such as permeability, diffusion, binding of neutral molecules, and spatial distribution of enzymes. These properties cannot be observed directly in other forms of microscopy.

Although molecule microscopy can be used to study problems in various fields, we think that the most significant and valuable applications, especially while the spatial resolution is of the order of 1 μm, will be to problems in the life sciences. Because there are many kinds of sample, sample preparation or treatment, sample stimulation, and molecular emissions, molecule microscopy is rich and complex and no single apparatus is the Molecule Microscope. For instance, the sample can be dead or alive, in vacuo, in vitro, or in vivo, denatured or surviving. Stimuli include heat, light, charged particles, currents, toxins, hormones, and so forth. The observed molecules may have come through the sample, been part of it, been previously placed on it as a stain, or may have been generated by it in such processes as specific enzyme catalyzed reactions or metabolism.

During recent years, we have constructed and tested a lot of apparatus and performed experiments relevant to understanding the various mechanisms involved. We have studied, more or less thoroughly, the desorption of water and ethanol from model biological surfaces by both thermal desorption and electron-stimulated desorption techniques, the interaction of CO with silicon surfaces, variations of permeability and metabolism of dead and surviving tissue (frog skin, toad bladder, and vascular smooth muscle), and immobilized and solubilized enzyme catalyzed reactions.

Now we are beginning to use our instruments and techniques in their preliminary form to study what we hope will prove to be important scientific problems. Our

collaborators are interested in such diverse systems as the mechanism of thrombus formation on materials, cell surface properties and active transport in tissue, enzymology, and toxicology.

1. SCANNING PINHOLE MOLECULE MICROSCOPE (SPMM)

The apparatus is being modified to allow the study of living tissue in vitro, thereby eliminating the problem of vacuum dehydration. The modified apparatus will be used to study, with spatial resolution, the active and passive transport properties of frog's bladder. This epithelium (a single layer of epithelial cells, ~15 μm on a side, on a thin, ~20 μm, basement membrane), as well as toad's bladder and frog's skin, has long been studied without spatial resolution by other researchers as a model of the human kidney. We intend to observe the epithelial cells in vitro by differential interference light microscopy simultaneously with SPMM to correlate transport properties with tissue morphology at the cellular level. This work is being done by Joseph A. Jarrell in collaboration with Dr. Alvin Essig and Dr. Michael Lang of the Boston University Medical Center.

2. DESORPTION EXPERIMENTS RELATED TO THE SCANNING DESORPTION MOLECULE MICROSCOPE (SDMM)

Bruce R. Silver has performed some experiments relating to scanning desorption molecule microscopy (SDMM) with emphasis on neutral molecule staining for biological surface studies. With this technique a scanning electron beam is used to desorb water or other small molecules as a means of mapping weak chemical properties of the surface monolayer. We are interested in direct electron stimulated desorption (ESD) and also in desorption by local electron beam heating.

The apparatus comprises a scanning electron beam, neutral molecule staining beam, quadrupole mass spectrometer, and sample holder. It has been used to measure the ESD cross sections of D_2O and ethanol stains from platinum and three model biological surfaces as a function of electron energy. The three biological surfaces included a protein (bovine serum albumin), a carbohydrate (glycogen), and a nonpolar lipid (tristearin). We compared the cross sections with binding energy data determined by flash desorption in the same apparatus.

The ethanol is desorbed with a total cross section, Q, of approximately 1×10^{-15} cm^2 at 1 kV, falling to 2×10^{-16} cm^2 at 4 kV, which is nearly the same for all four surfaces. The flash desorption data show similar binding energies and simple first-order kinetics for all four surfaces.

The D_2O data on tristearin and BSA surfaces show ESD cross sections of 1×10^{-15} cm^2 at 1 kV, falling to 1×10^{-16} cm^2 at 4 kV, while on platinum and glycogen surfaces Q is 3×10^{-16} cm^2 at 1.5 kV, falling to 5×10^{-17} cm^2 at 4 kV. The flash

desorption data indicate kinetics of order less than one, and can be interpreted in terms of condensed and mobile phases of the adsorbed D_2O. In this model, which is examined through the peak shift with coverage, peak width, and initial desorption rate, the binding energy of the mobile phase is found to be 3 kcal/mole for BSA and tristearin and 5 kcal/mole for platinum and glycogen, correlating with the ESD cross sections.

Dusan G. Lysy investigated the desorption of water on five different model biological surfaces by a thermal desorption technique. In the basic experiment a platinum ribbon was coated with a thin layer of the biological macromolecule under consideration and cooled to liquid nitrogen temperatures in vacuum, the adsorbed water molecules were thermally desorbed by ohmic heating of the sample ribbon, and then the desorbed water molecules were detected with a quadrupole mass spectrometer system. The resulting plot of the desorbed water flux as a function of the sample temperature exhibited a series of peaks corresponding to different binding states of the adsorbate molecules on the sample. The observed peaks divide naturally into three groups on the basis of the sample temperature: the low-temperature peak between -140°C and -50°C, the middle-temperature peaks between -50°C and 210°C, and the high-temperature peaks between 210°C and 560°C.

The samples investigated were a protein (bovine serum albumin), a polar and a nonpolar polypeptide (poly-L-lysine hydrobromide and poly-L-alanine), a carbohydrate (glycogen), and a completely nonpolar lipid (tristearin).

The low-temperature peak was present in all samples, as well as in the controls, and no sample specificity was demonstrated. At high coverages this peak can be interpreted as the sublimation of ice. Adsorption into this peak takes place with a sticking coefficient of at least very close to unity for sample temperatures during adsorption, $\lesssim$125°K, for coverages between ~0.1 and ~300 monolayers of water.

The middle peak groups showed very strong sample specific peak patterns with major peak energies from 16.5 to 22.2 kcal/mole, and desorption in the range of energies from 14.5 to 27.5 kcal/mole. The peaks each contained a range of activation energies for desorption, and the peak patterns were consistent with the assumption that the number and types of polar groups present in the sample determine the amount of water adsorption in this peak group and the complexity of the peak patterns, thereby giving the observed sample specificity. This peak group appears to correspond to the water adsorption traditionally measured by water adsorption-desorption isotherms taken near room temperature and often described by the Brunauer-Emmett-Teller (BET) theory of multilayer adsorption, with the important differences that in our experiment kinetic rather than equilibrium parameters were measured and that different adsorption states could easily be differentiated. Lower limits on the sample specific water adsorption in this peak group of ~15% of the BET monolayer values were established, and the observed coverages were shown to be correlated with the trends obtained from the BET monolayer values. The

sizes of these peaks were shown to be proportional to the sample amount, and the peak locations to be reproducible even when the amount of applied sample was varied.

The high-temperature peak group gave sample specific peak patterns. Evidence was found to support the interpretation of this peak group as representing pyrolysis of the sample.

3. MOLECULE FLUXES IN TISSUE

The application of mass spectrometry methods to the study of fluxes of volatile molecules through biological tissues and membranes continues. This work is being performed by Stanley J. Rosenthal in the laboratory of Dr. Alvin Essig at Boston University Medical School. Simultaneous measurement of O_2 consumption and CO_2 production has been demonstrated, and much time has been devoted to studies of calibration methods, design of appropriate Ussing chambers, and control and stabilization of the flow of Ringer's solution. We are now ready to start a series of investigations of various epithelia. Later, this approach can be extended to nonvolatile species such as lactate, by use of the Volatile Enzyme Product (VEP) method.

4. VOLATILE ENZYME PRODUCT (VEP) TECHNIQUE

Recently, we have been pursuing the development of a technique that interfaces enzyme-catalyzed reactions with a quadrupole mass spectrometer (employed as a sensitive mass-filter detector) by means of a semipermeable membrane.[1] All that is required is that at least one of the reactants of the enzyme-catalyzed reaction be volatile and able to permeate the membrane, so that a large number of enzymes can be considered. In short, the VEP technique offers the potential of high sensitivity, specificity, and speed in the assay of substrates, cofactors, effectors, and enzymes. Although much work needs to be done, the ultimate sensitivity should allow, for example, continuous monitoring of metabolic fluxes (e.g., CO_2 and lactate) from single cells with an associated time constant of approximately 10 seconds. Furthermore, in combination with scanning pinhole molecule microscopy, this method should permit mapping of suitable enzyme distributions in nonstained and nonfixed tissue slices.

Recent work continues to emphasize preliminary exploratory studies[2] and, most important at the present stage of development, improvement of the technique's capabilities. In order to facilitate understanding of results, all recent work emphasizes steady-state conditions, and transitions between steady states. Specifically, we have used both catalase (EC 1.11.1.6; volatile product is O_2) and urease (EC 3.5.1.5; volatile product is CO_2) to examine effects of volume flow rate, $\dot{V}$, passive continuous degassing, pH and continuous electronic averaging over the volatile product molecule's mass peak. In addition to using the two enzyme systems, brief trials with suspensions of viable

cells (one species of yeast) have been made.

Our current objectives include a continuing attack on limiting sources of noise (fluctuations in $\dot{V}$, residual partial pressures, electronics drift, and a nonoptimal value of counting efficiency), and exploratory studies of other enzymes.[2] Also, in addition to the continuous assays now being studied, the assay of small discrete samples (e.g., homogenized brain tissue) will be pursued, and application of the VEP technique to environmental measurements such as sensitive detection of pesticides will be explored.

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5. THERMAL ENZYME PROBE

The thermal enzyme probe (TEP)[1, 2] is a tantalizingly attractive biochemical transducer because of its potential universality and basic simplicity (two thermistors, one coated with immobilized enzyme, the other without). The steady-state response, which can be reached within a few seconds, is a temperature difference, ΔT, which is converted into an electrical signal. Almost any enzyme can be used, since nonzero enthalpy changes occur with almost every reaction. A major difficulty, however, is that the TEP is not a particularly sensitive device; both simple theory and experiments already performed show that small ΔT's, of the order of 10^{-4} °C for 10^{-3} molar substrate concentrations, are expected. For this reason, the primary technical problems involve the physics of differential thermometry in flowing aqueous solutions.

All recent work (primarily by Scott P. Fulton) has been directed toward understanding and reducing various sources of noise. It is still not clear what the fundamental limits of ΔT measurements are in a flowing aqueous solution. Based on the work of others,[3] as well as on our own,[4] a goal of $\Delta T = 10^{-6}$ °C seems feasible. Under the assumption of an associated typical enthalpy change of 10 kcal/mole^{-1}, this leads us to estimate the minimum detectable substrate concentration to be ~10 micromolar. We have achieved an rms noise level of approximately 10^{-5} °C and plan soon to use a recently improved apparatus with hexokinase (EC 2.7.1.1) or urease (EC 3.5.1.5) to study the TEP performance under a variety of conditions.

In the longer term, we believe that the use of state-of-the-art electronics, including microprocessors, might allow the TEP to provide the basis for a relatively simple and inexpensive biochemical "multimeter" that would be useful in a wide variety of research and clinical applications.

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6. LIQUID HELIUM RESEARCH

We are interested in studying droplets of liquid helium so small that their dissimilarity from bulk properties is significant. From a theoretical standpoint these droplets are similar to atomic nucleii, but have several interesting features. First, the interaction between pairs of helium atoms is well known, while the details of the nuclear force are not. Bulk liquid helium is available for measurement of such properties as equation of state, surface tension, and excitation spectrum, whereas nuclear matter can be explored only in the limit of large finite nucleii. We also have a choice of statistics between Bose ^{4}He and Fermi ^{3}He.

Several sources and detectors of helium clusters in the 1-100 atoms range have been proposed; we are now developing a supersonic nozzle beam source. When cold helium gas expands adiabatically through a nozzle into vacuum, much of the random thermal energy becomes directed along the streamlines; in a co-moving frame the gas cools, becomes supersaturated, and condenses into droplets. This process has been studied extensively, principally with other gases, by several investigators.

Peter W. Stephens has constructed a vacuum system with a supersonic helium beam capable of operating at 4.2°K, up to 760 T stagnation pressure, with an approximately 10 μm pinhole as a nozzle. The beam is detected by a mass spectrometer in a separately pumped chamber. Measurements of the size distribution of clusters are now being made.

Future work may include measuring the spin of ^{3}He drops by molecular beam resonance on the nuclear magnetic moment, and measurement of vibrational and rotational excitations by light scattering.

II. ELECTRON MATERIALS ANALYSIS BY AUGER ELECTRON MICROSCOPE (AEM)

Academic and Research Staff

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Prof. John G. King
Dr. Edward H. Jacobsen

Graduate Students

Michael R. Graham
Richard W. Sheppe, Jr.

1. ULTRAHIGH-SENSITIVITY ELECTRON OPTICAL DETERMINATION AND LOCATION OF IMPURITY SPECIES IN Si AND IN GaAs AND OTHER BINARY, TERNARY, AND QUARTERNARY COMPOUND SEMICONDUCTORS

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

John W. Coleman, Michael R. Graham

Our research objective is the elucidation of depth profiles in Si and GaAs, and in other binary compound semiconductors (and eventually ternary and quarternary compound semiconductors). We are especially interested in the sharpness of boundaries that isolate low-refractive-index components from high-refractive-index components in integrated optic devices, and that separate regions of different doping in integrated electronic circuit structures. We will also be probing profiles at semiconductor-encapsulant interfaces after controlled annealing of the semiconductor, which will help establish relationships between defects produced during annealing and outdiffusion during annealing of semiconductor atoms into the matrix of the encapsulating material. Such studies will clarify further the complex nature of these compounds, and help specify annealing-produced defects in crystal structure in terms of their effects on the optical and electrical properties of the semiconductor material.

We are now trying to obtain our first images with calibrated test specimens, and our research progress is following the schedule proposed to the Joint Services in September 1976.

III. SEMICONDUCTOR SURFACE STUDIES

Academic Research Staff

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Graduate Students

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1. ELECTRONIC STRUCTURE OF HOMOPOLAR AND HETEROPOLAR SEMICONDUCTING SURFACES

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

John D. Joannopoulos

We are interested in a theoretical investigation of the electronic states at the surfaces of Group IV, III-V, and II-VI semiconductors. Because of the lack of complete periodicity when dealing with a "semi-infinite" surface system, we are faced with severe obstacles in making a realistic theoretical investigation. Nevertheless, we have recently constructed a theorem demonstrating that any semi-infinite surface system that can be described by a Hamiltonian of finite range can be reduced to an effective one-dimensional problem that can be solved with transfer matrix techniques.

We have used this theorem with realistic tight-binding Hamiltonians to study the effects of surface atom relaxations in the heteropolar compounds. Our results show that the unfilled surface states are very sensitive to the nature of the Hamiltonian that is used. Given a relaxation, these states will move out of the gap if the cation/anion p-like character of the bulk conduction bands is large enough. In this way the behavior of states at the surface is directly related to properties of the bulk system. It is therefore of paramount importance for theoretical models to describe certain features of the bulk system correctly.

At present, we are investigating the effects of oxygen adsorption on the surface of GaAs. The O interaction integrals can be obtained from studies of molecular O_2 and GeO_2. In this way we hope to determine where the oxygen is adsorbed, and whether it is adsorbed as O or O_2 or in some type of mixed bridging configuration.

IV. PHOTOEMISSION SPECTROSCOPY

Academic Research Staff

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Graduate Students

Michael R. McClellan
Peter K. Smith

1. ELECTRONIC AND MAGNETIC STRUCTURE OF SOLID SURFACES USING PHOTOELECTRON SPECTROSCOPY

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

F. Read McFeely

As this is a recently initiated project, our efforts have been primarily devoted to the design and construction of the experimental apparatus that is to be used. Some preliminary results have already been obtained, however, for some theoretical work on photoemission processes which we have been pursuing in collaboration with the Semiconductor Surface Studies Group of Professor John D. Joannopoulos.

We have under construction an ultrahigh vacuum probe system that will operate in conjunction with the Hewlett-Packard 5950A photoelectron spectrometer in the Department of Chemistry, M. I. T. We hope this probe will be completed by March 1977. We shall use this system to study single crystals using high-energy ($h\nu$ = 1486.6 eV) angle-resolved photoemission spectroscopy. In this project we hope first to settle a controversy concerning the proper interpretation of these spectra. We then plan to extend these techniques by modifying the spectrometer to provide higher angular resolution. This will allow us to perform photoemission experiments that will yield densities of initial (valence band) states in selected regions of the Brillouin zone, and to study orbital symmetry effects. We are confident that this will prove to be a new and important form of band-structure spectroscopy for both metals and semiconductors.

In theoretical studies performed in collaboration with Professor Joannopoulos we have been examining the nature of the final states involved in high-energy photoemission experiments. Although, at the present time, the calculations are incomplete, there is an indication that the high-energy photoelectrons are much less effectively screened by the valence electrons from the ion cores of the solid. This indicates that a simple free-electron model will be inadequate to explain the spectra. We hope that these calculations, when completed, will serve to put the analysis of such photoemission spectra on a much more solid theoretical footing.

Final design work for our new spectrometer, designed primarily for surface studies, is being finished and construction should soon begin. Two first-year chemistry graduate

students have joined the group and are working on the photon sources to be used in our experiments. Michael R. McClellan, who came to M. I. T. from the University of California at Santa Barbara is designing a rotatable multiple reflection polarizer for He I and He II radiation. The use of polarization will be extremely valuable in the study of angular distribution of molecules on surfaces. This will allow us to obtain detailed information on the molecular nature of the oxidation properties of metal and semiconductor surfaces. Peter K. Smith, of St. Mary's University, Nova Scotia, is designing the x-ray source to provide Y Mξ x-rays. These x-rays will be very useful in the study of surfaces, since they produce valence band photoelectrons with escape depths that are near the minimum value attainable for many crystals.

V. ATOMIC RESONANCE AND SCATTERING

Academic and Research Staff

Prof. Daniel Kleppner
Prof. David E. Pritchard
Prof. Dieter Zimmermann

Dr. Claude Deutsch
Dr. Richard D. Driver

Dr. Theodore W. Ducas
Dr. William D. Phillips
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John A. Serri
David A. Smith

William R. Spencer
A. Ganesh Vaidanathan
Myron L. Zimmerman

1. SEEDED MOLECULAR BEAM SOURCE

National Science Foundation (Grant PHY75-15421-A01)

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

We have built and started to operate a molecular beam source designed to produce molecules in a low-temperature nonequilibrium environment for laser spectroscopy and molecular scattering experiments. The source is a rare-gas beam at very high pressure (>100 atm) which can be "seeded" with various minor constituents such as Na.

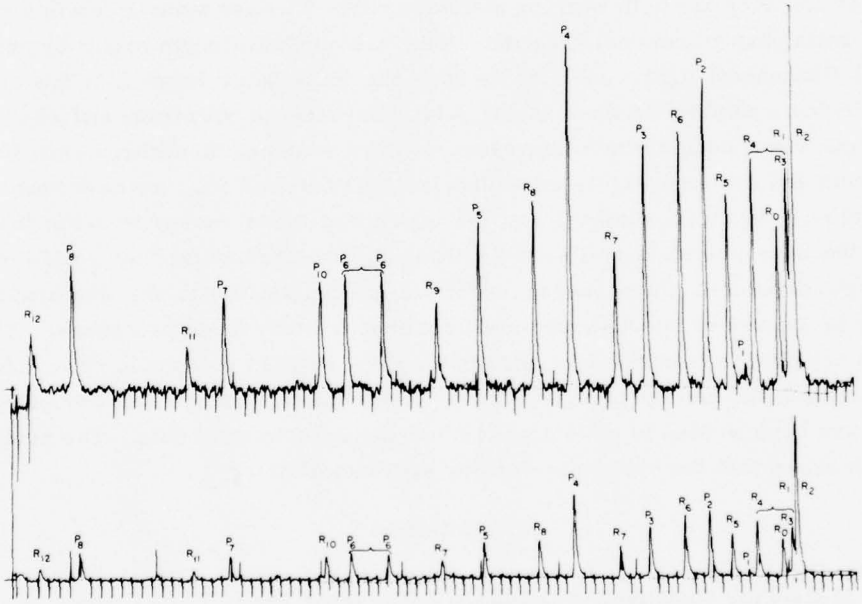

Fig. V-1. Sample spectrum with 7 K rotational temperature.

We have succeeded in producing NaNe molecules which are bound by only ~0.002 eV, and have observed several rotational bands of this molecule. We also have observed Na_2 bands with very low rotational temperatures. A sample spectrum with 7 K rotational temperature is shown in Fig. V-1.

2. ROTATIONAL ENERGY TRANSFER MEASUREMENTS WITH VELOCITY-SELECTED MOLECULES

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

David E. Pritchard, Richard D. Driver, Timothy A. Brunner, Neil Smith

We are studying the processes of rotational energy transfer for Na_2 molecules in collision with Ar atoms. By using the VSDS technique proposed by Phillips and Pritchard,[1] we shall measure the velocity-dependent cross sections of the collision process, $Na_2(\nu, J) + Ar = Na_2(\nu, J \pm \Delta J) + Ar + \Delta E$, where (ν, J) are the vibrational-rotational quantum numbers of the molecular initial state.

In July 1976 we received the first commercially available Coherent Radiation Model 599 cw dye laser. This has a single-mode output bandwidth of less than 10 MHz and is continuously tunable over a 30-GHz range. The Na_2 molecules are produced in a stainless-steel oven. Approximately 10% of the sodium vapor is in molecular form. The laser and oven are both working satisfactorily. We have made a detailed study of the Na_2 rotational-vibrational spectrum in the 610 mm wavelength region by observing the total fluorescent light signals as we scan the input laser beam into the oven. We have selected a number of lines in the total fluorescence spectrum and observed the wavelength dependence of their fluorescence with a scanning monochromator. Using such a spectrum and available published molecular constants for Na_2, we have been able to designate (ν, J) quantum numbers for the upper and lower energy levels of the transitions. We have observed collisionally induced, pressure-dependent satellites in the wavelength-dependent fluorescence spectrum corresponding to the rotational energy transfer processes of interest, and shall continue to study these processes.

Data acquisition is carried out with the aid of a PDP-11 computer. The detection system is buffered into the computer via a CAMAC molecular system. Computer programs have been written to collect and reduce the experimental data. The preliminary work has shown that the system is working satisfactorily.

References

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3. OPTICAL FREQUENCY STANDARDS

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

Walter P. Lapatovich, Philip E. Moskowitz, Kurt W. Offner, Abel Weinrib, David E. Pritchard

The Mark I optical-frequency reference system was used to make the frequency marks shown in Fig. V-2. A new Mark II optical-frequency reference system has been designed and a prototype has been tested. It will provide continuous fast read-out of the frequency so that it can be used to servo-control the laser frequency. The device will also be interfaced to a computer.

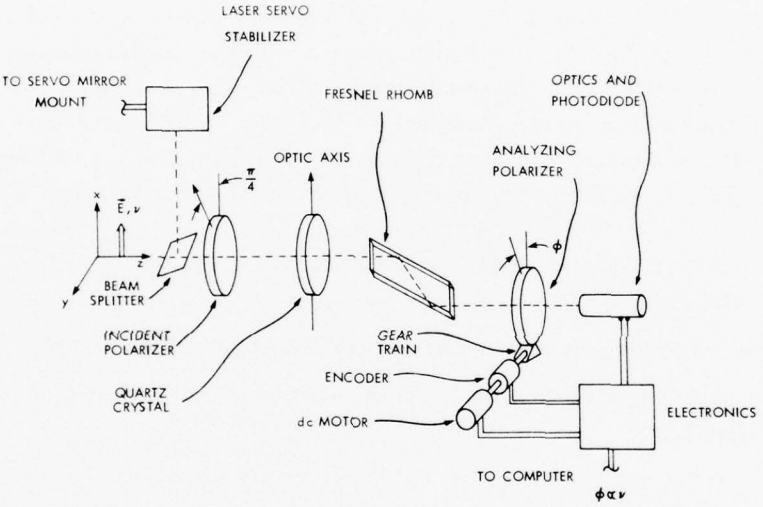

Fig. V-2. Optical-frequency reference system.

The heart of the new system is an optical interferometer that rotates the linear polarization of the incident laser light by an amount proportional to its frequency; in the device under construction the rotation is 1° for each ~600 MHz increase in frequency. This interferometer has a linear polarizer, a birefringent element (a quartz crystal is used in the prototype) whose optic axis is shifted 45° with respect to the polarizer, a quarter-wave plate set with its optic axis parallel to the polarizer, and an automated sensor for finding the angle of polarization. This device functions as follows: Two orthogonally linearly polarized light beams with a relative phase delay proportional to the frequency are produced by the birefringent element. These beams are converted into oppositely rotating circularly polarized light beams by the quarter-wave plate,

and they interfere to give a linearly polarized beam whose angle increases linearly with the phase delay. This angle is then converted into electrical information suitable for controlling or indicating the frequency.

4. SUBMILLIMETER PHOTON COUNTING

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

Daniel Kleppner, Myron L. Zimmerman, Michael G. Littman

We have started to develop a new technique for detecting millimeter and submillimeter radiation, using a gas of highly excited atoms as the working medium. Resonance transitions are induced between suitably chosen levels, and detected by field ionization of the final state. Under certain conditions, the system gives promise of allowing efficient and quiet photon counting in the millimeter and submillimeter ranges. Continuous tuning is possible by using the first-order Stark effect.

Experimental work includes construction of a CO_2 10 μm laser, and of a CH_3F 496 μm laser for use as spectral sources. Resonance transitions have been detected at 10 μm. Calculations of transition moments for Stark-shifted levels are in progress.

5. STUDIES IN OPTICAL PHYSICS AND EXCITED-STATE INTERACTIONS

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

Theodore W. Ducas, William R. Spencer, A. Ganesh Vaidanathan, Daniel Kleppner

New methods for exciting atoms to high Rydberg states are needed in a variety of experiments and for practical applications. We have undertaken the cw excitation of Rydberg states in an atomic beam, using two-photon transitions and single-photon transitions with frequency-doubled light. The frequency-doubling system has been brought into operation, and a new atomic beam apparatus has been constructed. This apparatus is designed to allow motion of Rydberg atoms from an excitation region to interaction and detection regions. The system should soon be fully operable.

6. THEORETICAL STUDY OF ATOMIC RYDBERG STATES

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

Claude Deutsch

In order to lend theoretical support to the experimental study of the Rydberg states of light elements and alkalies undertaken by Daniel Kleppner and his co-workers, we

have reconsidered and generalized the polarization model determination of the highly located hydrogenic levels. First, we considered neutral helium,[1] and obtained non-adiabatic corrections to the R^{-6} and R^{-7} polarization potential. The extension of this result to the alkalies by retaining the fine-structure term in the zero-order approximation is straightforward. We have also studied the behavior of hydrogen Rydberg states in the presence of a magnetic field so strong that perturbation theory is no longer valid. This problem has been approached by factorizing the nonrelativistic wave function into a product of a two-dimensional harmonic oscillator and a one-dimensional coulomb hydrogen atom. Extensions of this basic scheme to allow for the inclusion of magnetic intensities of any intermediate value are now being investigated.

References

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7. FIELD IONIZATION

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

Michael G. Littman, Daniel Kleppner

The problem of finding out how an atom ionizes in an applied electric field has received much attention for several years, and now the theory for hydrogen is well developed. We have carried out the first precise study of field ionization by measuring ionization rates for highly excited states of sodium. We have obtained excellent agreement with hydrogenic theory for some states, but the ionization rates are in serious disagreement for most states. The source of the disagreement was found to be the effects of level mixing that had been neglected previously. The problem is of theoretical interest and of considerable practical importance because field ionization is widely used for detecting highly excited atoms.

Further details of this work have been published recently.[1]

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8. ATOMS IN VERY HIGH MAGNETIC FIELDS

National Science Foundation (Grant PHY75-15421-A01)

Myron L. Zimmerman, Daniel Kleppner

The effect of magnetic fields on atoms is usually so weak that it can be treated as a first-order perturbation. At high fields diamagnetic terms become important. The interaction is of the form $\mathcal{H}_d = e^2B^2\langle x^2 + y^2\rangle/8mc^2$. The diamagnetic energy W_B scales as $\langle r^2\rangle B^2$. For an atom in a Rydberg state (a highly excited state), $\langle r^2\rangle \sim n^4$, where n is the principal quantum number. The electrostatic energy W_E scales as $1/n^2$, so that the ratio of electron and magnetic interactions, W_B/W_E, scales as n^6B^2. For $n \approx 30$, it is possible to achieve the condition $W_B > W_E$ with a field of 100 kG. In such a situation the atom loses many of its familiar properties and becomes essentially a new quantum system.

We have undertaken a study of Rydberg atoms in high magnetic fields, using previously developed techniques[1] for exciting and detecting atoms. An atomic beam apparatus has been constructed for use in conjunction with a 100 kG superconducting solenoid. The apparatus is essentially complete and we plan to start high-field measurements soon.

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VI. X-RAY SCATTERING SPECTROSCOPY

Academic Research Staff

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1. HIGH-RESOLUTION X-RAY SCATTERING SPECTROSCOPY OF CONDENSED MATTER

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

Robert J. Birgeneau

Our main activity since the initiation of this project has been the design and construction of a multipurpose x-ray scattering spectrometer. The spectrometer is designed to carry out x-ray diffuse scattering studies, crystallography research, defect studies, and inelastic x-ray spectroscopy. The essential components of this system are a 12-kW rotating anode x-ray source and a high-precision Huber two-axis goniometer combined with the PDP-11/34 computer control system. We have also constructed a temperature control oven (1 millidegree accuracy) for liquid crystal and ferroelectric phase transition studies. It is anticipated that the whole system will be operational in February 1977. Concurrently with this construction program, we have also carried on two separate x-ray scattering experiments, together with some theoretical work in structural phase transitions.

a. Spin-Peirls 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 because of its role as an archetype for magnetism in organic materials and also because of the analogy with the more familiar electronic Peirls 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. This work is still in progress, but our initial experiments demonstrate clearly that the transition involves a pairing that is fundamentally different than others have inferred from simple

molecular stacking considerations. Consequently, the dominant exchange paths differ from those implied by a naive consideration of the TTF molecular orbitals.

These results are a great surprise to us. There is very little microscopic information available for this class of materials; hence, these new data could have a significant impact on our understanding of the magnetism of one-dimensional organic charge-transfer salts.

b. Electronic Excitations in Liquid Helium

We have now completed an inelastic x-ray scattering study of the electronic excitations in liquid helium in collaboration with 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 the situation for simple metals like aluminum where many-body effects play a central role and theory is still able, at best, to provide a qualitative understanding. Thus this study in liquid helium supplies one physical system where theory and experiment for the electron density fluctuations are in accord.

c. Mean Field Theory and the Ginzburg Criterion

By applying a real-space version of the Ginzburg criterion, it is possible to assess the relative importance of critical fluctuations, and hence 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 $d^* = 2$, respectively. These "marginal dimensionalities" follow directly from the geometry of the critical fluctuations in phase space. We have shown that this approach provides a simple technique for assessing the self-consistency of Landau theory in a vast range of physical systems.

VII. QUANTUM ELECTRONICS

A. Laser Applications

Academic and Research Staff

Prof. Shaoul Ezekiel
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Graduate Students

Salvatore R. Balsamo, James L. Davis, Richard P. Hackel, James A. Cole, Stephan C. Goldstein, George W. Sparks, Jr.

1. FREQUENCY STABILIZATION OF A CONTINUOUS-WAVE DYE LASER

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

Shaoul Ezekiel, Frederick Y-F. 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.

During the past year we have been concerned with the short-term stabilization of commercially available cw dye lasers. The main emphasis has been on improving performance without major redesign of the cavity.

A Spectra-Physics single-frequency cw dye laser Model 580 was modified by extending the cavity approximately 10 cm and inserting an electro-optic phase modulator within this space. The phase modulator is an AD*P crystal, made by Interactive Radiation, Inc., and is free from resonances over a wide range of frequencies up to 400 MHz.

A composite wideband feedback loop with 2 MHz bandwidth was used to lock the laser frequency to the side of a transmission resonance of an external Fabry-Perot cavity having a 1-MHz resonance width. In this way, the high-frequency response was provided by the intracavity phase modulator and a large dynamic range was provided by the PZT length transducer on which the output mirror was mounted.

The use of this feedback loop reduced the rms jitter from 10 MHz to ~30 kHz. The reduction of the laser jitter was demonstrated by heterodyning two similar but independently stabilized dye lasers. The narrow laser linewidth was also demonstrated by the excitation of narrow hyperfine-structure resonances in a molecular beam of I_2. The 800 kHz measured linewidth of an individual I_2 line included a natural width of 400 kHz and residual Doppler broadening from molecular beam geometry.

2. MEASUREMENT OF THE SPECTRUM OF RESONANCE FLUORESCENCE FROM A TWO-LEVEL ATOM IN AN INTENSE MONOCHROMATIC FIELD

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

Shaoul Ezekiel, Robert E. Grove, Frederick Y-F. Wu

The spectrum of resonance fluorescence emitted by a carefully prepared two-level system has been measured. The data were in good agreement with the theoretically predicted spectrum.[1,2]

The $3\ ^2S_{1/2}$ $(F = 2)$-$3\ ^2P_{3/2}$ $(F' = 3)$ transition in atomic sodium was prepared as a two-level system by optical pumping of the degenerate magnetic sublevels with the resonant circularly polarized laser light. Thus we were able to excite the $m_F = 2$-$m_{F'} = 3$ transition selectively, thereby avoiding the complication caused by unequal matrix elements that connect other pairs of sublevels.

In our experimental arrangement a single-frequency cw dye laser is split into parallel "pump" and "signal" beams, which are separated 1.2 cm and intersect an atomic beam of sodium at right angles. The pump beam prepares the F = 2 ground-state atoms in the $m_F = 2$ sublevel before they interact with the intense signal beam. A weak magnetic field (0.7 G) parallel to the laser beams is required to prevent redistribution of the sublevel populations by stray fields in the region between laser beams. The fluorescence induced by the signal beam is collimated and analyzed by a Fabry-Perot interferometer with a 2-MHz instrument width.

To record the on-resonance spectrum, the pump and signal beams are locked to the $F = 2$-$F' = 3$ transition. For off-resonance spectra, an acousto-optic shifter is placed in the pump beam, and the laser is stabilized so that the shifted pump-beam frequency is resonant with the $F = 2$-$F' = 3$ transition, and thus the signal beam is held at an accurately known detuning from resonance.

For comparison of theory with experiment, we computed the convolution of the theoretical spectra with the 9.5 MHz wide instrumental line shape of our arrangement. The instrumental line shape, which includes Doppler and Fabry-Perot broadening, was determined by observing the weak field (elastic scattering) spectrum, which ideally is a delta function. The convolved spectra[3] agreed very well with Mollow's theory.[1]

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3. R. E. Grove, F. Y. Wu, and S. Ezekiel, "Measurement of the Spectrum of Resonance Fluorescence from a Two-Level Atom in an Intense Monochromatic Field," Phys. Rev. A 15, 227-233 (1977).

3. LASER STREAK VELOCIMETRY FOR TWO-DIMENSIONAL FLOWS IN GASES

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

Shaoul Ezekiel, George W. Sparks, Jr.

The present methods of flow measurement in gases are restricted to point-by-point measurements. A method of simultaneously measuring velocities over large areas and volumes is clearly needed for such applications as nonsteady vortex flow.

A new velocity measuring technique, Laser Streak Velocimetry (LSV), has been developed for two-dimensional flows in gases.[1] A 2-watt cw argon laser beam is formed into a thin sheet to illuminate a seeded flow in a two-dimensional plane around a body. Short-exposure streak photographs of the seed particles are recorded as they traverse the light sheet, and then the two-dimensional velocity vector is computed from the length and direction of each streak. The validity of this technique has been demonstrated by measuring the velocity profile in the boundary layer of a flat plate; the measurements showed agreement within 4% of theoretical predictions. In order to demonstrate the application to nonsteady flows, a mapping was made of the nonsteady vortex shedding of low Reynolds number flow past a circular cylinder. Because of current interest in low-speed aerodynamics, the LSV method was also used to obtain the velocities over the surface of a 60° delta wing at 15° angle of attack, and the results were compared with a related theory.

The primary advantage of LSV is the simplicity of the arrangement and its operation, coupled with reasonable accuracy and adaptability. Some of the limitations of LSV, such as particle size and uniformity, can be overcome by the design of an automatic generator and disperser of unit-density, spherical, 1-μm particles. A pulsed laser would permit the extension of LSV to velocities approaching sonic, while high-speed scanning of a pulsed sheet can map three-dimensional, nonsteady flows.

LSV has been shown to be an effective research tool, and extensions of the present method will be pursued to explore the full potential of this technique.

References

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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, Salvatore R. Balsamo, James A. Cole, Stephan C. Goldstein

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.

The performance of our experimental arrangement shows that such a scheme does not suffer from lock-in phenomena normally associated with ring laser gyroscopes. The rms fluctuation of the bias, at present, is less than 15 degrees/hour for an integration time of one second.

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

Aside from applications to navigation, we propose to examine the possibility of measuring earth rotation to better than one part in 10^8, using a cavity, 10 m on a side, and a 10-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.

5. 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

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.

During the last few years we have investigated the use of an I_2 molecular beam as a reference for the long-term stabilization of an argon ion laser. A long-term stability of one part in 10^{13} in an integration time of 200 s has been achieved. The argon lasers used in these experiments were homemade with power output of the order of milliwatts.

Recently, we have extended our effort to the stabilization of commercially made multiwatt argon lasers such as the 15 W Spectra-Physics laser. The short-term absolute jitter of ~30 MHz that is inherent in such a laser was reduced to less than 50 kHz by locking the laser frequency to an external Fabry-Perot cavity. A wide bandwidth (1 MHz) feedback loop was necessary, and was made possible by using an intracavity electro-optic phase shifter. Long-term stabilization was accomplished by locking the reference Fabry-Perot to a hyperfine transition observed in an I_2 molecular beam.

The performance of the laser was measured by heterodyning two high-power argon lasers, each independently stabilized to adjacent I_2 lines. A stability of 7 parts in 10^{14} was achieved in an integration time of 1000 seconds.

The residual short-term jitter of 50 kHz is set by the jitter of the reference Fabry-Perot and not by the bandwidth of the fast feedback loop. The laser jitter relative to the reference Fabry-Perot is less than 10 kHz.

The reproducibility of the laser frequency was studied by using a careful procedure for the orthogonal alignment of the laser with respect to the I_2 beam. A reproducibility of 1.5×10^{-12} was demonstrated.

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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VII. QUANTUM ELECTRONICS

B. Nonlinear Phenomena

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1. SHORT LASER PULSES

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

Hermann A. Haus

Saturable absorber (passive) mode locking of lasers has the faculty of producing pulses that are much shorter than those of actively mode-locked systems because the depth of modulation of the mode-locking element can be much larger in passive than in active mode locking.

Until recently, the design of passively mode-locked systems has been hampered by the absence of an analytic theory of passive mode locking. Development of this theory[1,2] permits determination of the parameters required for successful passive mode locking. The predicted pulse shapes have been verified experimentally.[3,4] We have attained further verification of this theory with the use of a system that had not previously been passively mode locked and that affords precise experimental determination of its parameters. A microwave system composed of an avalanche diode operating at 10 GHz as the active "medium" and a Schottky diode as the saturable absorber was cw mode locked successfully, with the time constants of the system chosen according to the theory.

The microwave system is of interest in its own right as a generator of nanosecond pulses. It is also of interest to laser mode locking because it provides a test system for novel methods of mode locking, and, in particular, since it permits an adjustment of experimental parameters over a wider range than is possible with any particular laser system.

We are planning to study the combined action of passive and active mode locking on the microwave system, and, using the microwave system as a prototype, we shall explore the potential for fast switching of laser devices.

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2. PICOSECOND PULSES FROM SEMICONDUCTOR LASERS

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

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

Mode-locked dye lasers have produced subpicosecond pulses with relaxation times of laser and absorber dyes in the nanosecond range.[1] It has been shown that this surprising result hinges on a careful balance between the saturation characteristics of the laser and the absorber.[2,3]

Semiconductor lasers generally have relaxation times of the order of nanoseconds, and hence are candidates for mode locking in configurations approximating dye laser systems.

Short pulses have been observed from semiconductor laser diodes.[4] The reproducibility of these pulses has been unsatisfactory. We hope that with the development of a better theory for passive mode locking a more methodical approach to the design of the mode-locking system will yield better results. Our approach is experimental and theoretical. In the first stage of our work we studied the spectra of commercial GaAs diodes to anticipate the potential for locking of modes in the spectrum in an external cavity. We shall attempt mode locking of a GaAs diode and a GaAs saturable absorber in an external cavity, with proper antireflection coating of one of the diode faces. This configuration corresponds closely to the dye laser mode-locking configuration.

In the theoretical approach we shall attempt a closed-form analysis of saturable absorber mode locking in a distributed system such as that in a physically "short" system realized by a segmented diode, with one segment playing the role of the laser and the other that of the absorber (with no external cavity). We shall try to develop design criteria for successful mode locking of such a distributed system.

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VII. 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 spatially periodic variation of index or gain.[1] The usual uniform periodic structure exhibits a threshold degeneracy: modes of equal threshold occur on either side of the Bragg frequency.

A system incorporating two uniform periodic structures, with a $\lambda/4$ (or $(2n+1)\,\lambda/4$) phase-shifting section between them, has a low threshold for one single mode at the Bragg frequency, and hence the threshold degeneracy is removed.[2] We shall investigate theoretically and experimentally the potential of these new structures.

It has been found that uniform periodic structures such as a grating of finite width etched into the surface of a guiding layer provide transverse confinement of the electromagnetic field near the Bragg frequency, thereby confining the field underneath the grating.[3] This property may obviate the need for an optical waveguide structure to confine the field underneath the grating. Modes of such grating structures will be investigated.

Grating structures have been fabricated in quartz with a periodicity of 7500 Å that corresponds to third-harmonic coupling at 5000 Å. The grating will be used with a dye-doped polyurethane layer to provide the lasing medium.

Success in manufacturing laser structures that incorporate the quarter-wave step may point the way toward novel tunable passband filters. If the phase shift in the "quarter-wave" section is changed (say, electro-optically by an applied electric field), the transmission frequency of the structure will be shifted. A theoretical investigation of the potential of this tunable filter design will be made.

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VIII. INFRARED INSTRUMENTATION AND ASTRONOMY

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1. INFRARED HETERODYNE DETECTION

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

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

The aim of this project is to develop a compact, continuously tunable, infrared heterodyne receiver for high-resolution spectroscopy of remote objects. Astrophysical applications have provided the principal motivation for the work, but the instrument is also useful for local measurements, as the observation of ozone in our atmosphere has demonstrated. The receiver uses a tunable diode injection laser as the local oscillator. The diodes that we have used have operated in the 9-12 μm range. A HgCdTe photodiode (kindly supplied by David L. Spears of M. I. T. Lincoln Laboratory) is used for the mixer. The complete receiver is assembled in a small liquid helium dewar suitable for bolting to a telescope.

The diode laser local oscillators used in previous experiments cannot be temperature-cycled without risk of degrading or altering their characteristics. This problem has now been alleviated, since our present laser (from Laser Analytics, Inc.) operates at liquid nitrogen temperature, which makes it convenient to store the apparatus at its operating temperature. We have used this laser in the receiver to observe the absorption spectrum of atmospheric ozone against the Sun. For comparison, we have also measured the spectrum in the laboratory, by passing the laser radiation through an absorption cell to a separate detector, and also by heterodyne detection of a blackbody source through the cell.

Figure VIII-1 shows some of the results obtained for ozone. Trace (a) is a laboratory absorption spectrum of 2% ozone in 48 Torr of oxygen at room temperature in a 1-m absorption cell. The laser, operating in a single mode over this range, was tuned by varying its current. Part (b) is a single trace of solar absorption by atmospheric ozone. The scan took approximately 10 minutes to complete. The IF bandwidth of 100 MHz yields an infrared resolution of 0.0067 cm^{-1}. Part (c) is the average of (b) and

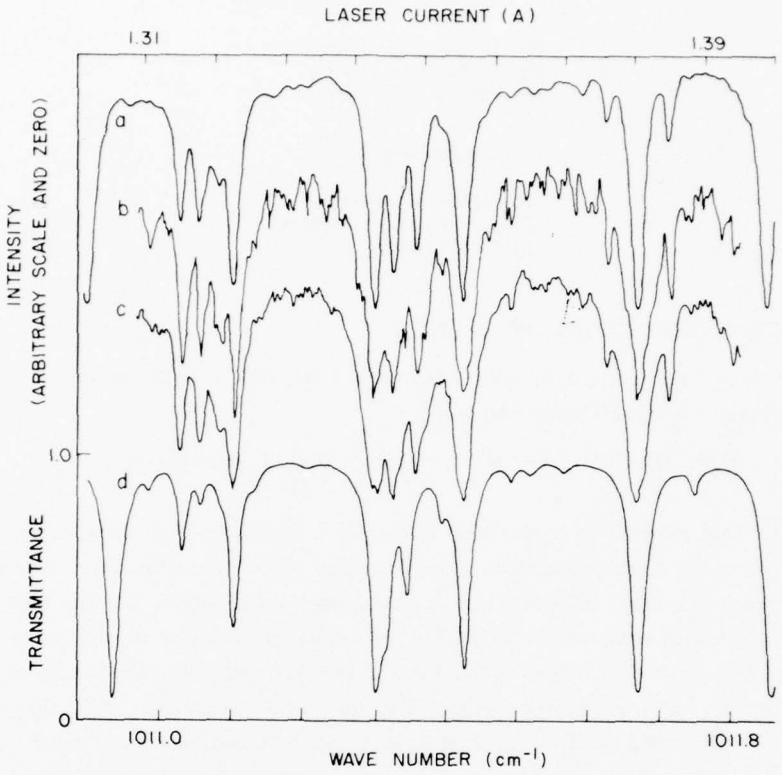

Fig. VIII-1. Ozone absorption spectra. (a) Spectrum obtained in a laboratory absorption cell. (b) Typical atmospheric absorption spectrum obtained against the Sun by using a heterodyne receiver. (c) Average of 6 atmospheric absorption spectra. (d) Spectrum calculated with AFCRL atmospheric absorption line parameters.

5 similar scans. The atmospheric data were obtained on 1 December 1976, with the Sun at an elevation angle between 23° and 26°. A fit to the laboratory spectrum (a) with the use of the Air Force Cambridge Research Laboratory compilation of line parameters[1] is shown in (d). There is only rough agreement between the observed and calculated spectra. According to S. A. Clough,[2] of Air Force Geophysics Laboratory (formerly AFCRL), the compiled ozone parameters in this frequency region are not very accurate, and so disagreement in detail between calculated and observed spectra is not surprising.

The ozone results presented here do not represent the ultimate capability of the heterodyne receiver. The local-oscillator power focused on the mixer was ~40 μW, more than five times lower than that required for shot-noise-limited detection. The output noise seen in Fig. VIII-1 was approximately 10 times larger than the amplifier noise,

primarily because of inadequate shielding against RF interference. Also, approximately two thirds of the available solar power was lost because of inefficient transfer optics. In spite of these less than optimum conditions, we feel that the usefulness of the infrared heterodyne receiver for high spectral resolution remote sensing has been demonstrated.

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2. DEVELOPMENT OF INTEGRATED SILICON BOLOMETERS

National Aeronautics and Space Administration (Contract NAS5-23731)

Patricia M. Downey, Rainer Weiss

In this project we have applied the techniques of integrated circuit manufacture to the ancient art of bolometer construction. An entire bolometer assembly – mounting frame, thermal links, and low heat capacity bolometer element – has been formed out of a single piece of silicon by masking and etching. The central bolometer element incorporates an ion-implanted resistance thermometer and a thin metallic film radiation absorber. Broadband detectors with time constants of 1/10 s and radiation noise equivalent power (NEP) of 10^{-15} at 1.5°K appear to be feasible. The techniques that are employed should produce high yield rates and lead to the manufacture of detector arrays. This project is being carried out in collaboration with the Microelectronics Group at M. I. T. Lincoln Laboratory.

3. MEASUREMENT OF THE LARGE ANGULAR SCALE ANISOTROPY OF THE PRIMEVAL COSMIC BACKGROUND RADIATION

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

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

The goal of this experiment is to search for intrinsic anisotropies of the cosmic backgound radiation, which is adduced to be a remnant of the primordial cosmic explosion. The high degree of isotropy of this radiation is a deep mystery and measurement of the angular distribution on both large and small angular scales constitutes one of the fundamental problems in cosmological observation. At some level the earliest vestige of galactic formation must have left its imprint on the primeval explosion,

and the explosion was not necessarily spherically symmetric. Observations of the background can also be turned around: Under the assumption of isotropy in some reference frame, a measure of a global anisotropy in a frame tied to the Earth will give a measure of the velocity of the Earth relative to the reference frame that was at average rest with the matter that last scattered the background radiation. The upper limits on this velocity, established by isotropy experiments of the background, are in conflict with earlier systematic anisotropies measured in the distribution of galactic red shifts.

In this project, which has been in progress for three years, we are conducting a balloon-borne survey of the sky, using a dual-channel differential radiometer with a 17° beamwidth. The two channels have bandwidths extending from 3 cm^{-1} to 10 cm^{-1} and from 10 cm^{-1} to 25 cm^{-1}. The lower frequency channel is chosen to include the bulk of the energy in the cosmic background radiation, while the higher frequency channel monitors inhomogeneities in the atmosphere and is sensitive to local astronomical sources such as interstellar dust clouds. With existing detectors, the survey sensitivity is approximately $0.1°K/Hz^{1/2}$ in the low-frequency channel. In a typical 8-hour flight it is possible to set fractional temperature anisotropy limits of 3×10^{-4} on global-scale anisotropies such as those caused by the velocity of the Earth relative to the universal co-moving frame. The results of 4 balloon flights, covering approximately one third of the celestial sphere, show no anisotropies larger than 1/1000 and, with a 90% confidence limit, indicate that the velocity of the Earth is less than 350 km/s relative to the co-moving frame. These limits are not set by the ultimate survey sensitivity but rather by systematic correlations in the data that may well be due to galactic dust clouds or intrinsic anisotropies in the background. Improved sensitivity in the survey, as well as greater sky coverage, are needed to unscramble the correlations.

4. SKY SURVEY AT MILLIMETER AND SUBMILLIMETER WAVELENGTHS

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

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

This project is closely related to the anisotropy measurements described in Section VIII-3. It is a balloon-borne survey of the sky to search for discrete sources with the spectral bands used in the anisotropy experiment but with a smaller beamwidth, approximately 1°. A spin-scanned telescope that has a sensitivity of $\sim 10^4$ flux units per angular resolution element is used in the experiment. With improved detectors such as those described in Section VIII-2, we hope to increase the sensitivity to 100 flux units. Aside from mapping the sky in this unknown spectral region, our goal is to measure the frequency dependence of the emissivity of typical dust clouds in our Galaxy. We have surveyed the galactic plane from longitude -5° to +50°. The emissivity of the dust in the

galactic center has been found to vary faster than linearly with frequency. Limits on the millimeter and submillimeter brightnesses of several sources observed at 100 μm have also been set.

5. COSMIC BACKGROUND EXPLORER SATELLITE (COBE)

National Aeronautics and Space Administration (Contract NAS5-23731)

Mark Halpern, Rainer Weiss

We are engaged in a one-year study with scientists from several other laboratories to investigate the feasibility of using a single integrated satellite to carry out the following measurements of the cosmic background radiation:

a. A precision measurement of the spectrum of the background radiation between 3 cm^{-1} and 20 cm^{-1} by using a cryogenic Fourier transform spectrometer. The design goal is to make an absolute determination of the spectrum with a signal-to-noise ratio of 1000/1 at the blackbody peak. The instrument is designed to measure the deviations from a Planckian spectrum.

b. An absolute measurement of the diffuse background in 6 broadband channels between 300 μm and 10 μm. The background radiation in this spectral region is virtually unknown, particularly in the 100 – 300 μm band.

c. A multiband measurement of the anisotropy of the cosmic backgound radiation, with the use of microwave differential radiometers at 20, 30, 55, and 90 GHz. The angular scale will be of the order of 7° with a fractional temperature sensitivity of 0.2 millidegrees per resolution element extending over the entire sky in a one-year flight.

This project, if approved by NASA for continued support, should lead to the most authoritative measurement of the background radiation. Collaborating with us are John Mather and Michael G. Hauser, of Goddard Space Flight Center, David T. Wilkinson, of Princeton University, Samuel Gulkis, of the Jet Propulsion Laboratory, California Institute of Technology, and George F. Smoot III, of the University of California at Berkeley.

IX. INFRARED NONLINEAR OPTICS

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1. INFRARED NONLINEAR PROCESSES IN SEMICONDUCTORS

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

Peter A. Wolff, Andrew Wood, Muhammed A. Khan, Lynn C. Detwiler, Roosevelt People

Over the past year we have set up a laboratory to study infrared, nonlinear optical processes in semiconductors. This facility involves two Q-switched CO_2 lasers, spectrometers, magnetic fields, detection equipment, and so forth. Our first experiments have been directed toward the problem of resonant, four-photon mixing in n-Ge. When pumped with two CO_2 lasers (ω_1 and ω_2), such a crystal generates radiation at frequency $\omega_3 \equiv 2\omega_1 - \omega_2$. The power $P(\omega_3)$ is sharply enhanced (250 fold) when $\omega_1 - \omega_2$ coincides with the valley-orbit splitting of the donor states. These results are in reasonable agreement with our calculations of impurity Raman scattering and the third-order nonlinear coefficient. We plan to use the resonant, four-photon mixing effect as a probe of impurity energy levels, and as a basis for nonlinear optic processes. In particular, our measurements imply that stimulated impurity Raman scattering should be achievable (with CO_2 or H_2O laser pumping) in a variety of semiconductors. These ideas will be tested with the large TEA lasers at the Francis Bitter National Magnet Laboratory, M.I.T., where we are collaborating with Dr. Roshan L. Aggarwal.

During the past year, we have also completed calculations of far infrared generation by nonlinear excitation of plasmons in thin semiconductor plates. An experiment to test the validity of this idea will be performed at NML. Ultimately, we hope to extend the plasmon work to multilayer sheets, achieved by controlled doping of semiconductor crystals.

During the coming year, our infrared work will expand to include collaborations with two materials groups – one at Honeywell; the other that of Professor August F. Witt in the Materials Science Center, M.I.T. Honeywell will provide us with $(Cd_xHg_{1-x})Te$ crystals; Professor Witt will grow n-InSb with spatially modulated doping, and ternary alloys such as In(Sb, Bi) and (In, Tl)Sb. These groups have Air Force Office of Scientific Research support for their work. With these new materials, we plan four-photon mixing, spin-flip Raman, and far infrared generation experiments.

(XIII. RADIO ASTRONOMY)

X. MICROWAVE AND MILLIMETER WAVE TECHNIQUES

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1. MICROWAVE DEVICE AND NOISE STUDY

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

Madhu S. Gupta

The objective of these studies is to develop improved signal and noise models for solid-state microwave devices. These models are useful for accurate prediction of device characteristics, optimization of design, and improvement of performance in circuit applications. The three devices of interest at present are silicon BARITT diodes, GaAs microwave FETs, and high-efficiency IMPATT diodes.

a. BARITT Diodes

We have fabricated BARITT diodes and made a detailed characterization of their nonlinear properties at microwave frequencies. The measured parameters include small-signal and large-signal device impedance, frequency-modulation sensitivity, and linearity of modulation. *We report the following achievements:*

(i) An improved method of measurement of large-signal impedance for nonlinear diodes. In this method the sensitivity of measurement is high even when the device impedance is small (VSWR high), and the RF voltage across the device can be measured independently.

(ii) We have devised a lumped-circuit model for BARITT diodes. This model has shown better agreement with experimentally measured devices; improvement has been found over a wider frequency range than in previous models and its elements can be given physical interpretation.

(iii) An extensive set of large-signal measurements for a device with known parameters has provided a data base for evaluating the theoretical nonlinear models of the BARITT diode. This work is reported in the Ph.D. thesis of Gary K. Montress,[1] and a paper is being prepared for publication.

b. GaAs Microwave FETs

In the past, work on GaAs FETs has been the experimental characterization of a

device in order to relate it to its model.[2] This model was used to design an optimum low-noise microwave amplifier with the device under low-temperature operating conditions.[3] An attempt has been made to construct this optimized amplifier.[4] Measurements on the amplifier have suggested that the biasing of the device can be modified to improve the stability, with a small sacrifice of amplifier performance.

c. High-Efficiency IMPATT Diodes

Our research on high-efficiency IMPATT diodes is directed toward measuring oscillator noise spectra. Quantitative agreement between experimentally measured and theoretically calculated noise spectra has not been achieved for high-efficiency IMPATT diodes. Recent theoretical analyses[5] show that the FM noise measure can be calculated reasonably well if the effect of signal power level upon temperature, and of temperature upon the reverse saturation current, is accounted for. We are attempting to measure both AM and FM noise spectra, as well as the correlation coefficient. These measurements will be used for comparison with theoretical results.

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2. ATMOSPHERIC REFRACTION AT MILLIMETER WAVELENGTHS

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

Bernard F. Burke, Alan Parrish, Thomas S. Giuffrida, Barry R. Allen

The microwave aperture synthesis interferometer (described in Section XIII-6 and in previous RLE Progress Reports) will be used to study refraction and absorption in the Earth's atmosphere. The initial measurements will be made at 13 mm. In January 1977, we shall begin to make measurements at high and low angles of elevation, under a variety of weather conditions. The system will be converted to operation at 7 mm

during 1977.

Interference fringes have been detected at 13 mm by the entire digital system. The 150-MHz correlator works well, and the measurement phase of the project awaits only the interfacing of the digital delay system with the computer, and the completion of the 3-element correlator and phase reference controls.

XI. MICROWAVE DEVICES EMPLOYING MAGNETIC WAVES

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1. MAGNETOSTATIC RACETRACK RESONATOR – NEW TYPE OF HIGH-Q MICROWAVE FILTER

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

Frederic R. Morgenthaler, Robert L. Kyhl, Dale Zeskind

We have undertaken a comprehensive program directed at developing and perfecting a novel class of microwave yttrium iron garnet (YIG) filters based upon our recent observations (in the Microwave and Quantum Mechanics Group of the Department of Electrical Engineering and Computer Science) of extremely sharp localized resonance in single crystals biased with spatially nonuniform fields. Such magnetically tunable filters would employ photolithographically derived planar microwave circuit elements for coupling energy into and out of the crystal, and it appears that multipole filters can be integrated within the same crystal to provide economy of scale and hence preclude costly time-consuming hand-alignment procedures.

Magnetic resonance is normally very much broadened if a ferrimagnetic sample is immersed in a spatially nonuniform field, and experimentalists measuring fundamental resonance parameters take great pains to employ ellipsoidal sample shapes (usually small spheres) that are positioned in fields of very high uniformity. Therefore it is very remarkable that in our work in the Microwave and Quantum Magnetics Group we recently observed extremely sharp resonances of a highly localized character in single-crystal YIG rectangular slabs that encounter highly nonuniform demagnetization fields because of the nonellipsoidal shape. One view of the newly discovered high-Q resonance is that magnetostatic mode patterns are formed for which the resonant energies are highly confined to certain regions or "tracks" within the crystal that allow wave propagation around them. If the mode amplitudes are very small at the edges and corners of the sample, the surface scattering (which would be expected to be enormous) can largely be prevented; consequently, the Q of the resonance is governed primarily by the intrinsic linewidth of the bulk crystal together with normal circuit-loading considerations. In effect, appropriately designed magnetic field profiles create surfaces of discontinuity where there are no actual surfaces; surface wave propagation at such

"surfaces" should be free of many of the drawbacks and loss mechanisms encountered at true surfaces. It is our intent to learn how to characterize, control, and efficiently couple to such modes so that we may create a new class of microwave magnetically tunable resonance filters.

This research effort was motivated by observations reported by Dale Zeskind[1] of new spatially localized modes of ferromagnetic resonance in rectangular slabs of single-crystal yttrium iron garnet (YIG), with dc magnetic field applied perpendicular to the plane of the slabs and microwave coupling provided between two closely spaced stripline antennas on the same surface of the YIG slab. With crystal dimensions of 0.190" × 0.161" × 0.016" and antenna separation of 0.0125" (antennas located along the center line of the slab) the resonance is characterized by a half-power bandwidth of 1.8 MHz at 2.5 GHz. The resonance center frequency is tunable over the range 2.2-3.0 GHz by changing dc bias field magnitude.

A hybrid stripline multiantenna device was constructed using microwave integrated circuit techniques. This device was used to plot the spatial distribution of the surface coupling phenomenon across the face of the crystal. Spatially localized points of resonance exhibit symmetry about the middle of the crystal with maximum response occurring at the midplane. Half-power spatial linewidths are approximately 0.0025".

A new sample holder with microstripline probes is being constructed and will be used in an attempt to provide definitive determinations of the high-Q mode distributions in existing crystals and in new crystals of both rectangular slab and circular disk geometries.

We have also initiated a program of device synthesis aimed at tailoring modes with characteristics that are best suited to high-Q filter applications and will still allow reasonably efficient coupling to input and output circuits. Two separate methods of creating "tracks" to support and guide surfacelike magnetostatic waves of prespecified group velocity in YIG will be compared.

In the first, spatially nonuniform magnetic fields of prespecified characteristics will be synthesized inside the crystal so as to form effective surfaces away from the actual crystal boundaries.

In the second, they will be formed by mechanical means (i.e., etched grooves, slots, etc.) followed by argon ion beam milling to remove damaged surface layers.

In both cases, control of the wave group velocities will be exercised so as to keep enough electromagnetic character to allow reasonable coupling efficiencies and still provide magnetostatic wavelength reductions and tunability, especially at lower microwave frequencies. Special emphasis is being given to creating modes that can constitute multisection filters of even higher selectivity and to configurations that will lend themselves to planar fabrication and integration techniques.

We have already made substantial progress in determining theoretically the

conditions necessary to cause a magnetostatic wave to be bound or confined by a dc magnetic field gradient located near the surface of a slab of ferrimagnetic crystal when the wave propagation is both parallel to the surface and perpendicular to the dc field direction.

In the course of this investigation we have found a class of special dc field profiles that can bind magnetic waves having simple analytical properties characterized by closed-form expressions for mode pattern, group velocity, and the like.

By proper choice of the gradient, the wave energy can be forced to occur either largely within or predominantly outside the crystal.

Of equal importance is the fact that the bound wave frequencies and group velocities can be gradient-controlled to a considerable extent. Therefore, in contrast with the Damon-Eshbach surface mode propagating on a thick substrate with negligible speed, which in YIG must lie above 2.5 GHz, frequencies can be made considerably lower and velocities much higher, if desired.

When no boundary is present in the vicinity of the gradient region, bound waves can still exist but the transverse mode pattern is more complicated. We have also considered situations in which the dc magnetic field profile is "well-shaped" with either positive or negative curvature, as required.

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2. MICROWAVE DEVICES EMPLOYING CONTROLLED FOCUSING OF MAGNETOSTATIC WAVES

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

Frederic R. Morgenthaler, Aryeh Platzker

Our recently reported magnetic field synthesis procedure[1] has been utilized by Platzker and Morgenthaler[2] to construct a series of broadband, low-loss linearly dispersive magnetoelastic microwave delay lines that have yielded the highest levels of performance achieved with this class of device.

The most striking features are the very broad instantaneous bandwidth, coupled with a very high degree of linearity of the delay time/frequency relation. These highly desirable features have been achieved without sacrifice of insertion loss, which remains relatively low and uniform across the operating frequency band.

Although the synthesis to exacting standards of prespecified magnetic field profiles

has made these achievements possible, it appears that extension to higher frequencies is feasible. Moreover, completely new types of linear and nonlinear filters can be developed, provided that proper control of focusing and defocusing characteristics of magnetostatic and/or magnetoelastic wave packets is exercised. Consequently, the Microwave and Quantum Magnetics Group of the Department of Electrical Engineering and Computer Science has initiated fundamental studies of controlled focusing. Experimentally, this has suddenly become feasible because of the magnetic field synthesis capability.

In the undergraduate thesis research of Syed H. Nawab, now nearing completion, an improved synthesis procedure for creating a prespecified magnetic field profile H(z) inside a single-crystal YIG cylinder has been applied. In this case, the field necessary for operating a microwave magnetoelastic delay line has linear frequency dispersion over the 1-2 GHz frequency band. The measured characteristics of the synthesized device will be correlated with those expected from the theoretical model and the latter will be used to determine the actual dc field profile within the crystal.

When this first phase is completed, we shall turn to the task of generating a special class of field profiles that have emerged from our analysis of magnetostatic wave focusing and defocusing. These "constant Q" profiles render the focusing parameter,

$$Q = \frac{2HM}{(H+M)^2}\left[\frac{3}{2} - \frac{(H+M)H''}{(H')^2}\right],$$

independent of position. Here M is the saturation magnetization and H' and H" are the first and second derivatives of H with respect to z. We are particularly interested in the predicted range $0 < Q < 1$ for providing optimum focusing.

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XII. MICROWAVE THERMOGRAPHY

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RESEARCH OBJECTIVES AND RESEARCH PROGRESS

National Institutes of Health (Grants 5 RO1 GM20370-04 and 5 SO5 RR07047-11)

Alan H. Barrett, Philip C. Myers

During the past year our microwave thermography research has continued in four directions: clinical evaluation of microwave thermography for breast cancer detection, development of new radiometers, development of new antennas with improved resolution, and development of new techniques for measuring sensitivity and resolution.

The clinical work has continued at Faulkner Hospital in collaboration with Dr. N. L. Sadowsky, Chief Radiologist. At present, we have examined more than 2000 normal patients and more than 30 with breast cancer confirmed by biopsy. The cancer detection performance of the 3.3 GHz radiometer depends on the choice of detection criterion. In the cases that we have investigated, the optimum criterion involves the mean right-left temperature difference, averaged over 9 right-left pairs for each patient. When the magnitude of this difference exceeds a chosen threshold value, the criterion indicates "cancer"; if the difference falls below the threshold, the criterion indicates "normal". With the threshold set at 0.32°C, this criterion correctly identifies approximately 70% of the cancers and 75% of the normals. The criterion is inherently one of coarse resolution, since it involves a spatial average over each breast; most of the cancers that were not detected by the microwave method have tumor size <1 cm. The need for a higher resolution antenna to detect early cancers is clearly indicated. Thus far, the detection performance of microwave thermography for patients examined by these three methods is comparable to that of infrared thermography but inferior to xeromammography. We find, however, that when the infrared and microwave techniques are combined so that either a positive microwave examination or a positive infrared examination indicates "cancer", then the cancer detection rate rises higher than 90%, and is comparable to that for xeromammography. Unlike xeromammography, the microwave and infrared methods send no radiation into the body; thus they cannot be considered dangerous.

(XII. MICROWAVE THERMOGRAPHY)

In October 1976, we installed a 1.3 GHz radiometer in the examining room at Faulkner Hospital to operate side-by-side with the 3.3 GHz instrument. This new system was developed in order to begin determining the optimum frequency for detection. A 6.0 GHz system is now being tested in our laboratory for the same purpose. These new radiometers can achieve a rms temperature sensitivity of less than 0.1°C in an integration time of 1 s.

Work has continued on development of higher resolution antennas. Evaluation of a dual-mode antenna, which propagates the TE_{10} and TE_{20} modes in order to form a difference beam, has been aided by implementation of a modulated-scattering technique for measuring the antenna power pattern at close distances.

A microprocessor system is being developed by arrangement with the Harvard-M.I.T. Biomedical Engineering Center for Clinical Instrumentation. This system will be a powerful adjunct to the present radiometer systems. It will be used to compute temperatures from the radiometer output voltages, automate the process of calibration and data taking, display measured temperature maps on a cathode-ray tube screen, compute diagnotic measures, and drive an automatic antenna scanner in order to permit greater flexibility in mapping and analysis.

We have begun to construct artificial phantom models of tumors embedded in fatty tissue, in order to evaluate our instrument detection capabilities in a more quantitative way than is possible with hospital data. By using a combination of epoxy, aluminum powder, and lampblack, whose recipe is readily available, we have made slabs of solid material that has the same dielectric properties as fatty tissue at microwave frequencies. We have made glass-walled, water-filled shells, with enclosed heating resistors and sensing thermistors, to simulate tumors whose temperature, size, and location beneath the top slab can be varied conveniently. With these models, we shall evaluate the sensitivity-resolution tradeoffs of our radiometer and antenna systems.

XIII. RADIO ASTRONOMY

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1. ASTROMETRIC INTERFEROMETER

M. I. T. Sloan Fund for Basic Research

David H. Staelin

A long-baseline Michelson interferometer is being developed for astrometric purposes. In principle, relative stellar positions should be measurable with $\sim 10^{-4}$-10^{-5} arc sec accuracy for stars brighter than ~10-5 mag, respectively, and separated less than ~1°-1 arc min, respectively. A 10-m baseline system with 12-cm optics would be appropriate for such purposes.

A preliminary 1.6-m baseline unit with 1-inch apertures has been operated from October to December 1976 at the M. I. T. Wallace Observatory near Tyngsboro, Massachusetts. The system incorporates two angle trackers, one for each arm of the interferometer, and one fringe-tracking servomechanism. A PDP-8 computer performs all computations; the system averages data in 10-ms units.

Fringes were not observed because of the excessive rate of fringe motion. The system can track only if the white fringe moves less than $\sim 30\ \lambda\ \text{sec}^{-1}$, which is approximately one quarter of the observed rate. Seeing was ~5 arc sec, and the winds were ~10 mi/h. A better site will eventually be needed.

(XIII. RADIO ASTRONOMY)

2. ENVIRONMENTAL REMOTE SENSING WITH THE NIMBUS PASSIVE MICROWAVE SPECTROMETER

National Aeronautics and Space Administration (Contract NAS5-21980)

David H. Staelin, Philip W. Rosenkranz

Passive observations of the Earth from space near the microwave molecular resonances of water vapor and oxygen yield information about the atmospheric temperature profile and, over ocean, about the atmospheric water vapor and liquid water content. Two 5-channel microwave spectrometers, the Nimbus 5 (Nimbus E) microwave spectrometer (NEMS) and the scanning microwave spectrometer (SCAMS), were launched on the Nimbus Observatory Satellites in 1972 and 1975, respectively. These spectrometers were fabricated at the Jet Propulsion Laboratory, C. I. T., and most of the scientific analysis has been performed in the Research Laboratory of Electronics, M. I. T. The present emphasis of this research is placed on: improving parameter estimation methods for determining atmospheric parameters, obtaining better methods for computing the propagation of electromagnetic radiation in scattering or inhomogeneous media, such as clouds or accumulations of ice and snow, and utilizing the microwave data for geophysical purposes.

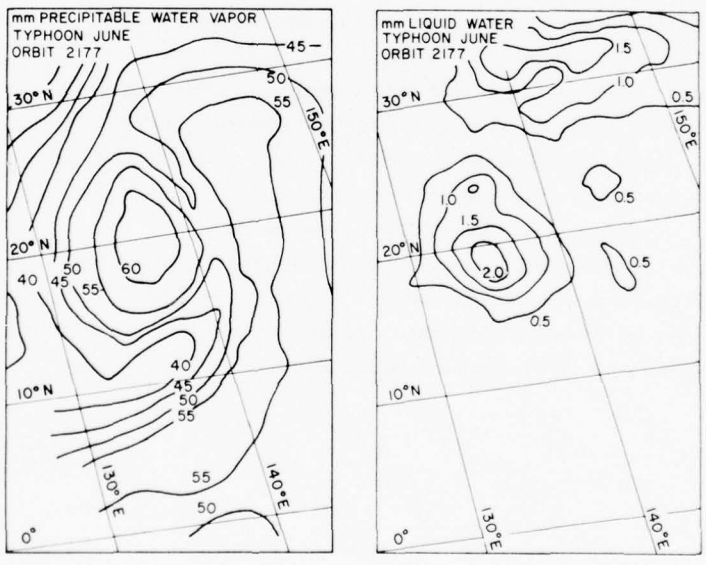

Fig. XIII-1. Retrieved abundances of water vapor and liquid water from SCAMS measurements, November 21, 1975.

The ability of NEMS to sound atmospheric temperature profiles has been determined from comparisons with radiosonde measurements of temperature[1,2] and wind.[3] Measurements with the Nimbus-6 scanning microwave spectrometer SCAMS have been discussed in preliminary fashion.[4,5] Both NEMS and SCAMS are yielding temperature retrieval accuracies close to those expected, 1.5-4 K rms errors. Small systematic residual errors have been attributed to some unknown combination of errors in present atmospheric transmittance expressions, the instrument calibration, and the radiosonde data sets.

Determinations of water vapor and liquid water abundances over ocean have been discussed for NEMS[6] and, in preliminary fashion, for SCAMS.[5,7] The SCAMS observations of Typhoon June, in November 1975, are particularly interesting. Representative maps of retrieved water vapor and liquid water abundances are illustrated in Fig. XIII-1.

Snow and ice observations from NEMS[8,9] revealed strong spectral variations with time and space that are related to subsurface inhomogeneities and loss tangents. A theory for electromagnetic wave propagation for these conditions has been developed and discussed with reference to the SCAMS data.[10,11]

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3. FEASIBILITY STUDY OF A MICROWAVE SPECTROMETER FOR METEOROLOGICAL OBSERVATIONS FROM SYNCHRONOUS SATELLITES

National Aeronautics and Space Administration (Contracts NAS5-22485 and NAS5-23677)

David H. Staelin, Philip W. Rosenkranz

Certain meteorological phenomena such as tropical and extratropical storms require almost constant surveillance in order to be monitored or possibly controlled properly; this is best accomplished from synchronous satellites. High spatial resolution is desired for rapidly varying phenomena, and this implies short wavelengths if the relatively cloud-insensitive microwave techniques are used for temperature and moisture mapping.

Satellite configurations employing the 118-GHz O_2 resonance and the 183-GHz H_2O resonance are being studied for such applications. The dominant technical problems are nonlinear parameter estimation and electromagnetic propagation in scattering atmospheres. It now appears that clouds will degrade the temperature profile measurements only somewhat more than they do near 60 GHz.

In support of this effort an 8-channel 118-GHz microwave spectrometer is being assembled and adapted to a NASA Convair 990 aircraft for flights in March 1977.

4. NIMBUS-G SCANNING MULTICHANNEL MICROWAVE RADIOMETER

National Aeronautics and Space Administration (Contract NAS5-22929)

David H. Staelin, Philip W. Rosenkranz

This instrument comprises 5 dual-polarized microwave channels at 6.6, 10, 18, 21, and 37 GHz wavelengths. The ground resolution varies from ~120 km to ~20 km, depending on frequency. The swath width for this polar-orbiting system will be ~750 km. Launch is scheduled for 1978.

The theoretical problems involve two-dimensional nonlinear parameter estimation. The problem is compounded because the different frequencies and polarizations have slightly different viewing zones. A preliminary approach to solving these problems has been developed.

5. ATMOSPHERIC MEASUREMENTS NEAR 118 GHz WITH PASSIVE MICROWAVE TECHNIQUES

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

David H. Staelin, Philip W. Rosenkranz

The use of the 118 GHz and 60 GHz spectral regions in combination is being studied for the purpose of determining the accuracy with which cloud liquid water can be measured. Theoretical procedures for computing high-order scattering in clouds were developed. The initial evaluations of cloud measurement accuracy were unfavorable because linear estimation techniques were used for the very nonlinear problem of heavy clouds and precipitation. Nonlinear procedures are being developed.

An 8-channel microwave spectrometer at 118 GHz is nearing completion. It incorporates a Gunn-diode oscillator plus doubler for the local oscillator, and a GaAs FET amplifier operating at 500-2000 MHz to yield an ~11-dB noise figure (double sideband). The 8 channels are each ~200 MHz wide and spaced over the band. The local oscillator is centered on the oxygen resonance.

The radiometer utilizes a microprocessor for synchronous detection, system control, and data recording. Limited real-time data reduction can also be performed.

6. GALACTIC AND EXTRAGALACTIC ASTRONOMY

National Science Foundation (Grant AST73-05043-A02)

Bernard F. Burke, Alan Parrish, Aubrey D. Haschick, Thomas S. Giuffrida, Robert C. Walker, Willem A. Baan, Patrick C. Crane, Barry R. Allen, Perry E. Greenfield, J. Antonio Garcia-Barreto, John W. Barrett, D. Cosmo Papa, John D. Kierstead

Our research in galactic and extragalactic astronomy includes the following programs:

(i) Studies of Very-Long-Baseline Interferometry (VLBI) of quasars, active radio galaxies, and interstellar masers.

(ii) Development of a microwave aperture synthesis interferometer for medium-resolution studies of galactic and extragalactic radio sources.

(iii) Studies of time variations of H_2O masers.

(iv) Radio continuum studies of nearby spiral galaxies, using the NRAO 3-element interferometer.

(v) Studies of 21-cm absorption lines in the spectra of quasars, radio galaxies, and Seyfert galaxies, including the effects of intervening high-velocity clouds of our Galaxy. Searches will be made for neutral hydrogen in clusters of galaxies.

(vi) Radio recombination lines in the interstellar medium and HII regions will be observed.

We report the following progress toward carrying out these objectives.

a. Microwave Aperture Synthesis Interferometer

Alan Parrish, Thomas S. Giuffrida, Barry R. Allen, John D. Kierstead, D. Cosmo Papa, Perry E. Greenfield, John W. Barrett, Bernard F. Burke

The electronics development for the M. I. T. microwave interferometer system was essentially completed during the past year. One set of finished components has been installed on two of the three antennas to make a finished interferometer pair. A block diagram of this system is shown in Fig. XIII-2. By using this system, fringes have been obtained on the Sun and on Cas A at 1.3 cm wavelength. We are now testing the equipment under field conditions and shall expand to full operation of the three simultaneous baselines obtainable from three antennas. The radiometer, wiring, and mechanical work for the third antenna are now complete. The additional local-oscillator reference cable length control servo required for this antenna in the system is being constructed, as well as the digital equipment that is necessary to correlate the two additional baselines.

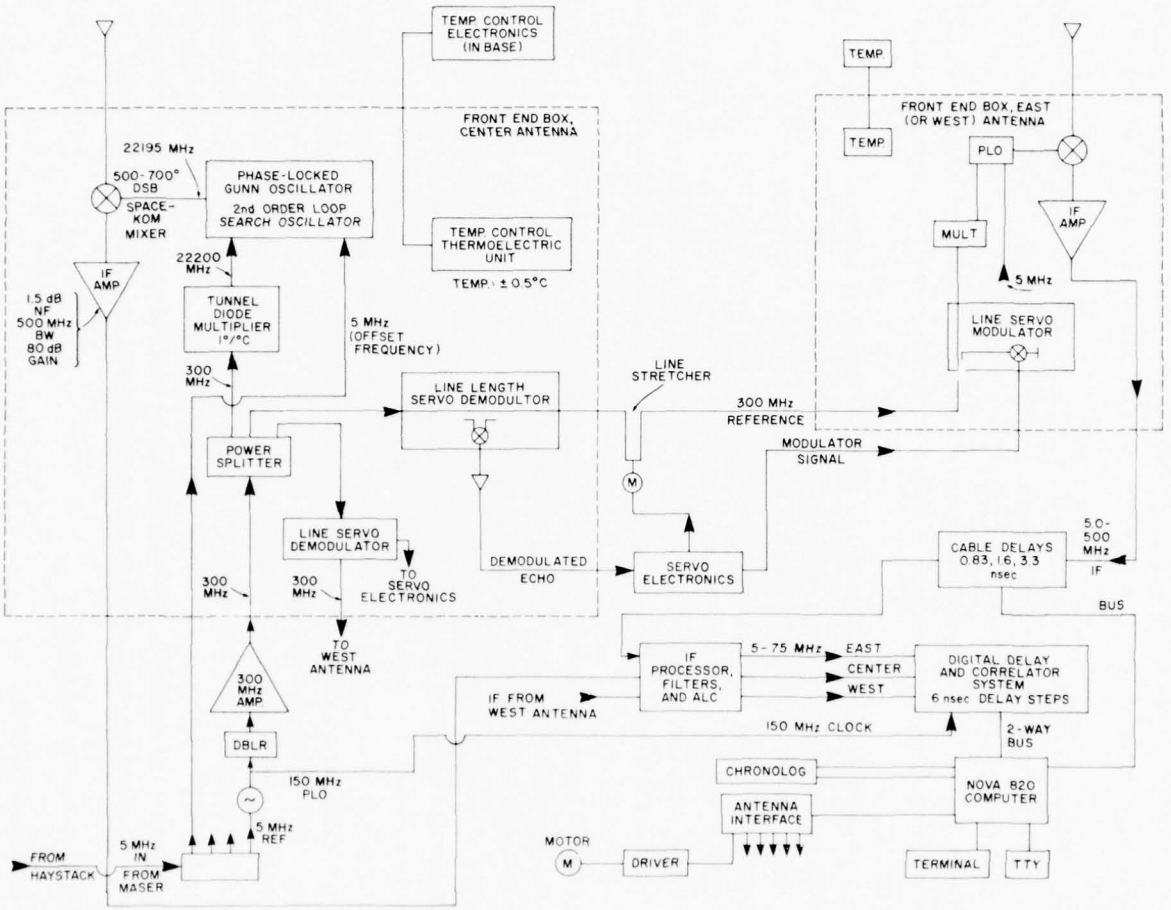

Fig. XIII-2. M. I. T. microwave aperture synthesis interferometer system.

The compactness and relative simplicity of the instrument depend largely on the digital delay and correlator system developed for it in this laboratory. This device, which essentially is a special-purpose digital computer with a cycle time of only 6.6 ns, is capable of crosscorrelating three pairs of noise signals, each of which has a 75 MHz bandwidth.

The components of the installed 2-element system were assembled in the laboratory, and the phase stability of this assembly has been measured to be 3.5° rms. It is expected that this order of phase stability will also be maintained in the field, since the critical variables, the focus box temperatures, are controlled by proportionally controlled thermoelectric systems, and all critical elements are installed in these packages.

The computer system is based on the Nova 820 interrupt system. An external real-time clock generates two interrupt chains, one every eighth second and the other every twelve milliseconds. The eighth-second interrupt causes the computer to perform the following tasks: time and display upkeep, pointing calculations, delay calculations, fringe fitting, and data tape creation. The 12-ms interrupt samples the correlators, pulses the antenna stepping motors, and sets the delays. All software and interfaces have operated successfully in the first phases of testing and are now undergoing system usage tests on site.

The digital sampler, delay lines, and correlator comprise a three-level 2-bit system. The sampler is an ECL system clocked at 150 MHz which gives a 75 MHz bandwidth. Since it would be very difficult to maintain such a clock rate, the high-speed serial data stream is separated into 8 parallel data streams. This allows all except the sampler and serial-to-parallel converter board to be clocked at 18.75 MHz, i.e., TTL logic speeds. The delays are shift registers, multiplexers, and latches that give delays from 6.6 ns to 1.2 μs in 6.6 ns steps. The correlators multiply the samples from each antenna and accumulate these products until the computer requests the accumulation. This system is now operating on site and all tests will soon be completed.

A NRAO program has been adapted to compute the rms surface accuracy of two of the antennas, by using surface measurements made by D. Cosmo Papa. The rms surface accuracy of the two antennas was found to be 0.022" and 0.036", which is in agreement with efficiency measurements, with astronomical sources used. The major fraction of the error is caused by panel setting, and rerigging will be done at a later time.

b. Studies of Nearby Galaxies

Thomas S. Giuffrida

In the thesis research of John H. Spencer[1] virtually no HII regions were detected in M31. Since several detections from observation in our Galaxy would have been predicted, we decided on making further observations of M31 and also of M81 and M101,

using the NRAO 3-element interferometer. Thus far we have detected one large HII region in M31, one HII region in M101, and a supernova in M101. Also, the nucleus of M81 was shown to be quite variable on time scales as short as one day.

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c. Neutral Hydrogen Absorption in Clusters of Galaxies

Aubrey D. Haschick, Willem A. Baan

Approximately 20 clusters of galaxies have been surveyed for neutral hydrogen absorption. In all cases, the illuminating radio source was either a background quasar or a radio galaxy within the cluster itself. Each cluster was searched over a 2000 kms^{-1} velocity range centered on the red shift of the cluster, which in all cases was less than 0.035. No absorption features were found down to a limiting antenna temperature ~0.08 K on the 300-ft telescope. This provides a limiting density of $\frac{\eta_H}{T_s} \sim 6 \times 10^{-7}$ cm^{-3} for neutral hydrogen in clusters of galaxies, and implies that the mass needed to bind clusters of galaxies gravitationally is probably not contained in cold HI clouds.

d. Neutral Hydrogen Absorption in the Spectra of Quasars and Radio Galaxies

Aubrey D. Haschick, Patrick C. Crane, Willem A. Baan

Recent observations of the neutral hydrogen spectrum of quasars near spiral galaxies in one case have revealed an absorption feature close to the red shift of a nearby galaxy. The absorbing cloud bears some resemblance to extragalactic HI clouds found by observers in the vicinity of galaxies, such as M81, NGC 55, and NGC 300. This has inspired further observations of radio source galaxy pairs that have revealed three more absorption lines. The absorption feature in the spectrum of the BLLAC-type object 1749+701 has a velocity higher than the velocity of the neutral hydrogen emission from the nearby galaxy NGC 5603. This reveals the presence of high-velocity clouds at distances of ~20 kpc from the nucleus of NGC 5603. The two other absorption lines were found in the spectrum of the nuclear source of the particular galaxy and probably arise from HI clouds either in the disk of the galaxy or in the halo region of the galaxy. Observations of radio galaxies continue in a search for more of these high-velocity hydrogen clouds in external systems. Of particular interest are size, spin temperature, and density of these clouds.

e. Water-Vapor Observations of Hydroxyl Masers in the Galactic Center

Aubrey D. Haschick, Bernard F. Burke

A survey has been conducted of the water-vapor frequency of 22.235 GHz for ~40 regions of OH maser emission in the galactic center. The Haystack 120-ft antenna equipped with a maser amplifier and a 1000-channel autocorrelator was used in the observations. Each position of OH emission was searched, by using a 5-position grid down to a limiting antenna temperature of 0.2 K.

Two new H_2O sources were discovered. One of these sources exhibits a complex spectrum with multiple features spread over a velocity range of ~70 kms^{-1}. The variable nature and multiplicity of the features bears a similarity to H_2O masers found in HII regions as opposed to those found in infrared stars, and hence indicates a possible region of star formation. The second source displays only a single feature that is more characteristic of H_2O masers found in infrared stars.

These observations were made with Dr. James M. Moran of the Smithsonian Astrophysical Observatory.

7. MICROWAVE SPECTROSCOPY OF THE INTERSTELLAR MEDIUM

National Science Foundation (Grant AST73-05042-A03)

Alan H. Barrett, Philip C. Myers

Microwave spectroscopic studies of the interstellar gas have shown that the spectral lines have their origin in regions believed to be intimately associated with star formation. Typical densities are 10^3-10^6 cm^{-3}, kinetic temperatures are in the range 5-100 K, and frequently the molecular clouds contain smaller regions of infrared and/or optical activity which are thought to be embryonic stars. We have studied some of these regions to further our understanding of their physical conditions and gain better insight into the processes involved in the chain of events from formation of a massive cloud to stellar development.

Using the Haystack Observatory, we have observed NH_3, CH_3OH, and H_2O, all of which have transitions in the 22-26 GHz range. We have observed CO and CS at millimeter wavelengths, using the 36-ft NRAO telescope on Kitt Peak, in Arizona. In most cases the angular resolution is ≈1.5 arc minutes. We have also observed the H, OH, and CH_2O lines, using the 140-ft NRAO telescope in Green Bank, West Virginia.

Briefly, the major results of our observations are as follows:

a. NH_3 Results

The NH_3 molecules form a common constituent of many interstellar clouds and the NH_3 abundant hyperfine structure permits the determination of the optical depth, provided it is neither too small ($\ll 1$) nor too large ($\gg 1$). Instances of the latter have never been found; instances of the former are not unusual. NH_3 also has many lines in a narrow frequency range, which allows us to sample a wide range of excitation conditions. We find the optical depth of NH_3 in Orion and in other dense molecular clouds to be ≈ 1-2. In Orion this has led to the conclusion that the NH_3 is nonuniformly distributed, occurring in "clumps" of the order of 0.04 pc in size. In the Taurus dust cloud, the narrow NH_3 lines permit us to set an upper limit of 30 K on the kinetic temperature. Systematic velocities such as would be due to collapse, for example, are less than 0.2 km/s.

b. CH_3OH Results

We have continued to monitor the time variations in the CH_3OH maser emission from the KL nebula in Orion. These observations are made typically every three months. The J = 6 and J = 7 lines are strongest and have continued to show time variations. Also, we now have evidence that the CH_3OH emission is linearly polarized at a level of $\approx 20\%$. Prior to September, 1976, we had set an upper limit of 5% on the linear polarization. The variation in polarization appears to be correlated with the variation in intensity.

c. Millimeter Wavelength Observations

The millimeter wavelength transitions of CO and CS, and their isotopes, have been observed in small, dense globules. OH, H, and CH_2O have also been observed in many of the same clouds. It is feasible to map emission over the entire globules because their angular size is less than 6 arc minutes. Two particularly interesting objects are B163 and CRL 437. The former appears to give evidence of fragmentation into at least two individual clouds. CRL 437 yields strong CO emission which permits detailed studies of the variation of line shape across the object. These have been interpreted in terms of systematic radial and rotational motions within the cloud.

d. Dark Cloud Observations

The Rho Ophiuchus cloud has been mapped in CO, H, OH, and CH_2O lines. The observations appear to indicate that the cloud is surrounded by an HI envelope and the molecular emission originates in a more dense central region. The cloud seems to be undergoing gravitational collapse. The existence of an HI envelope about clouds is apparently quite common but the HI self-absorption is not easy to detect. Continuum emission from dark clouds is less than 0.2 Jy at 5 GHz and 8 GHz, which sets limits on the number and spectral types in such clouds.

XIV. 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 1976 by the Joint Services Electronics Program which have been published, accepted for publication, submitted for publication, or presented at meetings are listed in the references.[1-17] The advantages of using horizontal magnetic dipole antennas were explored in detail for both isotropic and anisotropic layered earth.[1-3] We compared field calculations and experimental results for a horizontal electric dipole submerged in lake water.[4] In remote sensing we studied thermal microwave emission from random media and from media containing spherical scatterers.[5-13] In applied optics we investigated electro-optical modulators and developed theories for spatially modulated periodic media.

In the study of geophysical subsurface probing and communication with dipole antennas, the theory for surface waves and subsurface waves arising from dipole images has been developed. The surface waves are proportional to inverse distance squared and the subsurface waves to inverse distance. We shall evaluate the image contributions to second order in inverse distance and hope to attain a compatible, rigorous theory. In remote sensing we are now incorporating the surface roughness and subsurface inhomogeneous temperature distributions. In integrated optics and fiber optics we are studying the diffraction and guidance of a Gaussian beam by a spatially modulated periodic medium. Mode coupling and conversion mechanisms in guided optical systems will be applied to both optical communication and solar energy collection studies.

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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.[1-5] The model of a medium containing spherical scatterers has also been developed.[6-10] These theoretical models have been applied to the solid earth, as well as to clouds and rainfall.[9-10]

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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, 4] The theory for thermal microwave emission from a bounded medium containing spherical scatterers has also been developed.[5]

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XV. GRAVITATION RESEARCH

Academic Research Staff

Prof. Rainer Weiss

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

Rainer Weiss

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 $(\Delta\ell/\ell)^2 \sim 10^{-42}/\text{Hz}$.

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 $(\Delta\ell/\ell)^2 \sim 10^{-36}/\text{Hz}$. 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.

PLASMA DYNAMICS

XVI. PLASMA DYNAMICS

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XVI. PLASMA DYNAMICS

A. Basic Plasma Research

1. NONLINEAR WAVE INTERACTIONS

National Science Foundation (Grant ENG75-06242-A01)

Abraham Bers, George L. Johnston, Abhijit Sen, Frank W. Chambers, Allan H. Reiman, Nathaniel J. Fisch, Charles F. F. Karney, John L. Kulp, Jr., Stavros M. Macrakis, Vladimir B. Krapchev

This theoretical research is aimed at understanding the evolution of large-amplitude coherent waves and strong turbulence in a plasma. We are particularly interested in third-order perturbation theory for coherent waves in a magnetic field, nonlinear evolution of wave coupling and nonlinear propagation of waves in inhomogeneous plasmas, and resonance broadening and strong wave turbulence, based on soliton states.

Our work during the past year included:

(i) A new formulation for the nonlinear coupling of kinetic waves in a plasma.[1] This allows for a pump with finite wavevectors, and waves of arbitrary orientation to the magnetic field.

(ii) A complete analytic solution for the linearly unstable eigenmodes in an inhomogeneous plasma of finite extent.[2] This shows that the unstable eigenmodes persisting when the interaction length is increased are tied to the abrupt boundaries and may have no physical significance relative to the saturated gain convective instability.

(iii) An analysis that shows the interrelationship of oscillating two-stream (OTS) instabilities and modulational instabilities for finite pump wavevectors.[3]

(iv) A complete solution of time-space nonlinear evolution of three-coupled wave packets.[4, 5] We have recently extended this solution to describe the two-dimensional nonlinear interaction in an inhomogeneous medium.[5]

(v) A new derivation of our proposed resonance-broadening corrections to weak turbulence theory.[7] A particularly interesting aspect of this work is that we can begin to relate strong turbulence and stochasticity associated with large-amplitude coherent waves.

(vi) A summary presentation and publication of our work on symbolic computation (MACSYMA) in nonlinear wave interactions.[8]

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2. STUDIES OF NONLINEAR WAVE-PARTICLE INTERACTIONS

National Science Foundation (Grant ENG75-06242-A01)

Peter A. Politzer, Ady Hershcovitch, Gillis R. Otten

In order to study spatial and velocity diffusion processes in a controlled experiment, we are using a counterstreaming electron-beam facility to observe the time history of the particle velocity distribution function and the electric-field spectrum. We can apply a known spectrum of electric-field fluctuations to this system and observe the consequent diffusion. Measurements of the velocity-space diffusion coefficients as a function of the amplitude and width of the applied turbulence spectrum have been made. Using the formalism of strong turbulence theory, we have calculated the expected diffusion coefficients for this system, and these predictions agree well with observations. We are also concerned with the effects of externally applied turbulence on unstable plasmas, and have found theoretically that application of a controlled spectrum of high-frequency turbulence can disrupt particle orbits sufficiently to interfere with the growth of low-frequency instabilities, and even to suppress them entirely. We have applied this calculation to trapped-particle modes in toroidal devices and find that the power required, though large, is not unreasonable and that the cross-field transport can be considerably reduced. We have also applied this model to the half-cyclotron instability in the counterstreaming electron-beam system and have undertaken an experiment to check the predictions of power required to suppress this mode. Thus far, the results are in agreement with our predictions.

3. TRAPPED-PARTICLE EXPERIMENTS

National Science Foundation (Grant ENG75-06242-A01)

Lawrence M. Lidsky, Peter A. Politzer

The trapped electron scattering mode in periodic cylindrical geometry is a high mode number, drift-type mode propagating in the electron diamagnetic drift direction and standing in the direction parallel to B. Our earlier work showed that this mode saturated at relatively small amplitudes, which implied that this particular mode might not have especially serious consequences for particle containment or energy loss. The curve of fluctuation amplitude vs system pressure, however, did not quite level out at the lowest pressures attainable previously and it was not clear that the wave was truly nonlinearly saturated. We have recently modified the apparatus to allow operation at

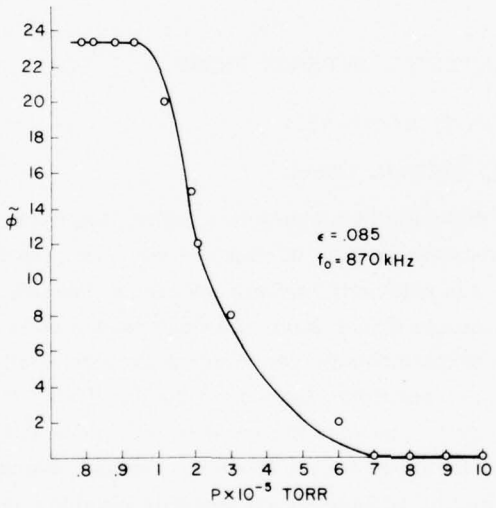

Fig. XVI-1.
Relative potential fluctuation amplitude as a function of normal gas pressure.

appreciably lower pressures and we have repeated our earlier measurements. The essential results of this study are shown in Fig. XVI-1. The collision frequency at the onset of the instability (6×10^{-5} Torr) is comparable to the electron axial bounce frequency in our apparatus. The saturation below 1.0×10^{-5} Torr is adequately demonstrated and we conclude that results that we reported earlier[1] are correct.

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4. RENORMALIZATION METHODS IN PLASMA TURBULENCE THEORY

National Science Foundation (Grant ENG75-06242-A01)

Thomas H. Dupree, David J. Tetreault

An improved version of strong turbulence theory has been developed to deal with predominantly two-dimensional turbulence involving E × B drifts and quasi-neutral fluctuations. This development leads to a renormalized quasi-linear theory that conserves energy and momentum, which earlier theories failed to do. This theory preserves the essential perpendicularity between the random drifts and the random electric fields. The nonlinear damping also vanishes, as it must, when the electron response is exactly adiabatic. We are now applying the theory to a variety of drift wavelike instabilities.

5. INTENSE RELATIVISTIC ELECTRON BEAMS

National Science Foundation (Grant ENG75-06242-A01)
U. S. Energy Research and Development Administration (Contract E(11-1)-2766)
U. S. Air Force – Office of Scientific Research (Grant AFOSR-77-3143)

George Bekefi

During the past year we have studied the microwave emission from relativistic electron diodes. In particular, we have constructed a relativistic electron beam magnetron that generates microwave powers in the gigawatt range.

In the coming year we shall concentrate on the following areas of study.

(i) We shall optimize the magnetron design in order to obtain higher powers with higher efficiencies. We shall measure the spectral output of the device. To investigate the scaling laws for these magnetrons, we shall go to higher voltages in the 1-MV range. This work will be carried out on higher voltage facilities such as those available at the Naval Research Laboratory and at Sandia Laboratories, Albuquerque, New Mexico.

(ii) This magnetron will be used as the microwave source in the study of nonlinear wave-plasma interaction. Specifically, by luminating an unmagnetized plasma, we are interested in determining the nonlinear absorption and reflection coefficients of the plasma medium.

(iii) By bouncing the microwave emission off another relativistic electron beam, the scattered radiation is shifted to higher frequency. As a result, intense millimeter and submillimeter radiation may be achieved. This work will be carried on in conjunction with the Naval Research Laboratory.

(iv) Because of instabilities, a self-pinched electron beam is expected to emit microwaves, and we shall study it.

XVI. PLASMA DYNAMICS

B. Plasma Research Related to Fusion

Confinement Systems

1. PHYSICS OF HIGH-TEMPERATURE PLASMAS

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

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 larger than 10^{14} 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[1] 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 led to its emergence as the preeminent toroidal confinement device. Specifically, we can point to the following achievements:

(i) Peak plasma densities up to $\sim 7.5 \times 10^{14}/\text{cm}^{-3}$, with energy confinement times of ~20 ms have been attained. This yields $n\tau$ values above 10^{13} sec/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 been able 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) Complete control over the plasma density level can be maintained during a given discharge by further exploitation of the gas injection technique, which was developed in previous years, and by using a new infrared laser interferometer for accurate density measurements. Consequently, a direct derivation of the scaling laws for the

particle confinement time has become possible. Direct measurements of the ion temperature in high-density regimes have also been made which have confirmed our expectations that it would be close to the electron temperature.

(iv) A numerical transport code has been developed which can simulate the high-density plasma regimes in Alcator. In fact, elaborate codes developed previously in other laboratories have been inadequate for reproducing these regimes.

The Alcator C device that we proposed in 1975 for funding by ERDA has now been approved and its construction is under way. A new power supply to exploit the design parameters of this device will be acquired and 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} sec/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 that features $a \approx 21$ 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.

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

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Research – Theoretical

2. RF HEATING AND HF MICROTURBULENCE

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Abraham Bers, Frank W. Chambers, George L. Johnston, Gérard P. Leclert, Abhijit Sen, Charles F. F. Karney, Miloslav S. Tekula, Nathaniel J. Fisch, John L. Kulp, Kim S. Theilhaber, Stavros M. Macrakis

We have continued our theoretical studies on problems associated with the need for supplementary heating of Tokamak plasmas. Several aspects related to RF heating with external power near the lower hybrid frequency have been analyzed in detail:

(a) A three-dimensional WKB formulation of group velocity ray tracing for a Tokamak plasma has been completed and prepared for computation.[1, 2] This formulation includes the effects of toroidal geometry, and of plasma and magnetic field inhomogeneity.

(b) Nonlinear phenomena associated with the propagation of high powers from localized sources at the wall have been studied. These include self-modulation and parametric excitations.[3, 4]

(c) The following heating mechanisms have been treated in some detail.

(i) Electron heating by the lower hybrid fields propagating in resonance cone structures in the plasma.[5, 6]

(ii) Stochastic ion heating induced either by the large-amplitude and short-wavelength lower hybrid fields or by their parametrically excited fields.[7]

(iii) Heating by parametric decay waves coupling to electrons and/or ions, which we have emphasized in the past.

Several reviews of our work have been presented during the past year.[8-10] Many aspects of this work are still incomplete and continue to receive our attention. Our work has included feasibility studies for RF heating experiments on Alcator A which we are now proposing.

We have also continued our studies of high-frequency microturbulence associated with the runaway tail in Tokamak plasmas. Three interrelated aspects are included: (i) anomalous radiation associated with instabilities driven by the electron velocity distribution function tail; (ii) evolution of the electron velocity distribution function in the presence of the applied E-field and the turbulence generated by the instabilities; and (iii) anomalous ion heating which has also been observed. During the past year we have begun to tie these together. A study on the generation of unstable plasma waves by a model electron distribution function has been completed.[11] A quasi-linear analysis of the tail evolution has been initiated and is nearly finished.[12] An important result of this work is that the power radiated by these instabilities can be an appreciable energy loss

mechanism in moderate density Tokamaks. It also is important for supplementary heating schemes in which the tail of the electron velocity distribution function may be modified significantly.

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3. NONLINEAR THEORY OF TRAPPED-PARTICLE INSTABILITIES

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Thomas H. Dupree, David A. Ehst

Strong-turbulence theory is being applied to trapped-electron and trapped-ion mode We have computed the rate of wave energy cascade in wave-number space, as well as the rate of wave energy absorption by the ions caused by stochastic ion motion at high turbulence levels. This permits calculation of many important transport properties of the steady turbulent state including mass and heat transport.

An important aspect of the theory is the prediction of the spectral density of the flu tuations, a quantity that can be compared in detail with experiments.

4. NODAL EXPANSION IN $2 + \epsilon$ DIMENSIONS

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Claude Deutsch

A one-component plasma (OCP) model with neutralizing background has been exten to real dimensionality $\nu = 2 + \epsilon$ with $-2 \leq \epsilon \leq 2$. The equilibrium properties (pair cor relation and thermodynamic functions) investigated within the Debye approximation, up to the second-order in the plasma parameter $e^2/k_B T \lambda_D^{\epsilon}$, with the aid of the Wilson qua ratures, interpolate between two- and three-dimensional results for $0 < \epsilon < 1$, and ext the $\nu = 3$ behavior to all $\nu \leq 2$. In this work, the dimensionality $\nu = 2$ has been shown to play a special role.[1] Quantum diffraction corrections are included in the high-temperature limit through a temperature-dependent effective Coulomb interaction. As a by-product, the particle diffusion coefficient (Bohm) of the strongly magnetized two-component plasma taken in the fluid limit may be given a finite volume-independent expression in the thermodynamic limit when $\nu = 2$, provided due attention is paid to th Tauberian properties of the Coulomb potential for $-2 \leq \epsilon \leq 0$.

This analysis is being extended to two-component plasmas, including this real mat ter at high temperature. The nodal expansion has been extended to the latter case.

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Research – Experimental

5. TOKAMAK RESEARCH

U.S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

George Bekefi, Lawrence M. Lidsky, Louis D. Smullin

During the past year we concentrated our efforts on three areas of Tokamak research:

a. A study of the impurity influx into the Tokamak discharge using ultraviolet spectroscopy of impurity ions. Spatial and temporal measurements of absolute line intensity were made at wavelengths in the 1000-2600 Å range.

b. A direct determination of the energy confinement time. The energy confinement time in Versator I was determined using a novel technique in which a short heating pulse was applied to the discharge and the subsequent decay of electron temperature was determined. The measured energy decay was 1.1 ms.

c. We have almost completed construction of the Versator II facility, which will become operational during the spring of 1977, and we shall carry out our ultraviolet studies and measurements of energy decay time in Versator II. We shall also perform the following investigations:

(i) Thomson scattering from the electrons with the goal of determining both the parallel and perpendicular electron temperatures of the Tokamak discharge. This work will be undertaken with the use of a 10 J ruby laser.

(ii) Ion fluctuations will be determined from the microwave scattering of 4-mm radiation. For this purpose we have designed a scattering system that contains a microwave source capable of generating 150 W of 4-mm waves.

(iii) Cyclotron radiation in both presence and absence of runaways will be investigated in Versator II in the 15-70 GHz frequency range.

(iv) Certain aspects of microwave heating at the lower hybrid frequency will be studied in Versator II. In particular, we shall attempt to determine the location of the heating signal by using microwave scattering as the diagnostic. We are also setting up the necessary microwave plumbing to study microwave breakdown at the input to the Tokamak. Particular attention will be paid to such questions as microwave breakdown caused by multipacting.

6. COHERENT SCATTERING EXPERIMENT – MEASUREMENT OF ION TEMPERATURE AND LOW-FREQUENCY TURBULENCE

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Puthenveetil K. John, Lawrence M. Lidsky

An experiment is in progress to measure the low-frequency "ion component" of 10.6 μm radiation scattered from a hollow-cathode discharge plasma. This experiment is based on modifications and improvements of apparatus already used successfully to measure the "electron component" of the same spectrum. Our goal is to develop a diagnostic suitable for measuring the relatively low-frequency turbulence that plays the most important role in ion transport and heat transfer.

We use apparatus developed previously and used successfully to detect and resolve high-frequency (electron wing) scattering from thermal level density fluctuations in a plasma with density of order $5 \times 10^{19}/m^3$ and electron temperature of order 5 eV. The radiation source was a 100 W steady-state, stabilized, single-frequency CO_2 laser, and the radiation was detected by a liquid-helium-cooled H_g:G_e photodetector after spectral resolution had been accomplished by means of a liquid-nitrogen-cooled Fabry-Perot spectrometer. The scattering at high frequency indicates that the collective density fluctuation level with wave number in the range 10^5 m^{-1} to 2.5×10^5 m^{-1} was very close to the thermal level. Furthermore, the shape of the scattered spectrum agrees very well with that predicted by theory (see Fig. XVI-2). Our attempts to resolve the ionic component have not been successful. In trying to understand this we have extended

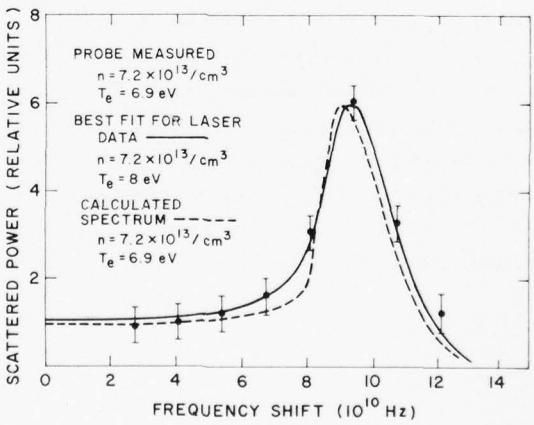

Fig. XVI-2. Comparison of laser and probe-measured plasma parameters.

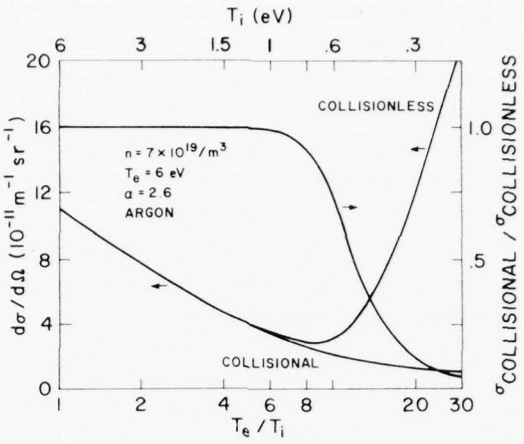

Fig. XVI-3. Total power scattered into the ionic component calculated with collisionless and collisional theories.

the theory of collective Thomson scattering to include the collisional effects in regimes where T_e/T_i is much greater than 1. In these regimes the collisionless Landau damping of the ion acoustic mode is very small and inclusion in the theory of collisional effects has been shown to lead to substantially reduced scattering. The results of calculations for plasmas in the regime of interest are shown in Fig. XVI-3. The scattering in the presence of collisions for the case of interest was reduced by nearly a factor of 10. We are now engaged in modifying the apparatus to improve resolution and signal-to-noise behavior and we hope this will enable us to observe a reduced scattering level.

7. LYMAN-α DOPPLER SPECTROMETER

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Peter A. Politzer, Louis S. Scaturro, Lawrence M. Lidsky

There is an acknowledged need for new diagnostic techniques for measuring plasma parameters in large confinement devices. In particular, we need accurate measurement of the ion temperature with good spatial and temporal resolution. We are designing an instrument to enable measurement of the ion energy distribution with approximately 10 ms time resolution and 2 cm spatial resolution, based on observation of the Doppler-broadened profile of the Lyman-α (1216 Å) emission line of atomic hydrogen. The source volume is defined by the intersection of the viewing light cone and a low-current neutral beam injected across the plasma. The beam energy is chosen to

give good probability of charge exchange with plasma ions directly into the n = 2 state. The lifetime of the neutralized ions in this state is very short, and hence they radiate before leaving the source volume and before collisional de-excitation is possible. The line profile is analyzed by using an echelle grating in 46^{th} order in a Czerny-Turner configuration, and a multichannel plate is used as detector. The dispersion of this instrument is 0.2 Å/mm, which enables us to measure the Doppler profile accurately. This instrument will provide a direct and unambiguous measurement of the ion energy distribution within the plasma. It alleviates some of the problems associated with alternative techniques such as neutral-particle energy analysis because the Lyman-α photons escape from the plasma without reabsorption.

8. BOLOMETRY

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Louis S. Scaturro, Lawrence M. Lidsky, Neil S. Novich

A fast-rise bolometric probe has been constructed and mounted flush with the vacuum vessel wall on the Alcator confinement system. The bolometer is a BeO substrate 0.0254 cm thick, flash-coated with molybdenum, backed with thermistor material. Radiative or particulate energy impinging on the surface heats the bolometer and is measured as a voltage change across the changing thermistor resistance. The bolometer was calibrated with a chopped CO_2 laser and found to have a total response of 2.7 volts/joule with a rise time of approximately 1 ms and a fall time of 0.1 s. Preliminary measurements during low-density operation in Alcator indicate a constant energy loss rate to the wall amounting to approximately 5-10% of the ohmic heating power input. For high-density operation ($n_e \gtrsim 1 \times 10^{14}$ cm^{-3}) the power output seems to scale like n_e during the pulsed-gas feed stage, but decreases when the electron density reaches a maximum constant value. These data may shed light on the processes leading to charged-particle density buildup in the central plasma regions when pulsed-gas feed is employed. If so, various theoretical models can be tested.

9. EXPERIMENTAL MIRROR STUDIES

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

Louis D. Smullin, James E. McCune, Robert E. Klinkowstein,
Joseph L. Jones, Kurt D. Cogswell

The purpose of this program is to study instabilities driven by loss-cone-generated velocity distributions.

The apparatus is a chamber 174 cm long and 27 cm in diameter within a mirror field with ratio ~2 and peak field ~4 kG. An array of ceramic bar magnets 64 cm long surrounds the plasma to produce a cusp field of various periodicities up to 12, and peak field at the faces ~1.5 kG. The plasma is injected from a Ti washer gun. Base pressures of (few) $\times 10^{-8}$ will be maintained by a combination of oil diffusion pump and Ti getters in the ends of the main chamber.

The system should be operative in January 1977. The recent success of the 2X11 minimum-B mirror system in achieving nearly classical loss rates has revived interest in mirror confinement systems. This success, in large part, was due to the empirical suppression of loss-cone instabilities by injection of cold plasma. The details of the suppression mechanism are not well understood and our studies are aimed at explaining this process.

The system will be pulsed with plasma injected from a Ti washer gun at one end. At the end of the gun pulse (in the afterglow), we shall measure $n(r, t)$, $f(v_{i\perp})$ (using a charge-exchange analyzer), and plasma potential, as well as fluctuation phenomena. A similar system at the Kurchatov Institute in Moscow has been in operation for some time, and our first efforts will be to correlate our results and plasma parameters with theirs. The Ti washer gun can be fired over a voltage range (on the delay-line capacitors) of 700-3000 volts. The pulse duration is 2 ms. After the installation of a crowbar ignition, pulse width will be adjustable to "arbitrarily" small widths below the maximum.

(XVI. PLASMA DYNAMICS)

10. NEUTRAL BEAM STUDIES

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

National Science Foundation (Grant ENG75-06242-A01)

Louis D. Smullin, Leslie Bromberg, Peter Kenyon, Yo Misaki

a. Theory

Louis D. Smullin, Leslie Bromberg

We have developed models that predict the operating characteristics of multifilament, low-pressure plasma sources as functions of geometry, gas filling, and applied voltage. The agreement with experiment is very good for the unmagnetized discharge (Berkeley multifilament arc). In the case of the magnetic cusp protected discharge (University of California at Los Angeles) there is some disagreement between experiment and theory, and we are trying to resolve this by discussions with the authors of the experimental results.

The theory of space-charge effects in cesium charge-exchange cells has been examined to determine whether ion beam blowup should be expected. This seems not to be the case, since a plasma builds up with densities approximately 100 times that of the drifting ion beam, and the resulting space potentials are quite low. The large cold electron density, however, poses a problem for extraction and acceleration of negative ions (D^-). The electrons will have to be separated from the negative ions by a decelerating grid of approximately -500 volts. It is not yet clear what other problems may be caused by this large plasma density and we plan to study this further.

This theoretical research will be submitted as the doctoral thesis of Leslie Bromberg.

b. Plasma Sources

Louis D. Smullin, Peter Kenyon

The work on the magnetron-cathode, θ-cusp plasma source will constitute the Master's thesis research of Peter Kenyon. It will include measurements of terminal characteristics, plasma density at the extraction plane, fluctuation characteristics, and some of the detailed measurements of plasma velocity distributions. With the completion of the detailed studies of the 4" diameter system, we shall now resume the study of a scaled-up 7" diameter system, whose construction was completed some time ago.

c. Charge Exchange between H^+ and Optically Excited Sodium

Louis D. Smullin, Yo Misaki

This study is concerned with measuring the change in the yield of the double charge-exchange process $I_{H^+} \rightarrow I'_{H^\circ} + I'_{H^-} + I'_{H^+}$ when a proton beam (H^+) is incident on an alkali metal vapor (Na), and the vapor has been excited by optical pumping. The system has a variable energy H^+ ion beam (1 - 4 keV) incident on a Na vapor region, with an optical source to excite the sodium to its first level (2.1 eV).

At present, we are studying illumination sources. Since the H^+ beam must pass through a Na vapor target of $\sim 10^{13}$-$10^{14}/cm^2$ (line density), we shall need an extended illumination source. Thus, lasers with their ability to focus to very small spot sizes have no particular advantages, and we are investigating the problem of adapting commercial low-pressure Na vapor lamps to our purpose. We plan to design and build a Na vapor channel integrated with an illumination source.

Fusion Technology Studies

U. S. Energy Research and Development Administration
(Contract EY-76-C-02-3070.*000)

The fusion technology program is an interdepartmental effort supported by the Development and Technology branch of ERDA DMFE. The program's goal is to investigate various engineering problems of controlled fusion reactors with particular emphasis on radiation damage, reactor fueling, reactor blanket analysis, safety and environmental studies, and "new concepts development." The fusion technology group is involved in studies of radiation damage, intense neutron source evaluation, fission-fusion symbiosis, EBT reactor design, fusion reactor blanket analysis, pellet fueling of fusion reactors, and reactor safety and environmental studies. 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.

11. HIGH-INTENSITY NEUTRON SOURCE

Lawrence M. Lidsky, Alan R. Forbes

The gas target source is a prime candidate for the intense 14 MeV facility that must be developed for testing fusion reactor materials. We are planning to perform experimental measurements of the detailed behavior of a beam-heated jet in a quarter-scale, intermittently pulsed model of such a device. Our goal is to generate experimental data to compare with theoretical predictions and the extensive numerical computations that have been done at M. I. T. and elsewhere.

This experiment utilizes a pulse circulating gas loop in counterflow with a 150 kV ion beam directed into the nozzle from a duoplasmatron. The gas loop and ion beam transport tubes have been designed, constructed, and tested. Parts needed to complete the duoplasmatron have been machined and the ion source test stand has been constructed. A feedback-stabilized, highly regulated pulsed power supply for the duoplasmatron has been designed and tested and the requisite step-up transformer is under construction. The E-beam gas density probe has been made and tested.

12. PELLET FUELING OF FUSION REACTOR

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. Because of the complexity of the interaction between a solid surface and a hot dense plasma, we do not know the ablation rate of a solid pellet, nor consequently the fuel deposition rate. In order to predict the required pellet velocity, we need to obtain a satisfactory model for the ablation process. We are undertaking this study in two ways. We have developed a computer model for the interaction between a very dense cold plasma cloud and a hot magnetized plasma. Unlike other ablation models, this model includes the effects of magnetic fields, and particularly magnetic shielding of the pellet surface. This code is being used in conjunction with models developed at Oak Ridge National Laboratory which describe the behavior of the ablation cloud in the region between the pellet surface and the layer in which the ablated particles become ionized. In order to have experimental verification of the model under conditions of plasma energy density corresponding to fusion reactors, we are constructing a Z-pinch discharge that will be able to sustain such conditions for short periods of time. We plan to inject plastic pellets into this plasma to get the scaling of ablation rate with plasma density and temperature. The discharge will be stabilized with a bias magnetic field and should provide a plasma with densities of $\sim 10^{16}$ cm^{-3}, temperatures of ~500 eV, for a 3-4 μs pulse length.

13. HIGH-ASPECT-RATIO TOROIDAL REACTORS – EBTRX

Lawrence M. Lidsky, James S. Herring, David L. Kaplan, Robert E. Potok

An ideal fusion reactor, from the viewpoint of a reactor designer, would be a steady-state device of moderate-β, relatively high aspect ratio, modular construction, "reasonable" surface/volume ratio, an operating wall loading of the order of several megawatts per square meter, and would allow for the relatively straightforward provision of a functional divertor. There is a relatively unexplored set of plasma configurations compatible with our understanding of plasma physics which apparently meets these requirements. One of these is the EBT concept pioneered at the Oak Ridge National Laboratory although there are others that, in fact, might be of greater ultimate interest. The Massachusetts Institute of Technology fusion group working in close collaboration with ORNL has evaluated the EBT primary concept as the basis for development of commercial fusion power. Inspired by the exciting potential of devices in this class, we are proceeding to carry out a more general study of moderate-β, high-aspect-ratio, ignited,

steady-state toroids. Our initial aim will be analysis of the Heliotron-Torsatron configuration.

The multidisciplinary, self-consistent treatment of EBT reactor scaling and design developed in conjunction with Oak Ridge National Laboratory has been completed and a reference design (EBTR-48) developed. This design, based on a realistic plasma model and relatively conservative engineering parameters, is based on a steady-state ignited-mode system of high plasma power density and aspect ratio. The major design features of the 4000 MW thermal plant are illustrated in Fig. XVI-4 and Table XVI-1. The design postulates a standard module, and the design power level for a particular plant is then determined by the number of modules used. Several design variants were investigated in detail to illustrate the effect of near-term and advanced technologies and to illustrate the design freedom offered by devices with low-field, high aspect ratio. The high aspect ratio simplifies many aspects of design, most notably those associated with remote maintenance, accessibility and repair. We concluded that a commercially successful EBTR could be constructed with only slight advances in existing technology if the

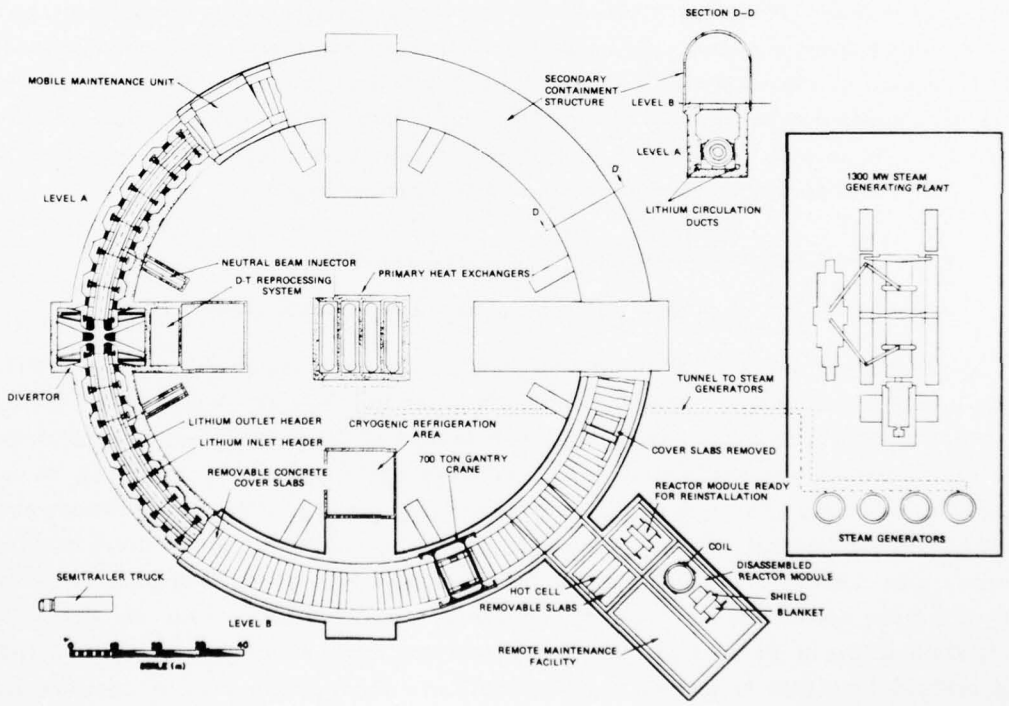

Fig. XVI-4. EBTR plan view.

Table XVI-1. EBT reactor reference parameters.

	EBTR-48
Plasma radius, a (m)	1.0
Aspect ratio, A	60
Major radius, R_o (m)	60
Mirror ratio, M	1.78
Ion temperature, keV	15
Ion density, $N_i \times 10^{-20}$	1.2
Beta, β (%)	25
Magnetic field on axis, B_T (T)	2.5-4.5
Number of coils, N	48
Power, P_{th} (MW)	4000
Power density, P_{th}/V_p (MW/m^3)	3.37
Neutron wall loading, L_w (MW/m^2)	1.13
Cold zone, δ (m)	0.2
Blanket and shield thickness, t_{sb} (m)	1.75
Coil inner radius, r_c (m)	2.95
Current density, J_c (A/cm^2)	1500
Coil radial thickness, t_c (m)	0.71
Coil half-length, L/2 (m)	1.30

plasma physics model could be extrapolated to the reactor regime. Studies are being carried out to investigate the effects of various assumptions regarding first-wall lifetime and power loading on a total operating cost of an EBT-based fusion reactor. Our tentative results indicate that wall loading of approximately 2.5 MW/m^2 neutron throughput yields the lowest total system operating cost.

We are now investigating other high-aspect-ratio moderate-β devices. A scheme has been devised in which the heliotron concept can be embodied in a design that allows individual reactor elements to be modular and self-contained. Detailed studies of magnetic field geometry and magnet design are in progress.

14. FISSION-FUSION STUDIES

Lawrence M. Lidsky, Andrew G. Cook

These studies concern aspects of fissile fuel generation in systems driven by fusion neutrons. Our previous work in this area has resulted in the development of a

hierarchical structure suitable for description of a wide variety of interrelated systems and some "figures of merit" suitable for choosing among alternatives. The potential value of hybrid or symbiotic fissile fuel generators is critically dependent upon the fuel and energy values assumed to exist at the time of introduction with particular emphasis given to the cost and availability of alternative enrichment schemes. We have developed self-consistent economic models capable of determining the allowable cost of fissile-producing systems as a function of pure fusion and pure fission core costs, electricity and fuel values, and the attainable Q of the fusion device. We are engaged in the development of optimized symbiotic fuel generators and an assessment of their place, if any, in the power economy.

a. Effect of Processing and Fabrication Costs on Design Choices for Hybrid and Symbiotic Fusion Reactor Blankets

Most designs of fissile breeding blankets for fusion reactors are based on existing fission reactor technology insofar as the choices of fuel composition, fuel configuration, coolant, and operating temperatures are concerned. Fusion-based systems tend, however, to have significantly lower flux levels and fissile inventory at discharge. Conceptual systems entailing high reprocessing and fabrication costs are at a significant disadvantage; for example, it can be shown that, for any reasonable choice of fissile fuel values and reprocessing costs, most oxide-fuel, rod-based configurations are not economical.

We have analyzed U^{233} and Pu^{239} breeding systems with solid metal fast fission zones for initial neutron multiplication. The analysis includes the five major components of fuel cycle economics: ore costs, fabrication charges, shipping charges, reprocessing costs, and fissile fuel revenues. Assuming that both the dominant costs (fabrication and reprocessing) are \$110/kg of heavy metal for rod-type systems, and taking similarly conservative values for the other portions of the cycle, we find that the total fuel cycle cost of a solid metal, batch-loaded Pu^{239} breeding system is

$$C_1 = 271 + N(16.88 - 3.5\ V)\ \$/kg,$$

where N is the in-core residence time in years, V is the value of the fissile product in \$/kg, and an 80% capacity factor has been assumed.

Fuel cycle costs for molten salt-based blankets are dominated by inventory costs and the prorated cost of the on-stream reprocessing system. For a U^{238} fission plate system with a thorium-based molten salt-breeding region operating at only 0.55 U^{233} atoms net breeding per incident neutron, the fuel cycle cost is

$$C_2 = 50.2 + N(2.7 - 1.19\ V)\ \$/kg$$

assuming the same capacity factor and the ratio of total to in-core inventory taken as 3:1.

COMMUNICATION SCIENCES
AND
ENGINEERING

XVII. OPTICAL PROPAGATION AND COMMUNICATION

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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 NGR 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, Robert S. Kennedy, Jeffrey H. Shapiro

Our main concern in this work is the extent to which commonly accepted conclusions concerning the limitations imposed by quantum effects upon system performance are correct. The issue is important because such effects often contribute the dominant "noise" in the optical communication systems that are now contemplated. Our goal is to determine whether the limits encountered thus far are fundamental in nature, or merely associated with the specific systems that have been considered. If they are not fundamental, there may be opportunities for substantial improvement in the performance of optical systems.

To determine the extent of possible improvement in performance, three major questions are being addressed:

(i) Assuming that we are only limited by physical laws rather than by present-day technology, what are the situations in which the performance of the systems now being considered falls substantially short of the performance of an optimum system?

(ii) What is the structure of the optimum quantum system for any given application, expressed in the abstract language of quantum physics?

(iii) How can a desired optimum quantum system be realized or approximated in

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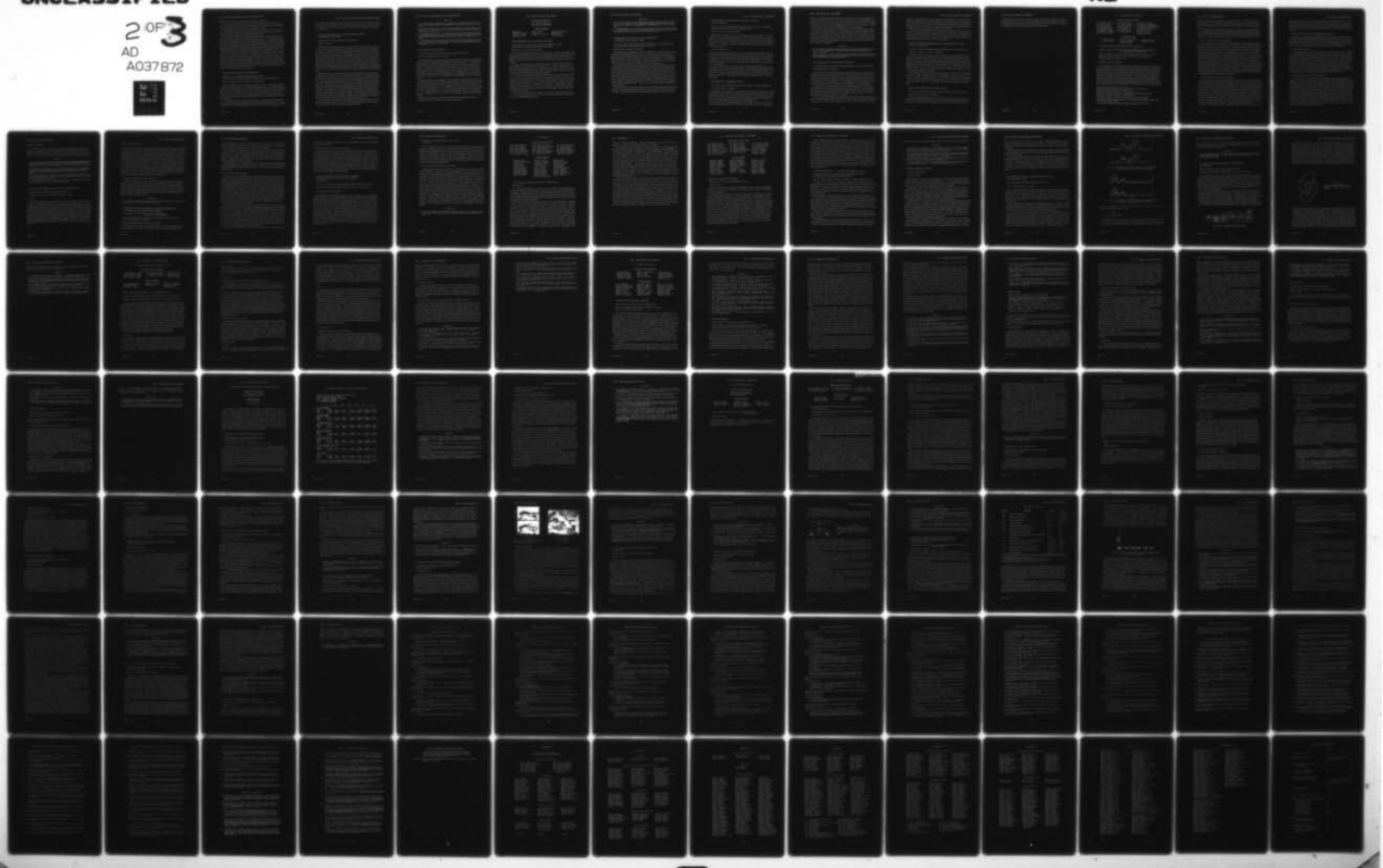

situations wherein it offers a significant performance advantage?

Our major effort during the past year was concentrated on determining the advantages of producing fields associated with two-photon coherent states and the advantages of optimal quantum receivers for coded communication systems.

The photodetection statistics for two-photon coherent states were determined for single-mode fields. It was also shown that ordinary homodyne detection is a realization of the optimum quantum measurement for these states.

The practical possibilities of realizing two-photon coherent states, in the form of ultrashort pulses, were further developed during the past year. We found that dissipation does not significantly alter the pulse formation, and that, to a first approximation, two-photon cascade systems, such as stimulated spin-flip Raman scattering, lead (both classically and quantum mechanically) to the desired two-photon behavior. This greatly increases the possibility of realizing stimulated two-photon emission experimentally. Detailed analysis of such cascade systems will be carried out during the coming year.

We have developed the general theory of quantum field propagation between a transmitter and a receiver. This work, in combination with previous work on channel modeling, yields a general framework for the representation of quantum channels. The results were applied to free-space propagation to obtain the two-photon results that we have described. We are also determining the extent to which an optimum quantum decoder can improve the performance of coded optical communication systems. A bound to the performance of such systems has been developed and will be compared with the performance attainable with existing systems.

2. IMPROVED LOW-VISIBILITY COMMUNICATION

National Science Foundation (Grant ENG74-00131-A02)
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 our 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. Measurements at larger optical thicknesses have been limited by system sensitivity. Efforts to correlate the experimental data with various propagation models are now in progress.

3. OPTICAL PROPAGATION AND COMMUNICATION THROUGH ATMOSPHERIC TURBULENCE

National Science Foundation (Grant ENG74-03996-A01)

Jeffrey H. Shapiro

Random spatiotemporal fluctuations in refractive index that result from turbulent mixing in the Earth's atmosphere have a profound effect on optical wave propagation. In particular, turbulence-induced optical phase perturbations restrict the resolution attainable in long-exposure telescopic photography to a few seconds of arc. The same phase perturbations gradually destroy the spatial coherence of a laser beam as it propagates through the atmosphere, and thus they limit the effectiveness of collimated or focused laser transmitters in communication and radar systems. Furthermore, atmospheric optical receivers are subject to severe temporal fading caused by turbulence-induced optical amplitude fluctuations. We have been working to quantify the performance limitations imposed by atmospheric turbulence on specific imaging and communication systems, and to develop system configurations that are immune to atmospheric fluctuations.

During the past year, several advances have been made toward realizing the preceding objectives. In research for a Master's thesis, Raymond J. Staron[1] studied and simulated phase-estimation procedures for mode-compression communication receivers. This work provides a useful quantitative sensitivity analysis for direct-detection linear least-squares phase estimation, and includes computer simulation results that offer some valuable insights into the nonlinear phase estimation performance. In other Master's thesis research, Mahmoud Tebyani[2] analyzed various diversity-combining techniques. His results have led us to an analytical framework for parametric performance comparisons between diffraction-limited, photon-bucket, channel matched-filter, and phase-compensated reception.[3] Finally, we have prepared a review article that unifies recent results on propagation, imaging, and communication through atmospheric turbulence;[4] some novel results are presented in this article.

In the coming year, we plan to develop Markov process (state-variable) models for atmospheric statistics, and use these models to study the ultimate limits on phase-tracking performance in imaging and communication systems.

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4. ULTRAVIOLET COMMUNICATION

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

Robert S. Kennedy, Horace P. H. Yuen

This investigation is concerned with determining whether broadcast (omnidirectional) optical systems can operate in low-visibility scattering atmospheres. The potential exists because in an omnidirectional system the power level at the receiving aperture is much less reduced by the presence of scattering than in a line-of-sight collimated system. To utilize this power the field of view of the receiver must be increased with an attendant increase in collected noise power. By operating in the 0.2-0.3 μm wavelength region, where detector and background noise is negligible, the noise limitation is greatly relaxed and the major limitations become multipath spread and boundary losses.

During the past year, the magnitude of the multipath spread and the width of the received angular spectrum for omnidirectional scatter have been estimated theoretically. The angular spectrum broadens quickly to fill the hemisphere as the optical thickness increases to approximately one. The multipath spread is of the order of $3\beta r^2/c$ seconds when there is no absorption. Here β is the scattering coefficient, r is the path length, and c is the velocity of light. A small amount of absorption changes this to approximately $0.5\sqrt{r/\beta}\,[(\alpha/\beta)-1]^{-3/4}/c$, where α is the extinction coefficient (absorption plus scatter).

Our theoretical results will be extended to include other scattering functions. A propagation experiment to confirm the results is also planned.

XVIII. DIGITAL SIGNAL PROCESSING

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1. TWO-DIMENSIONAL DIGITAL FILTER STRUCTURES

Joint Services Electronics Program (Contract DAAB07-76-C-1400)
National Science Foundation (Grant ENG71-02319-A02)

David S. K. Chan, James H. McClellan

The objective of this research is to develop insight into two-dimensional digital filter structures by synthesizing new structures and comparing them with existing structures. Such an undertaking is important for efficient implementation of 2-D filters and in the design of special structures that might permit real-time processing or distributed processing.

Contrary to the effect in the one-dimensional case, the signal flow graph has been found inadequate for representing 2-D filter structures. It fails to characterize how data are sequenced through a structure. Information of this kind is important because the order in which computations are performed can seriouly affect factors in a structure such as storage requirements and precedence relations.

We have been developing a more general framework for characterizing filter structures, and our work has resulted in a new representation based on a state-space approach.[1] This representation incorporates in the description of a structure the order in which data are computed, and, in a natural manner, also describes precedence relations between operations, an intrinsic part of any filter implementation. Such precedence relations characterize the inherent limitations of a structure with regard to parallel processing, and hence are important in considering such issues as pipelining and space/time tradeoffs.

This new representation also casts light on the 1-D filter implementation problem, and we are now investigating ways in which it may be applied to analysis and synthesis of 1-D and 2-D digital filter structures.

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2. RECONSTRUCTION OF VELOCITY STRUCTURES FROM TELESEISMIC FIRST ARRIVAL TIMES

U.S. Navy – Office of Naval Research (Contract N00014-75-C-0951-NR 049-308)
National Science Foundation (Grant ENG71-02319-A02)

David B. Harris, James H. McClellan

Many geophysical investigations require a knowledge of the spatial variation of the velocity of wave propagation in the earth's crust and upper mantle. Some aspects of earthquake prediction and determination of tectonic features fall into this category. Information about velocity structure on this scale is only available from measurements made at the earth's surface, for example, from measurements of the first arrival times of teleseismic P-waves recorded at an array of seismometers.

The purpose of this project is to determine the feasibility of applying the theory of reconstruction of functions from their projections to the problem of reconstruction of velocity structures from recorded first arrival times. The basis of this idea is that the arrival time of a P-wave at a seismometer is given by a line integral of the reciprocal velocity function along a path terminating at the seismometer. Thus, the first arrival times recorded at an array of seismometers constitute approximately a projection of the inverse velocity function onto the surface. Multiple projections from P-waves at different angles of incidence can be used to reconstruct the Fourier transform of the reciprocal velocity function. This may be inverse transformed to compute the velocity structure.

An implicit assumption of this technique is that the incoming waves have plane-wave structure. The effects of deviations from plane-wave structure on the quality of reconstructions are being investigated by using theoretically computed first arrival times.

3. APPLICATION OF HOMOMORPHIC FILTERING TO SEISMIC DATA PROCESSING

U. S. Navy – Office of Naval Research (Contract N00014-75-C-0951-NR 049-308)
National Science Foundation (Grant ENG71-02319-A02)

José M. Tribolet, Alan V. Oppenheim

Homomorphic filtering is a nonlinear signal-processing technique that has been applied to various deconvolution problems. The aim of this research is to study its application to the "seismic deconvolution problem." Seismic data can often be modeled on a short-time basis as a convolution of a bandpass wavelet p(n) with a sequence of impulses r(n). Letting w(n) represent a short-time window, we may represent a seismic trace segment x(n) as

$$x(n) = w(n)[p(n) * r(n)].$$

The seismic deconvolution problem is to recover the sequence of impulses r[n] from which the potential determination of the depths of the subsurface reflectors is possible.

Short-time seismic data models exhibit characteristics that have to be accounted for carefully in terms of their effects on homomorphic signal analysis. For example, their bandlimited nature has led to the generalization of homomorphic systems for this class of input signals.

The short-time model has led to an understanding of windowing effects in the cepstral domain, which, when conveniently explored, enable effective homomorphic wavelet estimation by means of low-time cepstral gating. The corresponding estimates may then be used to design optimum lag Wiener spiking filters that ultimately resolve the reflector series r[n]. This technique has been tested with good results on synthetic seismic data.

4. ENHANCEMENT OF DEGRADED SPEECH

U. S. Navy – Office of Naval Research (Contract N00014-75-C-0951-NR 049-308)

Jae S. Lim, Alan V. Oppenheim

The objective of this project is to develop speech enhancement techniques to increase the intelligibility and quality of degraded speech when the degradation is caused by addition of random noise. This research began last year and, as a starting point in our research, we considered two existing speech-enhancement techniques: comb filtering and the INTEL (Intelligibility Enhancement by Liftering) system.

The comb-filtering technique capitalizes on the periodic structure of speech waveforms and attempts to eliminate the frequency bands where speech contributes little

energy. By using this elimination process, we hope that more noise than speech will be rejected. In our laboratory, some modification has been made on the adaptive comb-filtering method[1] and the modified system was implemented on the PDP 11/50 computer. To determine the effect on the intelligibility score with the use of this system, nonsense sentences were processed and an intelligibility test is now in progress.

The INTEL system is based on the concept that speech and noise contribute differently to the autocorrelation function. In our laboratory, the original INTEL system[2] was reduced to a simpler form, which resulted in two important advantages: a 40% reduction in computation time, and the conceptual simplicity of a less complex system. The system was implemented on the PDP 11/50 computer. As before, to determine the effect of the system on the intelligibility score, we processed nonsense sentences and are testing their intelligibility.

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5. ENHANCEMENT OF LOWPASS FILTERED SPEECH

U.S. Navy – Office of Naval Research (Contract N00014-75-C-0951-NR 049-308)

Elliot Singer, Alan V. Oppenheim

This project is concerned with enhancing the quality of lowpass filtered speech by reinserting the missing spectral information. When only the low-frequency portion of the signal is present, it is possible that much of the missing high-frequency structure can be determined from an examination of the available spectral energy and thus the original speech can be reconstructed. This is especially true for voiced speech where the steady-state frequencies and amplitudes of the formants are well established.

In a broad sense, an enhancement system for lowpass filtered speech would incorporate algorithms for deducing the missing high-frequency structure and processing schemes for synthesizing the enhanced speech signal. Thus far, in our research we have concentrated on techniques that keep the high-frequency characteristics fixed in time, and hence adaptive filters are not required.

In order to achieve the most natural-sounding speech output, it was necessary to make use of the available signal as directly as possible. This principle has been applied to voice-excited vocoders with considerable success. In this system, the speech

synthesis is performed by extracting a subband of the original speech and processing it to make it a suitable excitation to the synthesizer. Linear prediction techniques may be used to flatten spectrally a lowpass speech signal whose spectrum has been broadened through rectification. Theoretically, this approach should produce a signal whose spectral harmonics are closely related to those of natural speech.

This technique was applied to an all-voiced sentence that had been lowpass filtered to 2 kHz. The resulting processed signal was superior in quality to the unenhanced original but suffered from a good deal of hoarseness. We believe that this hoarseness is attributable in part to the effects of spectral broadening and the manner in which the linear prediction process operates on the speech signal.

6. SPEECH ANALYSIS-SYNTHESIS BASED ON HOMOMORPHIC FILTERING AND CCD TECHNOLOGY

U.S. Navy – Office of Naval Research (Contract N00014-75-C-0951-NR 049-308)

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

A nonreal-time speech analysis-synthesis system based on homomorphic filtering and the real cepstrum has been completed. We are developing a modification of this simulation within the context of Charge Coupled Device (CCD) technology. In order to improve this system, we are incorporating the complex cepstrum into the homomorphic algorithm and studying the effects of phase on the quality of the synthesized speech. One important result is the sensitivity of the phase estimation to the time-domain window duration, shape, and onset. This work should lead to a fixed phase compensation, which can be implemented by CCD technology.

The FFT algorithm will be replaced by a skewed spectral analysis, the sliding chirp-z-transform, which is also well-suited to CCD technology. The sensitivity of this new spectral technique to the nonstationarity of the input speech waveform is being examined.

We are also investigating novel methods of filtering the log spectrum in frequency and the cepstrum in quefrency, which should reduce the raucous quality of vocoder speech.

7. SPEED TRANSFORMATIONS OF SPEECH SIGNALS

U.S. Navy – Office of Naval Research (Contract N00014-75-C-0951-NR 049-308)

Michael R. Portnoff, Alan V. Oppenheim

We have designed and implemented on our PDP-11 computer a speech analysis-synthesis system based on the discrete short-time Fourier transform. This system represents a speech signal by an appropriate set of time-variant parameters and has

the property that when it is time-scaled and used in the synthesis procedure it produces speed-transformed speech. We are now investigating two possible synthesis techniques and beginning our investigation of feature-dependent speed transformations by selectively transforming only the stationary portions of the speech signal.

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1. STUDIES OF SPEECH PRODUCTION AND PERCEPTION

National Institutes of Health (Grants 5 RO1 NS04332-14 and 5 T32 NS07040-02, and Fellowship 1 F22 NS00796-01)

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

a. Perception of Stop Consonants

We are engaged in several studies relating to the perception of stop consonants. In one of these studies we are reexamining the cues for place of articulation of consonants through experiments in which responses are obtained from stimuli whose acoustic characteristics of bursts and transitions are systematically manipulated. The experiments suggest that listeners process the abrupt acoustic events at the release of stop consonants by utilizing cues that result from integration of onset characteristics of bursts and formant transitions. These integrated cues appear to be more independent of context than the acoustic properties of the individual components that contribute to the cues. In other experiments we are investigating the range of conditions of burst amplitude

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and time location under which this cue integration occurs. The relationship between consonant cues in syllable-initial and syllable-final position is also being examined through experiments on the identification of these consonants and on selective adaptation.

In a collaborative study with the Eaton-Peabody Laboratory of the Massachusetts Eye and Ear Infirmary, the possible physiological correlates (in the auditory nerve) of abrupt stimulus onsets and offsets of the type that occur in stop consonants are being examined. Initially, we are using as stimuli sinusoids with abrupt onsets and offsets.

b. Study of Lexical Tones in Tone Languages

The aim of this study is to gain a better understanding of larynx behavior and of the features underlying it. We are interested in examining the various aspects of fundamental frequency (F_0) contours, such as rate of movement, direction, and timing of frequency changes, as they appear in various tone languages. Through a cross-language comparison of the use of F_0 contours for lexical tones, we hope to gain insight into the mechanism and the limitations on F_0 production and perception. In a series of perceptual experiments on Mandarin tones, syllables were synthesized by using "averaged" F_0 contours obtained from measured data. We found that these averaged contours possess some essential features for absolute identification. We also found that the frequency range spanned by these contours can be reduced by an order of magnitude without seriously impairing performance. The results of these experiments suggest a perceptual decoding mechanism based on simple property detectors. In ongoing perceptual experiments simple F_0 contours of various shapes are being used to determine those aspects of the contours that are distinctive. Acoustic measurements of F_0 contours for other tone languages are also being made and compared.

c. Acoustic-Phonetic Characteristics of English

We have begun a project whose ultimate goal is to produce a handbook describing the acoustic-phonetic characteristics of English. Speech data will be recorded from three men and three women in order to formulate a set of rules that describe the general acoustic characteristics of spoken English sentences. It is intended that this handbook will ultimately contain semicomplete normative data on the acoustic characteristics of a single dialect. The analyses should prove useful in the development of programs for speech synthesis by rule and for automatic speech recognition. In conjunction with background material on the physiology of speech production and the perception of speech, the acoustic analyses can also be used in programs for teaching spoken English (e.g., to teach second-language learners, the deaf, or the speech-handicapped), and to define objective criteria for the attainment of acceptable speaking performance.

Analysis techniques that will be employed include use of the traditional sound

spectrograph and several newer computer methods of spectral analysis. These newer methods include the discrete Fourier transform, linear prediction spectral analysis, automatic formant frequency tracking, and use of a digital spectral analyzer[1] that simulates processing which occurs in the human auditory system (based on psychophysical evidence).

d. Acoustic-Phonetic Studies in Languages Other than English

In an effort to develop further understanding of the acoustic mechanism of speech production and of the phonetic categories that it is capable of producing, several projects have been initiated. These include an acoustic study and interpretation of the various click sounds of Xhosa, and an acoustic and physiological investigation of stop consonants produced with various laryngeal configurations in several different languages.

e. Speech Synthesis by Rule

In a continuing effort to improve the quality of a speech synthesis-by-rule program,[2] a new programming language has been developed and the entire program has been rewritten in this higher level language.[3] Rules can now be stated in highly readable notation that is then automatically converted to Fortran code. The role of a phonological component in synthesis by rule has been defined and implemented.[3] The phonological component accepts as input a linear string of symbols produced by the (hypothetical) semantics component, syntactic component, and lexical component of a grammar of English. This abstract representation of an utterance is transformed by the phonological component into a narrow phonetic transcription and a specification of stress levels, segmental durations, and aspects of the fundamental frequency contour.

f. Segmental Duration as Part of the Speech Code

A review article has been prepared on the linguistic uses of segmental duration in English.[4] The pattern of durations of individual phonetic segments and pauses conveys information about the linguistic content of an utterance. Acoustic measures of segmental timing have been used by many investigators to determine the variables that influence the durational structure of a sentence. The literature on segmental duration is reviewed and related to perceptual data on the discrimination of duration and to psychophysical data on the ability of listeners to make linguistic decisions solely on the basis of durational cues. We conclude that, in English, duration often serves as a primary perceptual cue in making distinctions among (i) inherently long vowels and short vowels, (ii) voiced and voiceless fricatives, (iii) phrase-final and nonfinal syllables, (iv) voiced and voiceless postvocalic consonants, as indicated by changes in the duration of the preceding vowel in phase-final position, (v) stressed and unstressed or reduced vowels, and (vi) the presence or absence of emphasis.

g. Physiological Studies

Experiments are being performed on short-latency feedback effects of unexpected reductions in intraoral air pressure during the production of bilabial stops. We are looking at pressure-related changes in the timing of EMG signals from muscles of the larynx, lips, and mandible under conditions of normal lip sensation and labial anesthesia.

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2. SYNTACTIC-TO-PHONETIC CODING IN SPEECH PRODUCTION

National Institutes of Health (Grant 1 RO1 NS13028-01)

William E. Cooper, John M. Sorensen, Kenneth N. Stevens

a. Theory

A theory of syntactic-to-phonetic coding is being developed that focuses on two related issues: (i) What domains of syntactic coding influence aspects of phonetic coding, including influences on speech rhythm, intonation, and the blocking of phonological rules normally operating across word boundaries? and (ii) What details of syntactic coding are there in cases that are controversial on purely linguistic grounds? One specific objective in the theory concerns attaining a formal description of phrase and clause boundary strengths that utilizes the two structural properties of branching complexity and node height. This part of the theory is designed to account for differences in the magnitude of phrase-final lengthening and clause-final lengthening, as well as for differences in whether particular phrase and clause boundaries block the operation of phonological rules.

b. Studies of Speech Timing

Experimental studies have been conducted to test aspects of the theory. These include experiments on the blocking of phonological rules at syntactic boundaries, phrase-final lengthening, clause-conditioned lengthening for a segment just prior to the beginning of an embedded clause, and correlations of durations for nonadjacent word segments that lie within the same clause or span a clause boundary. Experiments have also been conducted on temporal disambiguities of structurally ambiguous sentences. The results of these studies have provided support for some of the major features of the theory and have stimulated revision and further development. We plan to continue conducting experimental studies on speech timing as a means of testing and developing the theory. The results of recent work in this area will also be used in designing new experiments on speech perception, to test the extent to which listeners detect syntactic influences on speech rhythm, and, more important, whether listeners actually utilize this information in decoding the syntactic representation of utterances.

c. Studies of Fundamental Frequency Contours

In addition to studies on speech timing, we are extending our work to fundamental frequency (F_0) contours, since these contours also reflect the influence of syntactic coding. We plan to obtain F_0 measurements for many of the experimental utterances already analyzed for syntactic influences on timing. Thus far, we have completed one such study involving complement clause structures.[1] Additional experiments are planned to test hypotheses about clause-conditioned resetting of F_0 declination and other aspects of syntactic influences on F_0.

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

National Institutes of Health (Grant 5 T32 NS07040-02 and Fellowship 1 F22 MH58258-02)

Jared Bernstein, Marcia A. Bush, Ursula G. Goldstein, Howard L. Golub, Lise Menn, Katherine Lee Williams

a. Speech and Sound Production by Infants and Children

A literature search has been conducted in an effort to establish the dimensions and growth of children's vocal tracts. The data from this search will be entered into a

computer data base for use with a vocal-tract model. The model will be used in an analysis-by-synthesis manner to estimate vocal-tract area functions and articulatory positions for various speech gestures by children of various ages.

Measurements of vowel formants of one two-year-old child are being made from spectrograms and by means of a linear prediction program. These measurements will be related to the average vocal-tract anatomy of a two-year-old child, through use of the vocal-tract model. An experiment on the adult perception of these vowels is planned. Segment and syllable durations for this child are also being examined from utterances taken at 18, 21, and 24 months.

In another project that is just beginning, we are attempting to apply 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.

b. Speech Discrimination by Infants

Two studies of stop-consonant place discrimination by infants 6-12 weeks old have been carried out by using a high-amplitude sucking procedure. In one experiment, two synthetic consonant-vowel pairs were used. Both have five-formant patterns with formant transitions appropriate for either an initial [d] or [g], followed by a steady-state portion appropriate for the vowel [a]. One pair also had a 5-ms noise burst prior to the transition onsets which modeled the acoustic characteristics of the natural speech versions of [d] or [g]. An analysis of the results, in terms of levels of significance for discrimination, indicates that there is a greater probability of infant discrimination of a [d/g] contrast with an initial release burst than without it. The results suggest that the strong integrated cue resulting from both burst and appropriate onsets of formant transitions is required for infant discrimination, whereas adult listeners are able to extract information from the weaker cue provided only by transitions, possibly as a consequence of experience with the stimuli.

The purpose of the second study was to investigate infants' ability to discriminate between two speech sounds that contrast in syllable-initial, syllable-medial and syllable-final position and for which the contrasting element in medial position may or may not be stressed. A comparison was made of infant discrimination of contrasts: [da] vs [ga], [ad] vs [ag], [adá] vs [agá], and [áda] vs [ága]. All stimuli were composed of 5 formant patterns characteristic of unreleased stop consonants and steady-state vowel portions, with stress conveyed by a sudden rise and fall in F_0. Preliminary analysis of the results indicates that infants can discriminate syllable-initial but not syllable-final contrasts. Discrimination of intervocalic contrasts depends on stress placement. The exact nature of this dependency is now being investigated.

Future studies are planned to study infant discrimination of segmental contrasts

in duration and fundamental frequency for various phonetic contexts and language environments of infants.

c. Speech Production and Perception by the Deaf

The goal of this research is to understand the nature and causes of phonetic differences between speech of the deaf and speech of those with hearing. Detailed descriptions of the speech of deaf children are being prepared, based on reported work and on new measurements. These descriptions include analysis of articulatory, phonatory, and rhythmic problems of deaf children. By synthesizing deaflike speech with selected combinations of these problems at various levels of severity, we hope to develop an analytic predictor of intelligibility based on measurable aspects of a speech sample. We are also trying to develop signal-processing techniques for classifying the phonatory behavior of children and to use these techniques to describe the distribution of phonation qualities in a large population of deaf children.

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

U. S. Army – Maryland Procurement Office (Contract MDA904-76-C-0331)

William L. Henke, Dennis H. Klatt, Kenneth N. Stevens, Victor W. Zue

a. Acoustic Study of Stop Consonants

The primary aim in the acoustic studies of stop consonants is to investigate the acoustic characteristics of these consonants under a controlled phonetic environment.[1] By controlling the environment and limiting the influence of the higher level sources of knowledge, we hope to isolate those acoustic attributes that are presumably invariant from those that are context- and speaker-dependent. The corpus of data used in this study is some 1700 nonsense [hə'CVC] utterances spoken by three males. Fifteen vowels and 27 singletons and clusters containing the English stops /p, t, k, b, d, g/ are included in the data base. Signal processing and statistical analysis programs are used to facilitate data analysis. Various aspects of the temporal and spectral characteristics of the stops have been quantified. The results suggest in general the presence of more context-independent attributes for the stop consonants than has been believed. This study is being extended to include other speech sounds and more complicated linguistic environments. Data are also being collected from more speakers to investigate inter-speaker differences.

b. Statistics of Fundamental-Frequency (F_o) Contours in Sentences

We have extracted F_o contours from several minutes of read and spontaneous speech produced by different speakers. The material has been divided into speech bursts or "breath groups," separated by pauses, and the statistics of the contours within breath groups are being examined. These include the distribution of maximum and minimum F_o values at different points in time within each breath group. The data show the contributions to the overall distribution of F_o for a given speaker that are due to the baseline fall of F_o within a breath group and also the fluctuations within an utterance that indicate stress and demarcate phrases.

c. Study of the Phonological Processes in English

The purpose of this study is to describe the phonological processes of English within a unified framework. Although most of the phonological processes have been known for some time, their treatment has been fragmental and has been based primarily on the introspection of the researcher working on his own speech, or judging the speech of an informant. Inherent in this approach is the danger of faulty judgment. As a consequence, description of these processes may be inaccurate and lead to incorrect formulation of rules. In our study we hope to avoid controversy over the phonetic corpus by documenting each process with acoustic and articulatory measurements, when these do not already exist. By making measurements of processes that have not been studied, we hope to improve on fragmental data, and develop a comprehensive and unified corpus of processes that will serve as the data base not only for this study but also for anyone interested in investigating phonological processes of natural language. Ongoing research includes classification, annotation, and cross-referencing of phonological processes. Acoustic data are also being collected from quite a few speakers. Measurements will be made on spectrograms to provide us with quantitative data on the nature of such phonological processes as nasalization, palatalization, and dental flapping.

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XX. LINGUISTICS

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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 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.

XXI. COGNITIVE INFORMATION PROCESSING

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1. NATURAL LANGUAGE PROCESSING

National Science Foundation (Grant SED74-12653-A01)

Jonathan Allen

Our overall objective is to develop a comprehensive model for converting English text to speech. This requires development of a modular research system, and construction of special hardware.

The backbone of the project is the modular research system. We intend to construct a flexible configuration of algorithms, coded in a higher level language (BCPL), which uses well-defined file interfaces for module interconnection. These modules include a morphological analyzer, parts-of-speech determiner, parser, letter-to-sound converter, lexical stress analyzer, prosodic correlate determiner (pitch and timing), and phonemic synthesizer. Each is coded as an independent module with well-defined input and output data structure files. This enables independent development of the individual modules, and permits us to perform experiments using many different configurations of the total system. In this research system, emphasis is placed on flexibility of design, ease of understanding, ability to modify quickly and easily, and relative machine independence. In the coming year we shall continue to refine the system, with emphasis on prosodic algorithms, parsing, and phonemic synthesis. Although we do not intend to optimize the system for minimum memory space or execution time, some attention will be devoted to reduction of the morph lexicon.

Once the modular research system is developed, we shall seek to implement these algorithms in special-purpose hardware, which is intended to provide application-oriented performance that is efficient in space and time. Thus far, a microprocessor-based design has been constructed for computation of speech parameter values from an input phonemic segment specification, and an all-digital vocal-tract model has been built that produces a speech waveform from an input set of speech parameters. These are prototype designs that must be tested and evaluated extensively. In addition, we are designing a new special processor to perform the morphological analysis and parsing tasks, both of which are expressed in augmented transition network formalism. The eventual goal is to perform all of the tasks involved in text-to-speech conversion utilizing specially constructed processors suited to the structures involved. This should lead to practical implementations of this speech output capability, suitable for a wide range of applications.

2. PATTERN RECOGNITION OF CONVENTIONAL SYMBOL SYSTEMS

Joint Services Electronics Program (Contract DAAB07-76-C-1400)
National Science Foundation (Grant ENG74-24344)

Barry A. Blesser, Robert J. Shillman, Theodore T. Kuklinski, Makoto Yasuhara

The objective of this research is to design a computer algorithm capable of recognizing handprinted or machine-printed characters at error rates comparable with human performance. Our approach has been to investigate human cognition in an attempt to discover what features are crucial to letter identity and then to incorporate these features in an OCR algorithm.[1] Results of the effort of the past six months toward this goal are as follows.

We have devised an algorithm for low error rate recognition of handprinted U and V.[2] These characters, which are among the most difficult for both humans and computers to recognize, were investigated in detail by using various psychophysical techniques. The experiments indicated that the slope of the legs and the curvature of the base are important features in U-V discrimination. A computer algorithm incorporating these features was designed and resulted in a recognition rate of more than 94% on a standard data set of unconstrained handprinted U and V.

Studies based on an ABX paradigm show that letter discrimination peaks at inter-letter labeling boundaries.[3] This lends additional support to the distinctive-feature theory of letter recognition and provides another technique for investigating the perceptual letter space.

A mathematical model for incorporating contextual information has been devised and successfully tested. The model, based on the range-frequency theory of Parducci and Perrett,[4] should provide a basis for predicting changes attributable to graphical

context of the Physical-to-Functional Rules (PFRs) that operate in letter recognition.

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3. DIGITAL WIREPHOTO SYSTEM

Associated Press (Grant)

Donald E. Troxel

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.

4. RECOGNITION OF PARTIAL DENATURATION MAPS (PDM) OF BACTERIAL PHAGE

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

Ian T. Young, Donald S. Levinstone

In our effort to determine the PDM of long DNA molecules we have attempted automatic determination of the location of the PDM of short DNA molecules from a virus such as P22. Thus if the P22 or λ phage were inserted in the DNA of E. coli in vitro, then by discerning the location of the inserted molecule we ought to be able to determine the PDM of the E. coli DNA molecule in the neighborhood of the insertion site.

A key requirement of an automatic procedure such as this is to be able to identify the PDM histogram of the inserted molecule against the background PDM histogram of the longer molecule. To determine whether the procedures that we have developed previously[1] have this sensitivity, we performed the following experiment.

A set of 60 curves of P22 phage waveforms was divided into a training group and a test group, each with a set of 30 curves. A set of 55 curves of BP5, a deletion phage of P22, was divided into a training set of 25 curves and a test set of 30 curves. It can be seen from Figs. XXI-1 and XXI-2 that the training patterns are quite similar to the histograms of the complete sets of curves. The two test groups were combined into a single shuffled test set of 60 molecules. Then each curve was compared with the training set histograms of P22 and BP5 to obtain a correlation coefficient as a

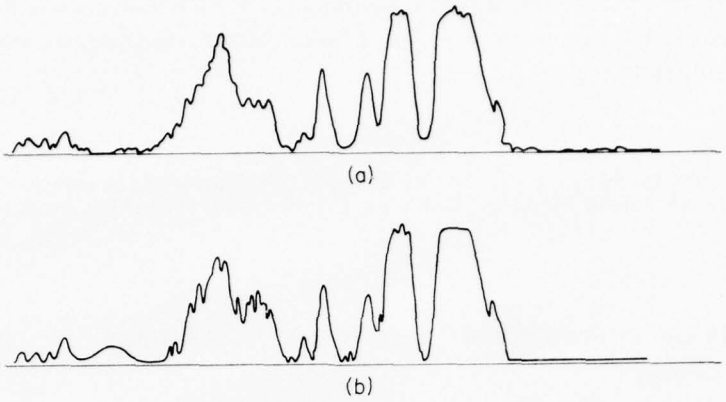

Fig. XXI-1. PDM histograms for P22 molecules. (a) Complete set of 60 molecules. (b) Training set of 30 molecules.

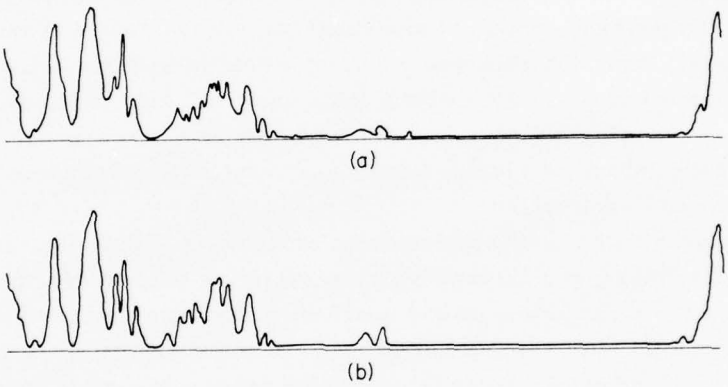

Fig. XXI-2. PDM histograms for BP5 molecules. (a) Complete set of 55 molecules. (b) Training set of 25 molecules.

measure of similarity. The i^{th} curve (molecule) from the test set was classified according to the following decision rule:

$$\rho_{i,\,P22} \underset{i \in BP5}{\overset{i \in P22}{\gtrless}} \rho_{i,\,BP5}$$

An analysis of the results shows that 29 of the thirty P22 curves and 26 of the thirty BP5 curves were correctly assigned. For the set of P22 curves, the quantity ($\rho_{i,\,P22} - \rho_{i,\,BP5}$) had average .19 with variance .09; for the set of BP5 curves, the average was

-.12, with variance .11. This is quite significant because biologically the BP5 curves would be expected to have some portions of their patterns in common with those of P22, since BP5 is a deletion phage of P22.

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5. ANALYSIS OF CHROMOSOME IMAGES: MULTIPLE-CELL KARYOTYPING

National Institutes of Health (Grant 2 PO1 GM19428-04)

Goesta H. Granlund, Ian T. Young, Gregory W. Zack, Murray Eden

In our studies of the automated karyotyping of human chromosomes we have formed a new potentially powerful concept of statistical karyotyping, which is that a karyotype can be developed from the chromosome complement of several cells. An obvious advantage is that we can take for analysis from each cell only chromosomes that are not touching, overlapping, or otherwise distorted. An even more important advantage is that information about the average behavior of descriptive parameters of each chromosome class can be assembled.

The reason for analyzing the chromosome complement is that clinical judgment is necessary rather than just an assembly of the karyotype picture of a particular cell. If we have only the chromosome spread image of a particular cell, we get very little information about the chromosome complement. If something unexpected is observed, we must obtain one or more images to confirm or reject a suspected irregularity.

The system that we have built is shown in Fig. XXI-3. It has been described elsewhere[1-5] and tested on Giemsa-banded metaphase cells. Because of its organization

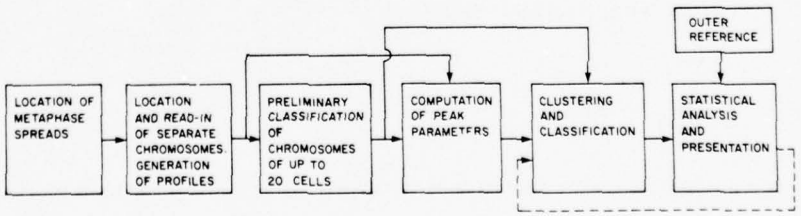

Fig. XXI-3. Automated karyotyping system.

and function, it is difficult to compare it with conventional systems or to specify its accuracy in well-known terms. An important factor in evaluating a conventional karyotyping system is the recognition rate of the system; that is, the percentage of correctly classified chromosomes. With our system, by observing the data output from the clustering and classification block, we have achieved a recognition rate of 90%, plus or minus a few percent depending upon the quality of the preparation and the care taken in the selection of spreads. This matter, however, is not pertinent for our system. Instead of error, we have an overlap of classes, as well as in homologues within classes. It can be shown that the error rate is directly related to the overlap of the distributions. The situation illustrated in Fig. XXI-4 shows two classes of chromosomes

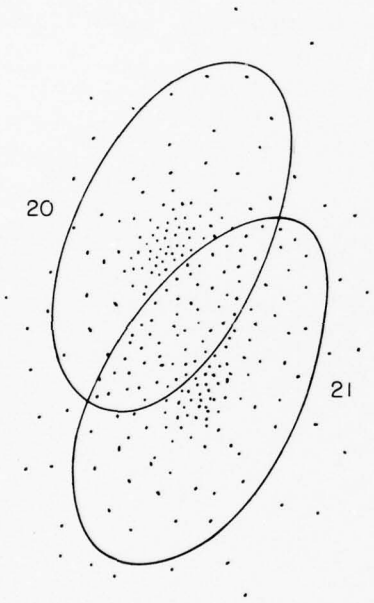

Fig. XXI-4.

Example of feature overlap of two classes: chromosomes No. 20 and No. 21.

with an overlap in the distributions of two features. We cannot tell to which distribution the points in the overlap region belong, but that is not important for our purpose. What is important is to find the means and variances of these two distributions, since they reflect the average behavior of these features, and we can now obtain this information.

These methods can be used to detect aberrations in the chromosome complement. Since the discovery of the banding stains, great variability in banding patterns has been observed, which is sometimes linked to clinical syndromes. Several hospitals now make investigations routinely in order to find chromosomal abnormalities that can be linked to observed syndromes. Some of these abnormalities are visible in the

karyotypes, while others can only be suspected. The methods that we have described may be and have been used to resolve such problems.

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XXII. 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 RO1 NS11000-03 and 1 PO1 NS13126-01)

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

In recent years we have found opportunities to apply results of our basic research to clinical problems. Interaction with clinical investigators in such projects is an important part of a new program supported by the National Institutes of Health in which a consortium of four institutions (Massachusetts Institute of Technology, Massachusetts Eye and Ear Infirmary, Harvard Medical School, and Massachusetts General Hospital) is cooperating on basic and clinical studies of the auditory system. Specific clinical problem areas are those involving pathologies of the ear and of the brain. In cooperation with otologists at Massachusetts Eye and Ear Infirmary we are working on the interpretation of auditory nerve action potentials recorded from patients who appear to have hearing defects. Methods for localizing abnormal regions in the brain are also being developed, including the use of electric responses of the lower brain centers and the characteristics of the acoustic middle-ear muscle reflex. These clinical components will complement continuing basic studies on the processes of hearing.

We have made progress during the past year in the following studies:

a. Middle Ear

Using physical and psychophysical methods, William M. Rabinowitz has measured changes in the input impedance and the transmission of the middle ear that occur during the acoustic reflex. The dependence of these changes on the frequency and on the level of the eliciting stimulus can be interpreted in terms of a change in stiffness of elements in the middle ear. The growth of the reflex effect with increases in eliciting stimulus level indicates that the neural system involved in the reflex has frequency-dependent

characteristics.[1]

We have completed measurements of the input impedance of the inner ear in cats,[2] and have demonstrated that variations in cerebrospinal fluid pressure can affect the acoustic compliance of middle-ear ligaments.

b. Inner Ear

(i) Cellular Mechanisms of Transduction in the Alligator Lizard

The dc potentials in the cochlea, the intracellular resting potential and the extracellular endolymphatic potential are thought to be important for the generation of responses to sound in the receptor cells. We have described properties of these potentials.[3]

A paper describing intercellular junctional complexes using transmission electron microscopy and freeze-fractured preparations has been accepted for publication.[4]

Within the past year we have concentrated our efforts on the use of new techniques for intracellular recording. The combined use of new facilities at the Massachusetts Eye and Ear Infirmary and the use of a mechanical micropipet drive has enabled us to record stable intracellular potentials for longer time intervals than has been possible previously. By using beveled, double-barreled micropipets we have been able to record intracellular potentials from one barrel while passing current through the second barrel. Such techniques will be employed in investigating the mechanisms of mechanoelectric transduction in hair cells and perhaps in measuring the electrical characteristics of supporting and hair cells.

(ii) Cochlear Potentials in Lizards

Both cochlear microphonic (CM) and neural response components can be recorded by means of a gross wire electrode placed near the round window. In response to clicks the two components are partially separable in time. In response to tones, the resultant wave shape is a complex composite of such components. In order to isolate these components, we used a potent neurotoxin, tetrodotoxin, to attempt to eliminate the component attributable to action potentials in cochlear nerve fibers.[5] Results showed that the apparently complex dependence of the N_1 component of the response to clicks on the stimulus parameters in an intact ear probably results from the interaction of a neural component with a low-frequency CM component.

c. Auditory Nerve

(i) Lizard

Since it is feasible to study intracellular responses in the lizard basilar papilla, it is essential to determine whether results obtained in this preparation have general validity

for sensory transduction in vertebrate auditory organs. Therefore we studied responses of cochlear nerve fibers in this animal and compared our results with those obtained by using the same techniques in the cat. Thus far, we have systematically studied the frequency tuning properties,[6] the spontaneous activity,[7] and the phenomenon of two-tone rate suppression and we have observed responses to clicks and tone bursts. We find characteristic differences in the response properties of apical and basal fibers that go to morphologically different regions of the basilar papilla. The response properties of apical fibers resemble those of mammalian fibers more closely than do those of basal fibers.

(ii) Cat

The spontaneous activity of auditory-nerve fibers in the absence of acoustic stimuli was studied by recording simultaneously from pairs of fibers. The discharges were shown to be statistically independent even when the characteristic frequencies of the fibers were essentially identical. This result indicates that acoustic noise, including Brownian motion, is not the dominant source of spontaneous discharges.[8]

Studies of acoustically traumatized and "normal" cats suggest that cochlear abnormalities exist even in "normal" animals.[9] To obtain baseline data from animals known to be free from previous exposure to high-level environmental sound, kittens are being raised in a "sound-proofed" room. The study of cats subjected to acoustic trauma has demonstrated several correlations between abnormal single-fiber responses and the condition of hair cells and neurons in the cochlea observed with the light microscope.[10] These findings are of interest not only because of their implications for interpretation of the damage resulting from high-intensity sounds but also for the light they shed on normal cochlear mechanisms. For instance, the fact that some abnormal fibers exhibit a supernormal sensitivity to certain acoustic stimuli suggests an interaction of excitatory processes in the normal cochlea.

d. Cochlear Nucleus

(i) Signal Transformations of AVCN Neurons

A survey has been completed of the physiological properties of single units in the anteroventral cochlear nucleus (AVCN) of the cat, based on spike responses recorded extracellularly.[11] Localization of extracellularly recorded spikes has made it possible to compare various categories of spike responses with descriptions of cell morphology. The spatial distribution of "primarylike" units strongly suggests their correlation with the bushy cells, particularly in the most rostral subdivision of the AVCN where both predominate. The complex spike waveforms consistently found for "primarylike" units are interpreted as a physiological correlate of the presence of very large synaptic

endings (end-bulbs of Held) on the bushy cells. In posterior AVCN where the end-bulbs are smaller, the complex waveform is less prominent. The two other major categories of units in the AVCN, "chopper" and "on", presumably correspond to stellate cells. Since at least two subcategories of "chopper" units were found to be differentially distributed within the AVCN and the "on" units showed a range of characteristics, we expect that subsequent anatomical studies will reveal further distinctions among the stellate neurons.

(ii) Synaptic Mechanisms

To understand the cellular processes involved in the signal transformations, we have worked on methods for recording responses intracellularly and are preparing results from an initial study for publication. The current effort is concentrated on technical improvements aimed at extending the intracellular recording time and introducing sets of stimulating electrodes to allow antrodomic activation and stimulation of efferent pathways.

e. Superior Olivary Complex: Neural Pathways of the Middle-Ear Reflex

Experiments on unanesthetized decerebrate cats in which electric stimuli have been used have indicated that the pathways of the middle-ear reflex involve neurons that are in the vicinity of the ventral and medial nuclei of the trapezoid body but do not go through the medial superior-olivary nuclei as had been suggested previously. These electric stimulation experiments do not give precise locations for the neurons that are involved. Therefore we have begun injecting the enzyme horseradish peroxidase (HRP) into the VIIth motor nuclei (through which the stapedius reflex is known to pass). The HRP should be transported along the nerve fibers in retrograde direction and should make the cell bodies of the neurons that innervate the VIIth motor nuclei histologically detectable.

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XXII. COMMUNICATIONS BIOPHYSICS

B. Auditory Psychophysics

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1. INTENSITY PERCEPTION AND LOUDNESS

National Institutes of Health (Grant 1 ROl NS11153-01)

Louis D. Braida, Nathaniel I. Durlach, Adrian J. M. Houtsma, Jae S. Lim, William M. Rabinowitz

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.[1-8] 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, 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, our funds for this project have been extremely limited and our efforts have been confined primarily to preparation of a new grant proposal, preparation of previous results for publication,[7,8] and further testing of our theory of loudness matching.[7,9]

The work on loudness matching has been directed toward an experimental evaluation of the theory's prediction that two stimuli S_1 and S_2 at intensities I_1 and I_2 are matched in loudness if and only if I_1 and I_2 divide the dynamic ranges of S_1 and S_2 proportionately

in terms of number of just-noticeable differences (jnds) in intensity. The stimulus pairs considered were a tone signal vs the same tone signal in a background of noise, and a tone signal vs a noise signal. The results of these experiments, although very preliminary, tend to support the theory.

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2. BINAURAL HEARING

National Institutes of Health (Grant 2 RO1 NS10916-02)

H. Steven Colburn, Nathaniel I. Durlach, Philip W. Herman, Jr., Allen W. Mills, William M. Siebert, Ronald A. Siegel, Richard M. Stern, Jr.

The 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. During the past year, we have continued to pursue the formulation of our theory, further developed our laboratory facilities, and conducted several experimental studies.

Theoretical work has continued to focus on the development of our theory of binaural interaction based on auditory-nerve data.[1,2] This theory incorporates explicitly the transformation from acoustic stimulus to auditory-nerve firing patterns and postulates that decisions are made on the basis of an optimum linear combination of outputs from

a binaural displayer that processes the time structure of the firing patterns on fibers from the two ears. This model describes essentially all of our data on the binaural detection of tones in noise,[2] but is unable to describe the dependence of the just-noticeable difference (jnd) in interaural time delay on the interaural phase and amplitude difference of a tone.[3]

We have modified our theory by restricting the information that is available for making decisions within the model.[4] Whereas earlier versions of the model postulate that the displayer outputs are combined optimally, the modified version postulates that the displayer outputs are processed nonoptimally to give a decision variable that is related to subjective lateral position and that represents the only information available, aside from pitch and loudness information. This model has been evaluated for 500-Hz tonal stimuli and describes the lateral-position-matching data of Domnitz,[5] as well as most interaural discrimination results. The only cases for which the predictions of this model are inconsistent with discrimination results are those for which the mean lateral position (i.e., the mean of our decision variable) is the same for both stimuli in the discrimination task. For example, predictions are inconsistent with interaural time jnds when the graph of mean lateral position vs interaural time delay has zero slope. In these cases, empirical data are generally quite variable within and among subjects, but some subjects, with training, can perform significantly better than predicted.

When the predictions of the modified model are compared with binaural detection results, only a subset of the data can be described.[6] In particular, the dependence of thresholds on the interaural parameters of the masking noise cannot be described, although the model seems adequate to describe detection situations with interaurally identical masking noise. To encompass all detection cases within the domain of the modified model, we have postulated a decision variable in addition to the one related to lateral position (and in addition to the implicit pitch and energy-based loudness variables). The model that assumes optimum use of these two variables in binaural situations makes use of considerably less information than the original model that uses the optimum linear combination of displayer outputs, and this modified model is consistent with most of the data from lateralization, discrimination, and detection experiments with 500-Hz tones.[6] Further information on this work is available in the doctoral thesis of R. M. Stern, Jr.[7]

We have also pursued the extension of our binaural interaction model to high frequencies for which the auditory-nerve patterns are not synchronized to the detailed time structure of the stimulus.[8] All of our work is consistent with the hypothesis that the only differences between high- and low-frequency processing reside in the peripheral transformation from acoustic waveform to firing patterns on the auditory nerve fibers. The processing of the information in the patterns would thus be described by a

mechanism that gives equivalent treatment to all fibers whether they are primarily sensitive to high or low frequencies.

We have expanded our laboratory facilities by developing a computer-controlled acoustic monitor-and-adjust system.[9] (We had previously determined the need for a monitor-and-adjust procedure for certain binaural experiments and developed a manual monitor system.[10]) The new system synthesizes a pair of waveforms with the desired interaural relationships, monitors acoustically the stimuli presented at the ear canals of the subject during each stimulus presentation of an experiment, computes the corrections that are required to remove deviations from the desired interaural relationships, and makes the computed corrections on the next stimulus presentation (which is also monitored, etc.). The system has been evaluated for tone-burst stimuli, in which the problems of synthesis and estimation of interaural phase and amplitude parameters are relatively simple. In order to use the system for wideband stimuli, a more complex interaural parameter estimation scheme such as the fast Fourier transform would have to be used.

Experimentally, we completed a project on the discrimination of interaural time delay for 500-Hz tonal stimuli.[11] Interaural time jnd measurements were made on several subjects using parameter values near points of perceptual ambiguity, specifically at time delays in the neighborhood of 750 μs. Results in this region show large differences from subject to subject and large training effects for some subjects. Also, we have initiated projects on interaural adaptation effects, tradeability of interaural time and amplitude differences, and localization of tones in a background of masking noise. All of these projects are being continued.

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3. HEARING AIDS

National Institutes of Health (Grant 1 ROl NS12846-01)

[Part of this work is being carried out in collaboration with the Harvard-M. I. T. Rehabilitation Engineering Center, with support from the U. S. Department of Health, Education, and Welfare (Grant 23-P-55854).]

Ian M. Beguesse, Louis D. Braida, Michael C. Coln, Mark A. Clements, Steven DeGennaro, Leonard C. Dowdy, Nathaniel I. Durlach, Bruce L. Hicks, Richard P. Lippmann, Douglas R. Mook, Susan J. Norton, Yvonne M. Perlmutter, Michael A. Picheny, William M. Rabinowitz, Charlotte M. Reed, Martin C. Schultz, Edgar Villchur

The goal of this program is to develop improved signal-processing and display schemes to match acoustical signals to residual sensory capacity in people with nonconductive hearing impairments.

The research activities of this program are subdivided into three areas: signal enhancement, matching speech to residual auditory function, and tactile aids.

a. Signal Enhancement

In this work we are seeking to develop preprocessing schemes to assist hard-of-hearing listeners in noisy and reverberant environments. A speech intelligibility enhancement system[1] based on adaptive comb filtering has been implemented and evaluated quantitatively for listeners with normal hearing. Sentences spoken by males and females were used as both targets and maskers. Tests were conducted with various combinations of system parameters (duration of filter impulse response, treatment of unvoiced segments), talkers, and target-to-masker amplitude ratios. Baseline tests were conducted for processed materials in the absence of interference, as well as for

unprocessed materials at various target-to-masker ratios. The results indicate that comb filtering attenuates the masker amplitude 2-10 dB, and that greater attenuation corresponds to longer filter impulse-response durations and to male-female speaker combinations. The processing also degrades the intelligibility of targets presented in the absence of maskers, particularly for the longer filter impulse responses. Adaptive comb filtering failed to increase intelligibility in the presence of interference; in fact, in all of these cases scores were inferior to those for unprocessed materials. Further work in this area is required to understand these results. In addition, the comb-filtering system will be evaluated for maskers consisting of broadband random noise. Further details are available in the Master's thesis of Yvonne M. Perlmutter.[2]

b. Matching Speech to Residual Auditory Function

We are continuing to focus on multiband amplitude compression for listeners with reduced dynamic range and on frequency lowering for listeners with negligible hearing at high frequencies.

Our present work on multiband amplitude compression is directed toward comparative evaluation of a multiband compression system adjusted to restore normal loudness function for tones and several linear amplification systems. In these studies we employ a small number of listeners with sensorineural impairments characterized by reduced dynamic range and recruitment. Performance of the systems is being studied for male and female speakers in both quiet and reverberant noisy environments.

Our work on frequency lowering is directed toward evaluating pitch-invariant processing techniques, including both lowering and warping.[3] In initial studies we are comparing the ability of listeners who have normal hearing to understand warped-lowered speech with their ability to understand lowpass filtered speech. The results of preliminary tests of CV nonsense syllable identification have indicated the need for including multiple tokens of test items to prevent artifacts from providing reliable cues. Since our facilities do not permit us to perform the warping-lowering operation in real time, we have had to provide for random-access storage of a large vocabulary of preprocessed test materials. This has taken a little extra time, but we hope that significant results will soon be obtained.

We have prepared a series of three detailed articles on signal processing for hearing aids, including linear amplification,[4] amplitude compression,[5] and frequency lowering.[6]

c. Tactile Aids

We are working on the development of a simple, wearable, vibrotactile aid to provide the profoundly deaf with a general awareness of acoustical signals and with the gross amplitude and temporal characteristics of these signals. In one such aid now

being considered,[7] the envelope of the acoustical signal is used to modulate the amplitude of a 250-Hz tone. The circuit design also includes preemphasis of high frequencies and automatic gain control. Preliminary psychophysical tests involving detection of tones in silence and in background noise and recognition of environmental sounds and sentences in closed sets indicate that this device is superior to a simple linear amplification system.

We are also exploring different encoding and display schemes for the tactile perception of speech using the Optacon transducer system. Among the schemes that are being compared are a unidimensional frequency display, a two-dimensional frequency-amplitude display, and a two-dimensional time-swept frequency display. The software for this project, which makes use of a computer system for processing and control, has been completed and experiments concerned with the discriminability of selected pairs of speech elements are now under way.

An evaluation is being made of tactile speech communication using the Tadoma method, in which the "reader" monitors the articulatory features of speech directly by placing his hand on the talker's face. Preliminary experiments with a deaf-blind, experienced Tadoma user[8] have included tests of the discriminability of speech elements, recognition of words in isolation and in sentences, and perception and comprehension of syntactic and prosodic features of speech. Preliminary experiments with comparatively inexperienced normal subjects (for whom deafness and blindness are simulated) have focused on the discriminability of speech elements. In general, the results of these various experiments have not only demonstrated that good tactile perception of speech is indeed possible but also have documented the types of errors made in Tadoma and have provided insight into the perceptual cues used in Tadoma.

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4. MUSICAL PITCH

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

Howard L. Golub, Adrian J. M. Houtsma, Afarin Ordubadi,
Roger W. Wicke

The objective of this project is to obtain a better understanding of the auditory processes that underlie the transformation of a complex sound into a sensation of musical pitch.

a. Pitch of Harmonic Two-Tone Complexes

Musical interval identification experiments were conducted with dichotically presented two-tone complexes of nonsuccessive harmonic numbers. As expected, we found that for complexes of harmonics n, n+2 identification performance is identical to that for successive harmonics of twice the fundamental frequency when n is even. When n is odd, fundamental tracking is worse than for successive harmonics, although it is still significant. For n, n+3 complexes, no significant evidence for fundamental tracking was found. These last two results cannot be explained by any currently available model on pitch processing.[1-3]

b. Pitch of Amplitude-Modulated Noise

The musical interval identification paradigm was also used to study the pitch of square-wave, sine-wave, and pulse-modulated wideband noise. The noise was lowpass filtered before modulation, and the lowpass cutoff frequency served to control the amount of statistical correlation between successive periodic noise samples. Results seem to indicate that there are two different and independent pitch mechanisms at work, one of which may be spectral, the other almost certainly temporal.[4]

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5. MUSICAL ACOUSTICS

National Institutes of Health (Grant 1 RO1 NS!1680-01)

Adrian J. M. Houtsma, Ernest J. Perevoski

We are seeking to understand the physical behavior of musical instruments, particularly stringed instruments.

a. An Electronic Pickup System for the Classical Guitar

When an acoustically weak instrument such as the classical guitar is played in a symphony orchestra concert, the intensity unbalance makes electronic amplification of the guitar necessary. The conventional technique of amplifying a near-field microphone recording, typically a few inches from the sound hole, gives a less than optimal representation of the far-field acoustic spectrum of the instrument. We are trying to find a limited array of point pickups that by linear mixing can provide a close approximation of the acoustic far field measured in a flat-response reverberant chamber.

We have made aural comparisons of white noise driven inputs at the bridge and of actually played instruments. Results thus far indicate that best matches can be obtained through a linear combination of an acoustic air-pressure signal taken at the sound hole and the integrated output of an accelerometer placed on the bridge that represents the velocity of the string termination point.[2]

b. Development of a "Melograph"

In folk music the musicologist is faced with the problem of charting the exact timing and pitch structure of actually performed melodies. This is often accomplished with a device called a melograph that charts pitch vs time. Problems are encountered with currently available equipment when musical signals are measured that are largely upper harmonics or that have more than one major peak per period, since this equipment usually works through filtering and fundamental-frequency tracking or through peak

detection.[1] Various hardware and software schemes are being investigated to find an efficient means of tracking the pitch of fast-changing periodic or quasi-periodic sounds, irrespective of their harmonic nature.

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XXII. COMMUNICATIONS BIOPHYSICS

C. Transduction Mechanisms in Lateral Line and Vestibular Organs

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

Graduate Students

Scott K. Peterson

Our broad goal is to understand the mechanisms of transduction in the receptor organs of the acustico-lateralis system of vertebrates. Study of the mechanical, electrical, and synaptic events in hair cell organs and their relation to nerve activity is basic to such understanding. In pursuit of these goals we have during the past year: (i) determined the composition of the inner-ear fluids in representative species of several classes of vertebrates; (ii) estimated experimentally an upper bound on the magnitude of cupula motion in the ampulla of the semicircular canal of the skate in response to maintained caloric stimulation and begun to measure afferent response characteristics of ampullary nerve fibers in this preparation; and (iii) continued our effort to identify the hair cell afferent synaptic transmitter.

1. ANALYSIS OF VERTEBRATE INNER-EAR FLUIDS

National Institutes of Health (Grant 5 RO1 NS11080-03)
M. I. T. Health Sciences Fund (Grant 76-07)

Scott K. Peterson, Lawrence S. Frishkopf, Charles M. Oman

Vertebrate hair cells – the receptor cells of the auditory, vestibular, and lateral line systems – are part of an epithelial membrane that separates fluids of different compositions. These fluids, called endolymph and perilymph, bathe the apical hair-bearing and basal synaptic portions of the hair cells, respectively; tight junctions between cells at the epithelial surface appear to present an effective barrier to ionic movement across the membrane. Ions present in endolymph and perilymph may play a significant role in mechanical-to-electrical transduction and synaptic and neural transmission in these receptor organs. Therefore a knowledge of their concentrations could be important in understanding these processes. Much is already known of the composition of the inner-ear lymphs.[1,2]

In collaboration with Professor Thomas F. Weiss of the Communications Biophysics Group, RLE and Dr. Claude Lechene of Harvard Medical School, we have obtained

Table XXII-1. Summary of composition measurements.*

CONCENTRATIONS ARE IN MILLIMOLES PER LITER
MEAN = MEAN OF ANIMAL MEANS
SEM = STANDARD ERROR OF THE MEAN
NA = NUMBER OF ANIMALS
NS = NUMBER OF SAMPLES

	K	NA	CL	CA	MG	P	S
CAT PERILYMPH							
NA = 3 ; NS = 8							
MEAN	3.196	154.8	165.7	1.883	0.7556	0.6244	1.128
SEM	0.6031	9.806	13.37	0.2205	0.0973	0.0296	0.4311
CAT ENDOLYMPH							
NA = 3 ; NS = 6							
MEAN	191.6	0.9983	208.4	0.3939	0.0022	0.5028	1.174
SEM	1.72	0.4994	4.062	0.0056	0.0022	0.0255	0.6311
LIZARD PERILYMPH							
NA = 17 ; NS = 42							
MEAN	2.873	172.2	160.2	1.745	1.065	0.4469	2.029
SEM	0.1133	3.597	4.806	0.0737	0.0522	0.0814	0.2791
SKATE PERILYMPH							
NA = 5 ; NS = 18							
MEAN	4.324	173	230.7	3.964	3.36	1.626	6.404
SEM	0.5887	19.84	19.99	0.5945	1.17	0.253	0.974
SKATE ENDOLYMPH							
NA = 5 ; NS = 13							
MEAN	91.64	248.3	408.1	3.796	0.4866	0.6845	1.56
SEM	8.733	24.02	27.21	0.3557	0.1042	0.1051	0.4377
SKATE CEREBROSPINAL FLUID							
NA = 4 ; NS = 4							
MEAN	3.217	180.3	226.9	2.725	1.562	1.527	9.33
SEM	0.3657	23.81	28.6	0.3774	0.4417	0.2633	3.472
SEA WATER							
NA = 4 ; NS = 8							
MEAN	8.165	330.5	451.7	8.905	40.82	0.7725	25.73
SEM	0.4081	24.82	20.55	0.3967	1.019	0.1797	1.273

*Because of the difficulty of obtaining endolymph in the lizard and the high variability in the data, no estimates for this fluid have been included in the table.

samples of endolymph and perilymph by micropuncture of the inner ears of three vertebrate species, skate, alligator lizard, and cat. These samples have been analyzed for concentrations of seven elements (Na, K, Cl, Ca, Mg, S, P), using the technique of electron probe microanalysis.[3] Some of the results of this study are shown in Table XXII-1. The skate data form the basis of formulations of artificial endolymph and perilymph that we have used in physiological experiments on the excised inner ear of this species, as described in Section XXII-C. 2.

Two aspects of this study seem unique: first, it provides a comparison of inner-ear lymph concentrations of representative species of several vertebrate classes, by using a single technique; second, for the first time data have been obtained in these species on the concentrations of Ca and Mg, elements whose significance in the functioning of nerve, muscle and receptor cells, and of synapses is well documented. Ca^{++} appears to play a significant role in hair cell transduction.[4] Limited data on Ca and Mg concentrations in inner-ear fluids have been available previously for only a few species.[1, 5]

We have measured element concentrations in endolymph from the ampulla of the skate's semicircular canal before and after prolonged excitatory or inhibitory stimulation. Preliminary results indicate a significant increase in concentrations of four elements (Na, K, Cl, and Ca) during excitation and a significant decrease during inhibition. Although of variable magnitude from preparation to preparation, the direction of these changes was consistent under a variety of stimulus conditions.

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2. STUDIES OF CUPULA MOTION IN THE SKATE SEMICIRCULAR CANAL

M. I. T. Health Sciences Fund (Grant 76-07)
National Institutes of Health (Grant 5 RO1 NS11080-03)

Charles M. Oman, Lawrence S. Frishkopf

During the past year, we determined experimentally an upper bound on the physiological range of cupula motion in the skate semicircular canal, and have begun to study the response characteristics of different types of afferent units in the ampullary nerve.

The question of what constitutes the naturally occurring magnitude and mechanical mode of cupula motion is one of the oldest problems in vestibular physiology, one that cannot be satisfactorily resolved purely on the basis of anatomical studies. Investigators have therefore attempted to answer the question by means of observations in vivo. Experimental studies[1-4] have reported cupula motions well in excess of 5 μm. Theoretical considerations,[5] however, led us to question whether physiological cupula motions, in fact, are large enough to be visualized when looking through the wall of the ampulla, and whether earlier workers imposed traumatically large stimuli on the semicircular canal ampulla.

Working in the isolated labyrinth of the skate Raja erinacea, we visualized the cupula by puncturing the ampullary wall with a sharpened glass pipette and by staining local regions by slow infusion of small amounts of Alcian blue dye. Single and multiunit activity in the ampullary nerve was monitored while caloric stimulation was applied with a spot of light focused on the canal duct. Caloric stimuli that more than doubled the level of afferent activity and recruited many previously silent units were found to produce no detectable motion of stained regions of the cupula as monitored visually through the ampullary wall. If the cupula was first visibly displaced by rapid dye injection, however, motion of the top of the cupula was thereafter observed in response to an identical caloric stimulus. The basis of this traumatic change in the mechanical stiffness of the cupula resulting from rapid dye injection could not be determined.

We concluded that the physiologic range of cupula motion in this animal is probably less than the resolution of our optical method, which we conservatively estimate as 3-5 μm. Experimentally observed motions of the cupula an order of magnitude larger are probably not physiological, and may result from trauma-induced changes in the mechanical characteristics. These results were presented at the 6th Annual Meeting of the Society for Neuroscience in Toronto, Canada,[6] and a detailed report is being prepared for publication.

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XXII. COMMUNICATIONS BIOPHYSICS

D. Biomedical Engineering

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National Institutes of Health (Grants 5 T32 GM07301-02, and
5 TO1 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.

(XXIII. NEUROPHYSIOLOGY)

XXIII. NEUROPHYSIOLOGY

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1. B-WAVE SENSITIVITY DURING LONG-TERM DARK ADAPTATION IN THE FROG'S EYE

National Institutes of Health (Grants 5 TO1 EY00090-03 and 3 RO1 EY01149-03S1)

Eric Newman, Jerome Y. Lettvin

A preliminary study on long-term, dark adaptation of the frog retina has been completed, using the threshold of the B-wave of the electroretinogram (ERG) as a measure of the sensitivity of the eye. In order to study the entire span of dark adaptation, care was taken to maintain the eye in a condition that was as "physiologically normal" as possible. To this end, a preparation was developed that allowed the recording of the B-wave of the ERG from the intact, normally circulated eye of a frog that was restrained by a few pins but allowed to breathe continuously in a normal fashion. It was not necessary to treat the frogs with either anesthetics or paralyzing agents to achieve satisfactory recordings.

The threshold of the B-wave of the ERG was determined in two series of experiments. In the first series, the light intensity (a 10-ms flash of white light) needed to produce a criterion B-wave response, which ranged from 15-80 μV, was determined during the entire course of dark adaptation. It was found that following an intense bleaching flash of light, the threshold of the B-wave fell steadily and did not reach a constant value for an average of 9 hr (range: 6-11 hr). This long, dark-adaptation period was seen in all preparations (7 frogs) which remained healthy for at least 12 hr.

It was observed that the test flashes used in producing the criterion B-wave responses were sufficiently dim so as not to affect the adaptation state of the eye. In order to rule out completely the possibility that the testing light flashes were in some way affecting retinal threshold so as to produce a seemingly lengthened adaptation period, a second series of experiments was conducted. In these experiments, the threshold of the B-wave was assessed indirectly by measuring the amplitude of the B-wave response (60-μV maximum) to identical test flashes presented at regular intervals, either 0.5 or 1 hr. It was found that following a bleaching adaptation light, the

amplitude of the B-wave did not reach a maximum value until 5 to 10 hours of dark adaptation had elapsed, depending on the intensity of the bleaching light. In one case, it was possible to maintain a preparation for 3 days. In this case, the B-wave, having reached a stable value after 10 hr in the dark, maintained that amplitude for the duration of the experiment.

These experiments indicate that the sensitivity of the B-wave process of the ERG requires up to 9 hr of dark adaptation to attain a maximal value and thereafter maintains that value in the dark for at least 3 days.

2. TRANSRETINAL CURRENT AND THE ACTIVITY OF FROG RETINAL GANGLION CELLS

National Institutes of Health (Grants 5 TO1 EY00090-03 and 3 RO1 EY01149-03S1)
Bell Laboratories (Grant)

Eric Newman, Jerome Y. Lettvin

The existence of a nonsynaptic mechanism of information transfer within the retina has been suggested by the work of Dr. Mark Lurie,[1] who demonstrated a correlation between the activity of type-four ganglion cells of the frog retina and the C-wave of the electroretinogram (ERG). Lurie has proposed that current produced by the pigment epithelium, which generates the C-wave, might modulate the activity of the retina.

Experiments have been conducted on the intact, circulated eyes of curarized frogs in order to confirm Lurie's results and to test the hypothesis of retinal sensitivity to pigment epithelium currents. The activity of the pigment epithelium was monitored with intraretinal electrodes by measuring the voltage across the proximal retina (between the receptor region of the retina and the vitreous). Ganglion cell activity was monitored simultaneously with Wood's metal electrodes positioned in the ganglion cell layer of a nearby portion of the retina. In this manner the activity of a ganglion cell could be compared with the local transretinal current from the same region of the retina.

Simultaneous recordings of type-four ganglion cells and retinal voltages following flashes of light presented to dark-adapted eyes have shown that there is a good correspondence between the peak of the transretinal voltage and the onset of periods of ganglion cell activity. This has been seen for a range of flash intensities producing delays of 3 to 50 seconds. Recordings from some type-three ganglion cells have shown a similar correlation between the onset of a prolonged burst of ganglion cell activity and the peak of the transretinal voltage.

Unit recordings were made from the optic tectum of the frog in order to monitor the activity of type-two ganglion cells. It was found that this type of cell, although it does

not respond to a diffuse flash of light, will give a delayed burst of activity following a flash if a black spot of the proper size is placed within the receptive field of the cell. The duration of the delay preceding the burst is roughly proportional to the log of the flash intensity. Thus, although this is difficult to show directly, it is possible that type-two ganglion cells, as well as type-three and type-four, display a time course of activity coincident with the transretinal component of the C-wave of the ERG.

Externally generated current was passed across the dark-adapted retina while recording from type-four ganglion cells in order to test whether the transretinal current previously seen to be correlated with ganglion cell activity was sufficient to account for the modulation of activity. It was found that externally generated current (applied between the vitreous and the choroid) of the same magnitude as the currents seen during the C-wave (measured by the IR drop across the proximal retina) produced significant modulation of ganglion cell activity. The polarity of the effect, however, is roughly opposite in the two cases. When transretinal current is generated by the eye in response to light, ganglion cell activity begins at the peak of the transretinal current and continues as the current decreases. When current is applied externally, activity is greatest as the current increases and stops when peak positive current is reached.

These experiments have demonstrated that the retina is sensitive to currents of the magnitude generated during the C-wave of the ERG as measured by ganglion-cell response. Because currents of internal and external origin seem to affect the retina with opposite polarities, however, it seems likely that those retinal elements sensitive to transretinal current do not lie in the proximal retina.

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3. THRESHOLD OF NERVE MEMBRANE

National Institutes of Health (Grant 3 RO1 EY01149-03S1)
Bell Laboratories (Grant)

Stephen A. Raymond

We have begun an experimental program to investigate the nature of the processes that interact to determine the threshold for generation of the nerve impulse. We have also worked on interpreting and presenting our past work on the relationship of activity to threshold changes. We continue to propose that the aftereffects of activity are important in determining which branches of an axon (or dendrite) will be invaded.

Activity-dependent connectivity appears to be a basic form of information handling by the nervous system. The experiments summarized here are part of a larger effort to elucidate the rules for the transformation of temporal patterns of impulses into spatio-temporal patterns of active subsets of terminal branches of a nerve. For the moment, we are concentrating our attention on the influence of the ion pumps and extracellular concentration changes. Temperature has some interesting effects, and we have made a new observation in that area.

a. Intermittent Conduction and Nerve Threshold

Stephen A. Raymond, Paul A. Pangaro

A 16-mm color film on intermittent conduction and nerve threshold was presented at the 6th Annual Meeting of the Society for Neuroscience, Toronto, Canada, November 7-11, 1976. The film makes the relationship between threshold and conduction more vivid and understandable than has been achieved through static plots and logic. The ideas that threshold affects conduction, and that activity affects threshold, are fundamental for our notions concerning information handling. Investigators have made curious observations for which these ideas lead to clear hypotheses. One of our purposes in making the film was to induce investigators working on a variety of systems to tell us of cases where activity-dependent threshold shifts provide an explanation of their observations. The film has been well received and two new cases of activity-dependent threshold shifts in invertebrates have been reported to us. Our notions about generation of repetitive firing, presynaptic inhibition, and uninvadable branches have all received more experimental support.

b. Effects of Nerve Impulses on Threshold of Frog Sciatic-Nerve Fibers

Stephen A. Raymond

A new series of experiments was undertaken to determine the shape of threshold curves with activity. The main improvement was to develop a scheme for quantifying the threshold axis. These experiments have been arranged in a logical progression that leads to a description of the threshold curve as a continuous function of activity. A paper covering observations and experiments from 1971 to the present will be submitted for publication. It will be the first published account of the relations that we have described.[1]

c. Activity-Induced Changes in Nerve Threshold Cause Intermittent Conduction

Stephen A. Raymond, Paul A. Pangaro

Based on the results of our studies of nerve fibers, equations have been written for each fiber's threshold curve. Intermittent responsiveness was observed during repetitive stimulation with a near-threshold stimulus magnitude. The period of the intermittence changed with the rate of stimulation. It also changed with the magnitude of stimulation. The equations for threshold showed the same rate-period and magnitude-period relations observed in the nerve. Our conclusion is that this evidence shows that res-paribus conduction depends on threshold changes; in fact, in this experiment conduction or block could be predicted well by threshold curves taken alone.

d. Effect of Ion Pumps

Stephen A. Raymond

Ouabain and strophanthidin counter the buildup of depression of threshold. These pump poisons completely eliminate depression that has been developed by maintained impulse activity in the nerve. The threshold drops below resting threshold within 10 minutes following the administration of the poison. It reaches the level associated with maximum superexcitability. At 10-30 ms intervals after a conditioning impulse, when the membrane in an unpoisoned axon is near peak superexcitability, the threshold of poisoned axons shows a slight transient depression. In other words, the superexcitable phase reverses: Processes that make an unpoisoned axon superexcitable make a poisoned axon depressed. This work suggests that depression is entirely due to metabolic action, presumably ion pumping, and that the nerve at rest is held away from its point of maximum excitability by the action of the pump. This work was reported at the 6th Annual Meeting of the Society for Neuroscience.[2]

e. Justification for the Hunter Circuit

Louis L. Odette, Stephen A. Raymond

We have examined our method of measuring thresholds by using the success or failure of each trial to modify the stimulus for the next trial. We had noticed that the output of the hunter circuit was tracking in a very narrow band near the center of the range of stimulus magnitudes between 0% and 100% probability of firing (the gray region). Outside the gray region large stimuli will always produce a response, and that will reduce the next stimulus; the opposite is true for deterministic stimuli that are too small. Thus the hunter paradigm converges. Within the probabilistic range two features operate.

First, the probability of success is greater with large stimuli, and hence the probability of a return is larger the farther the stimulus is from the center of the distribution. Second, the probability of a string many jumps in a row is very small ; the successively smaller probabilities of continuing a jump in the same direction are multiplied. A short note on the general problem of measuring thresholds is in preparation.

f. Conduction Velocity Variation with Threshold

Stephen A. Raymond

Variations in latency have been observed during our experiments. An instrument has been built to allow the systematic determination of the relationship by plotting the latency of each trial with time.

g. Temperature Effects

Stephen A. Raymond, Michael J. Binder

[The work of M. J. Binder was supported by the National Institutes of Health (Grant 5 TO1 EY00090-03).]

We have previously[3] reported a curious compensation of the nerve for temperature changes in a broad range from 10°C to 30°C. Our evidence that the threshold was regulated actively and not merely carefully balanced is that there were transients in the threshold accompanying fast changes in the temperature. In a few minutes these would die away leaving the nerve at its resting threshold. During the summer we noticed that nerve fibers consistently did not show the transients. Even at rest, extremely rapid changes of temperature evoked no variation of threshold at all. In the autumn the transients reappeared. We suspect that what underlies this observation is the difference between summer and winter frogs. In any case, some active temperature-compensating mechanism seems to exist for threshold.

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4. THRESHOLD HUNTER DEVICE

National Institutes of Health (Grant 3 RO1 EY01149-03S1)
Bell Laboratories (Grant)

Stephen A. Raymond, Louis L. Odette

We have invented this device to serve as a general system for automatically measuring and tracking the threshold of nerve cells. It will work equally well for measuring thresholds of other mechanical, chemical or electronic bistable systems. The usual method of determining threshold is to use a series of trial stimuli that are analyzed to obtain the probability of response for each level of stimulus. The threshold hunter is designed to vary the stimulus so as to home in on the threshold. The outcome of each trial conditions the next stimulus as the threshold of the system varies, which it does with temperature and other variables. The output of the threshold hunter, which is a voltage proportional to the stimulus, follows the variations. The extent of trial-to-trial variation of the hunter contains information about the threshold "noise" of the system under study. We have proved the conceptual validity of the convergence of the threshold hunter to the system threshold, and have investigated optimal hunting strategies for a variety of situations. With some analysis, the hunter output will yield the probability of response to the stimulus magnitude ogive. Changes in this distribution, if they occur, can be read from the threshold hunter.

5. NERVE THRESHOLD CHEMOGRAPH

National Institutes of Health (Grant 3 RO1 EY01149-03S1)
Bell Laboratories (Grant)

Stephen A. Raymond

This device is an application of the threshold hunter device. A living axon membrane is used as a detector for neuropharmaceuticals. The threshold hunter monitors the threshold curves characteristic of the axon, and chemicals are circulated past the membrane. Those chemicals having an effect on the nerve membrane produce changes in the threshold that can be discerned easily by connecting the threshold hunter to a chart recorder. Our experience thus far indicates that any compound affecting the nervous system (strychnine, ACh, choline, pH, ethanol, pentobarbitol, digitalis, N_2O) has its own characteristic effect on nerve threshold. We are eager to find out whether these characteristic effects, once they are compiled for a wide sample of chemical agents, will be sufficiently indicative of the kind of drug and its effect so as to be useful in detecting novel neuropharmaceuticals of clinical importance.

6. NERVE MEMBRANE MODELS

Bell Laboratories (Grant)

Louis L. Odette

We are analyzing and synthesizing electronic analog models of nerve membrane. These models are monostables based on the equivalent circuit for the membrane, with the relation between the steady-state values of the variable conductances and the "transmembrane" voltage derived from a single functional.

We have constructed a circuit that demonstrates many electrical properties of the squid giant axon: the form of the membrane action potential, as well as subthreshold response; anode break excitation; and the current-voltage-time relations revealed through voltage-clamp experiments.

With this background we shall explore the relations between the models and physical representations of the nerve membrane.

7. PROPERTIES OF THE CHOLINERGIC SYSTEM IN THE OPTIC NERVE AND OPTIC TECTUM

Bell Laboratories (Grant)

Edward R. Gruberg, Jerome Y. Lettvin

Optic nerve fibers were studied as a potential cholinergic system. Using ^{14}C-choline as substrate, we found active uptake of choline in the nerve. The uptake was higher per unit protein than in the tectum, the striatum, the pallium, the ventral root fibers, and the dorsal root fibers. The Q_{10} of uptake was 2.3 and was highly sodium-dependent. Optic nerve acetylcholine (ACh) synthesis from ^{14}C-choline is approximately the same as in the ventral root and an order of magnitude greater than in the dorsal root. High acetylcholinesterase activity is also associated with each of the optic nerve terminal projections. These results imply that the optic fibers are cholinergic.

The optic fibers are not sufficient to account for all the cholinergic activity of the tectum. Cutting the optic nerve leads to an increase of ACh synthesis in the contralateral tectal lobe. Isolating the tectum from lateral inputs leads to a decrease in ACh synthesis. The origin of these fibers was determined by iontophoresis of horseradish peroxidase (N.R.P.) into the tectum. N.R.P. is transported retrograde in axons to their cell bodies. The only cells stained were a discrete group in the nucleus isthmi. Electrolytic lesion of the nucleus isthmi reduces ACh synthesis in the ipsilateral tectal lobe to the same extent as lateral tectal lesion.

By iontophoresis of ^{3}H-proline into the nucleus isthmi and subsequent autoradiography, we have traced a bilateral projection of fibers to the tectum. The ipsilateral

projection ends diffusely in a pattern coincident with optic nerve fibers but restricted only to the medial aspect. The contralateral projection is rostral for the most part and in two thin layers of the superficial tectum. The projections have been confirmed by Fink-Heimer degeneration studies.

We are now engaged in two related studies. In the first, we fill the optic fibers with an electron-dense material while simultaneously labeling cholinergic endings with labeled α-bungarotoxin and doing electron microscope autoradiography. In the second, we attempt to see anatomically whether we can find sprouting of nucleus isthmi fibers in response to optic nerve lesions.

8. DESIGN AND CONSTRUCTION OF AN ARTIFICIAL LARYNX

National Institutes of Health (Grants 3 RO1 EY01149-03S1 and 5 TO1 EY00090-03)
Bell Laboratories (Grant)

Donald W. Schoendorfer, Stephen A. Raymond

The major thrust in the work of the past few months has been the development and optimization of an internal artificial larynx for laryngectomized patients. We have been working with Dr. Donald P. Shedd of Roswell Park Memorial Institute, Buffalo, New York. He has developed a reed fistula technique of speech rehabilitation.[1,2] His technique has advantages over alternative rehabilitation techniques.

a. An artificial vocal source is used which in principle can be designed to produce an accurate reproduction of the sound made by the normal larynx at physiological pressures and airflows. It is, therefore, easier for the patient to relearn speech. Other techniques require that the patient first learn to produce an acoustic excitation for his vocal tract; for example, esophageal speech is done by burping air from the stomach.

b. The patient is able to use exhaled air from the lungs to power and control the artificial larynx, as in normal speech.

c. The artificial sound source is introduced low in the vocal tract so that the transfer functions of the patient's tract are similar to those prior to the operation.

In the past, Dr. Shedd's patients have used large external artificial devices that fit over the tracheostoma and rest on the lower neck. The sound output of these external devices was routed into the vocal tract by way of a skin fistula constructed during the laryngectomy. These skin fistulas vary in length from 3 cm to 20 cm and are 3/8" in diameter.

The external larynx is acoustically undesirable for two important reasons. First, it permits a large amount of sound to radiate from its thin walls and interfere with the voiced sounds from the mouth. Second, the downstream tube connecting the external larynx to the vocal tract introduces its own formants on the source spectrum. These

formants are relatively stationary but drastically decrease the normality of the patient's speech.

These two problems could be diminished by making an artificial larynx small enough to be placed at the end of the fistula. There would then be no downstream tube between it and the vocal tract, and its direct sound radiation would be damped by the tissues of the neck. A device of 3/8" or less in diameter was needed to turn the steady air flow from the lungs into pulsitile air flow with a sound spectrum of the shape generated by the normal larynx. We used a relaxation oscillator modeled after the common duck call, with a vibrating cantilever reed to interrupt the driving air flow. The spectrum of the device was tuned by mass-loading the reed at specific locations and by varying its nonlinear stiffness. The frequency of oscillation of the device could be varied by changing the driving pressure, which allows inflection in the patient's speech.

Two patients are now testing the new internal larynxes. Intelligibility tests will soon be conducted. We are of the opinion that this internal system improves the patient's speech.

A problem associated with the internal larynx technique is leakage of fluids from the pharynx through the fistula tube. A pressure-inflated cuff surrounding the internal larynx is used to impede leakage from around the device. The pressure of the cuff must be regulated to prevent overinflation, which will stretch the skin fistula. Leakage through the artificial larynx has been stopped by a tiny, one-way flap valve. The coordination of these two methods should enable the patient to eat and drink without removing the system from his fistula and plugging the hole with his thumb. The technique is now being tested clinically.

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9. AN APPLICATION OF FLOW-THROUGH COLLAPSIBLE TUBES: WILL THEY FUNCTION AS PROSTHETIC VOCAL CORDS?

National Institutes of Health (Grant 3 RO1 EY01149-03S1 and 5 TO1 EY00090-03)
Bell Laboratories (Grant)

Donald W. Schoendorfer, Stephen A. Raymond

Collapsible tube flow has been studied by numerous investigators.[1-3] We have become interested in the possibility of using one of the many relaxation oscillators, the

Starling resistor (named after E. H. Starling who, in 1912, used collapsible tubes as hydraulic analogs for flow in veins) as a possible vocal-cord prosthesis. We have constructed a model of the Starling resistor, and investigated its flow characteristics. We found that the system could operate at pressures and air flows produced by the lungs, and that the frequency of oscillation could be in the 100-400 Hz range. The resulting output sound spectrum was remarkably close in shape and intensity to that of normal vocal cords.

This model was tested as an external larynx by two laryngectomized patients of Dr. Donald P. Shedd, Roswell Park Memorial Institute, Buffalo, New York. The output sound was directed to the vocal tract by a fistula tube, and the resulting speech was satisfying.

A simplified analysis of the pertinent physical laws of air flow through the Starling resistor has furthered our understanding of the mechanism of oscillation. The analysis indicated also that it would be difficult to miniaturize the Starling resistor to the point where it could be used as an internal artificial larynx. A paper describing this work will soon be submitted for publication.

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10. TERRITORIAL BEHAVIOR OF Macrozoarces americanus

National Institutes of Health (Grant 5 TO1 EY00090-03)
Bell Laboratories (Grant)

William M. Saidel

The ocean pout, Macrozoarces americanus, exhibits a territorial behavior in an aquarium that is similar to the response directed at a scuba diver in the ocean. The aquarium behavior described in this report was studied during the winter of 1973 in the National Oceanic and Atmospheric Administration aquarium at Wood's Hole, Massachusetts; scuba observations were made during the summer of 1976 along the coast of Massachusetts. In the aquarium the territorial display had three sequential movements: an alert, or head-up position (Fig. XXIII-1), an oral display (Fig. XXIII-2), and a nipping motion. For an incident to occur, one of the fish had to be within its territory on the aquarium bottom: two pout meeting outside either pout's territory never

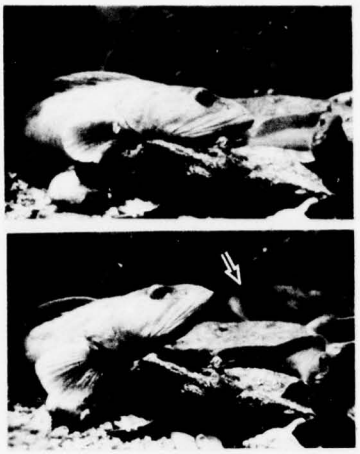

Fig. XXIII-1.
Head-up position initiated by the presence of a second pout (arrow).

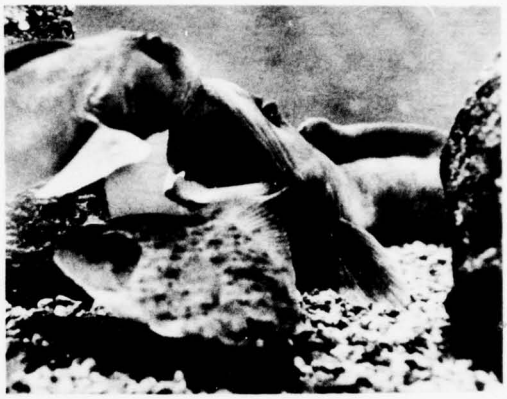

Fig. XXIII-2.
Oral display.

displayed this behavior.

Thirty-seven percent of all incidents in which a display was utilized by one or both fish were resolved by an alert posture; 49% by oral display; and 14% by the nipping motion. A resident pout initiated a display three times as often as an intruder. An intruder responded to a resident-initiated display with a display of its own only 30% of the time, while a resident responded to an intruder-initiated display more than 70% of the time. The nipping motion, always following the head-up and oral displays, was utilized only during provocative situations, such as when the fish were fed, when the fish were establishing their territories, and when a new pout was added to the tank. A resident pout always retained its territory when challenged regardless of the physical characteristics of the intruder such as size.

The territorial behavior was predominantly intraspecific. A small fraction (<14%) of the total incidents (not included in the percentage calculations) were with other genera such as Pseudopleuronectes and Gadus.

Five of the sixteen pout I encountered while diving responded to my presence with a territorial display. The maximal position used by three of them was the alert position; the two others followed the alert position with an oral display. All of these fish inhabited a protected area, e.g., at the juncture of three boulders, much like the territories defined by the pout in the aquarium. Ten of the eleven nondisplaying pout that immediately swam away were lying either on open sand or in seaweed. The eleventh fish retreated into a hole.

A territorial behavior, similar in form to that described for Macrozoarces has been

reported previously for members of the genera Blennius[1,2] and Hypsoblennius,[3,4] but this report is the first to deal with this behavior in the genus Zoarces. Despite the ten-fold difference in size between members of the family Zoarcidae and of the family Blenniidae, all three genera exist in what could be described as ecologically similar niches. The similarity of the territorial behaviors reflects this fact.

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11. ENERGY REQUIREMENTS DURING PIGMENT GRANULE MIGRATION

National Institutes of Health (Grant 5 TO1 EY00090-03)

William M. Saidel

Migration of pigment granules within the melanophore is bidirectional. The actual motion that an individual melanosome makes during migration in each direction is not identical. The movement of a granule during the inward migration, induced by catecholamines,[1] is a smooth, continuous motion, whereas the outwardly directed movement occurs in discontinuous "jumps."[2] As has been observed since the early 1900's, the inwardly directed movement is 1 to 4 times as fast as the distally directed migration.

Recent experiments have been performed that shed light upon the energetic requirements of these movements. DNP (2,4-dinitrophenol) uncouples cellular oxidative metabolism from phosphorylation of ATP.[3] Normal flatfish saline[4] containing a 10^{-3} M concentration of DNP reversibly induces pigment aggregation in melanophores of the flatfish Pseudopleuronectes americanus. This aggregation is not due to the stimulation of the α-adrenergic site on the melanophore membrane because tolazoline hydrochioride, an α-site blocker,[5] does not affect the DNP-induced inward migration. This evidence strongly suggests that the outward pigment granule migration requires the breakdown of ATP, whereas the inward migration does not.

Two other pieces of information support this contention. The time course of

aggregation induced by DNP is approximately one fifth of the time of aggregation induced by a just maximal concentration of adrenalin. This suggests the presence of an endogenous ATP pool that must be used prior to the onset of aggregation. Second, in the absence of Ca^{2+}, a melanophore aggregates rapidly. This suggests, as in actin-myosin utilization of ATP in muscle,[6] that Ca^{2+} is a cofactor in the ATP breakdown, inducing distally directed pigment migration.

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12. BINOCULAR EFFECTS IN CHROMATIC ADAPTATION

National Institutes of Health (Grant 5 TO1 EY00090-03)
Bell Laboratories (Grant)

Michael H. Brill

Investigators have long sought to quantify the change in appearance of test lights arising from changes in an observer's state of chromatic adaptation. This is generally done by changing the spectral composition of a light presented to an observer in one adaptation state until this light matches a comparison light presented to the observer in another adaptation state.

In order to avoid the impreciseness inherent in performing color comparisons from memory, attempts have been made to place the observer in two adaptation states at the same time, e.g., by adapting the observer's eyes separately.[1-3] If one is to be able to infer properties of monocular chromatic adaptation from binocular comparisons, the lights presented to one eye must not affect the colors perceived by the other. Previous studies have indicated that the transfer of conditioning effects from one eye to the other is not significant.[4] Those experiments, however, used a single test patch on a spatially homogeneous background. Following a suggestion by J. Y. Lettvin, we have shown that this transfer is far more pronounced when the test field is a set of three differently

colored patches that are mutually contiguous in space.

The experimental arrangement is shown in Fig. XXIII-3. A piece of white matte board with 3 attached Color Aid papers hangs over an assembly of 4 mirrors. The display is illuminated by a tungsten lamp placed sufficiently far away that the white matte

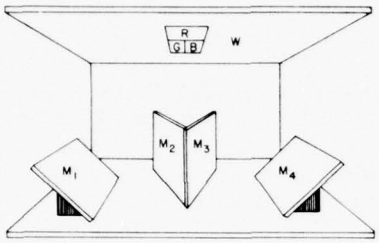

Fig. XXIII-3.
Apparatus for observing binocular effects of chromatic adaptation. M_1-M_4, mirrors; W, white matte board; R,G,B, Color Aid papers.

board appears uniformly lit. An observer preadapts one eye by looking through half a ping-pong ball at a projected colored light. Throughout the 20 seconds or so of chromatic adaptation, the other eye is open to ambient room illumination. When the observer then looks with one eye at mirror M_2 and with the other at mirror M_3 (Fig. XXIII-3), he will see two images of the triple patch, twofold rotated and displaced from each other on the white background.

If the right eye is adapted to red light, the colors seen by this eye are greener than those seen by the left eye, as expected. When the right eye is closed, however, the colors seen by the left eye become less red than they were. Reopening the right eye increases the redness of the colors seen by the left eye.

If the right eye is adapted to green light, there is a similar effect. The colors seen by the right eye are redder than those seen by the left. Closing the right eye makes the colors seen by the left appear less green; reopening the right eye makes the colors seen by the left appear more green.

After a few seconds, the effects of chromatic adaptation will weaken. If the left and right eyes are closed alternately, the colors seen by the two eyes will soon appear identical. But if both eyes are opened simultaneously, the color differences reappear, although by this time they will be quite attenuated.

This phenomenon is reminiscent of simultaneous contrast in monocular vision, and shows that the stimulation of one eye can influence color perception by the other. This is an interesting corollary to the results of dichoptic increment threshold experiments with achromatic lights.[5] We know[6] that the space of perceived colors is determined by spatial and temporal juxtaposition of lights presented to the eye: now it seems that color space can also be determined by binocular assessments.

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13. CONDUCTION VELOCITY AND SPIKE CONFIGURATION IN MYELINATED FIBERS: COMPUTED DEPENDENCE ON INTERNODE DISTANCE

National Institutes of Health (Grants 5 RO1 NS12307-02, 5 TO1 EY00090-03, and KO4 NS00010)

Bell Laboratories (Grant)

Michael H. Brill, Stephen G. Waxman, John W. Moore, Ronald W. Joyner

[Dr. J. W. Moore and Dr. R. W. Joyner are at Duke University School of Medicine.]

In previous anatomical studies[1,2] we showed that some central nerve fibers are characterized by closely spaced nodes of Ranvier. We have now begun to simulate impulse conduction in these fibers.

Huxley and Stämpfli[3] suggested that conduction velocity in myelinated nerve fibers should have a maximum at a particular internode length, and that the maximum should be relatively flat. They also predicted that the internodal distances of normal peripheral nerve fibers should fall close to the value for maximum conduction velocity. Other studies[4,5] have tended to confirm this prediction but failed to cover other "similarity classes" because internode lengths that were used were not short enough (less than one-half normal). Therefore, we have used computer simulations of conduction in myelinated fibers to examine the dependence of conduction velocity and spike duration on internode length. Throughout these simulations the nodal length (NL) and area are fixed and only the internode length (L) is varied (see Table XXIII-1).

We used a modification of the Fitzhugh model.[6] The equations were numerically integrated by the Crank-Nicholson method implemented in FORTRAN on a PDP-9 computer. This method had been used for unmyelinated fibers[7] and was adapted for the

Table XXIII-1. Parameters.

Symbol	Meaning	Value	Units
$\bar{g}_{Na}$	sodium conductance	1.2	mho/cm^2
$\bar{g}_K$	potassium conductance	0.09	mho/cm^2
g_L	leakage conductance	0.02	mho/cm^2
V_r	resting potential	0	mV
V_{Na}	sodium equilibrium potential[1]	115	mV
V_K	potassium equilibrium potential	-12	mV
V_L	leakage equilibrium potential	-0.05	mV
d	axon diameter (inner diameter of myelin sheath)	10	μm
NL	nodal length[2]	3.183	μm
r_a	axoplasmic resistance per unit axon length[3]	1.26×10^8	ohm/cm
g_M	myelin conductance per unit length	5.60×10^{-9}	mho/cm
c_M	myelin capacitance per unit axon length	1.87×10^{-11}	F/cm
c_N	nodal capacitance per unit axon length[4]	3.14×10^{-9}	F/cm
L	*internodal* length	variable	

1. All voltage signs are reversed from those of the original Hodgkin-Huxley formulation.
2. Calculated from nodal area of 100 μm^2.
3. Calculated from specific axoplasmic resistance of 100 ohm-cm.
4. Calculated from capacitance per unit area of 10^{-6} F/cm^2.

myelinated fiber by R. W. Joyner. This modified Crank-Nicholson method was found to give fast and accurate computation of impulse propagation and will be described in detail by Moore, Joyner, Brill, Waxman, and Najar (in preparation for publication). Extensive investigations into the variety of mathematical models for myelinated fibers have shown that the impulse propagation velocity is sensitive to the relative values of nodal-to-internodal characteristics but rather insensitive to changes in the description of the nodal membrane ionic currents.

Because of the insensitivity of propagation velocity to nodal ionic descriptions, we chose to describe the nodal membrane by the most convenient expression for excitable membranes, the Hodgkin-Huxley equations. The parameters used to describe our standard myelinated fiber are listed in Table XXIII-1. The numbers of sodium and potassium channels were increased by factors of 10 and 2.5, respectively, to match the nodal

conductances measured by voltage-clamp methods.[8] The nodal resting resistance was made compatible with the 55 MΩ resistance measured by Tasaki[9] by increasing g_L from 0.003 to 0.02 mho/cm^2. Then, to restore the resting potential to 0 mV, we changed V_L from +10.6 mV to -0.05 mV. We adjusted the rate constants to 20°C by multiplying all rate constants by $3^{(20-6.3)/10}$. We used a value of 5.60×10^{-9} mho/cm for g_M, the myelin conductance, and a value of 1.87×10^{-11} F/cm for c_M, the myelin capacitance.

Our results indicate that, for a 10 μm fiber, the internodal conduction time is a monotonically increasing function of internodal length L. For small L, the relationship is linear, but it departs from linearity as it goes above 2000 μm. Figure XXIII-4 presents these data in the form of impulse velocity as a function of L. There is a broad

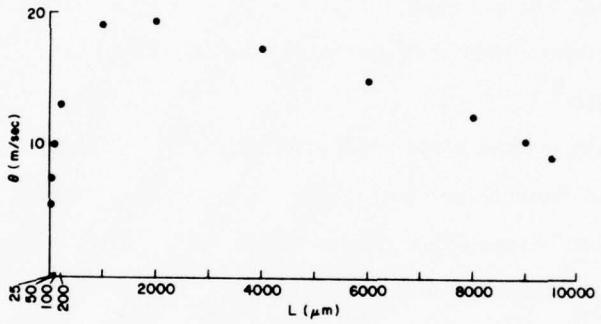

Fig. XXIII-4. Plot of the velocity θ of a steadily propagating action potential vs internodal length L.

maximum between 1000 μm and 2000 μm, which corresponds to observations on frog sciatic nerve[6] and agrees with the predictions of Huxley and Stämpfli.[3] Velocity decreases steadily for L above 2000 μm, and there is conduction failure before L reaches 10,000 μm. For internodal lengths less than 1000 μm, the velocity decreases dramatically. It is clear from Fig. XXIII-4 that, for short internode lengths, the velocity is very sensitive to L. For small values of L, the travel time (per unit distance) depends almost linearly on equal relative changes in L. The travel time is least sensitive to L in the 1000-2000 μm region.

Having carried out these computations for only one value of d (10 μm, which henceforth we call d_o), we can take any point on the curve to represent a different "similarity class." By using Rushton's correspondence principle,[10] we can interpret Fig. XXIII-4 more generally for different axon diameters. Rushton postulated that peripheral nerve fibers fall into an equivalence class in which fibers exhibit "dimensional similarity." Dimensional similarity requires that internode length, myelin thickness, and nodal area vary directly with fiber diameter. Given a class of fibers that exhibits dimensional

similarity and in which the intrinsic membrane properties are all the same, Rushton showed that internodal conduction time should be the same for all fibers of the class; i.e., conduction velocity varies linearly with fiber diameter.

Therefore, given a fiber with certain internode length L and impulse velocity θ, we can generalize Fig. XXIII-4 to fibers of other diameters by scaling θ and L by d/d_o.

From the maximum in Fig. XXIII-4, it is clear that fibers with L/d = 200 do not suffer large changes in θ when L/d is changed modestly. This is consistent with the observation that in remyelinated peripheral axons, as compared with control axons, conduction velocity is reduced but to a statistically insignificant degree.[11] On the other hand, the simulations predict that fibers with small L/d would be quite sensitive to variations in L/d. This sensitivity might provide insight into the possible physiological significance of the fact that some CNS fibers have an L/d ratio that is much less than that for peripheral nerve fibers.[1,2,12] Because the peripheral nerve impulse velocity is insensitive to small changes in L/d, there would not seem to be any signal-processing significance to minor local changes in L. On the other hand, for CNS fibers with small L/d ratios, we cannot ignore the effects on signal processing of small local changes in L because the velocity of propagation depends so dramatically on L. Local changes in L may allow fine tuning of the times of arrival of impulses at synapses or provide a convenient way of presetting route-dependent travel times in the central nervous system.[2,13]

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14. CYTOCHEMISTRY OF THE AXON SURFACE

National Institutes of Health (Grants 5 RO1 NS12307-02, KO4 NS00010, and 5 TO1 EY00090-03)

Bell Laboratories (Grant)

Stephen G. Waxman, Donald C. Quick

As part of our studies on the morphophysiology of the axon surface, we have studied the differential staining of the axon membrane at nodes of Ranvier and in internodal regions of normal peripheral nerve fibers, and at several types of nodes of Ranvier along the highly differentiated axons that comprise the electric organ in the gymnotid fish, Sternarchus albifrons.

Using a modified ferric ion-ferrocyanide method, we have noted a specific staining of the cytoplasmic surface of the nodal axon membrane. Our results indicate a high degree of local differentiation of the axon membrane with respect to staining properties with ferric ion-ferrocyanide, and demonstrate that nodal and internodal membrane exhibit structural differences.[1]

In the present study, we studied myelinated axons in rat sciatic nerve and in the electric organs of Sternarchus albifrons. The first site was chosen as an example of normal peripheral nerve. The second was chosen because the Sternarchus electrocyte axons exhibit two types of nodes of Ranvier, which are differentiated in terms of electrical properties as well as of morphology. In particular, the electrocyte axons have nodes with a normal morphology, which exhibit spike electrogenesis, and larger nodes, which do not generate spikes but rather function as a series capacity.[2-4] These axons thus provide an opportunity for comparison of membrane staining properties at active and inactive regions of single axons.

In rat sciatic nerve the nodes of Ranvier are intensely stained by the ferric ion-ferrocyanide method. Similar staining occurs at the narrow (1-2 μm) nodes of the Sternarchus electrocyte axons. By light microscopy, the stain appears as a dense ring roughly coincident with the unmyelinated gap at the node. In 3-5 μm sections examined

by light microscopy, other parts of the nerve fibers, including axoplasm, compact myelin, and myelin terminal loops, are also stained in light blue, but the color is much fainter.

In ultrathin sections examined by electron microscopy, the heaviest deposits of stain are found as dense aggregates on the inner aspects of nodal axolemmae. At the most densely stained nodes, the stain is deposited in a layer 20-100 nm thick, immediately subjacent to the nodal axon membrane. The dense aggregation of stain in all cases is confined to the nodal (i.e., unmyelinated) axon membrane, and dense aggregates do not appear subjacent to the terminating myelin loops on either side of the nodal gap.

In contrast to the axolemmae at the nodes of Ranvier, internodal regions of the axon membrane are not stained. Absence of staining of the internodal axolemmae is also observed near the cut ends of axons that have been severed after fixation and before exposure to the staining solutions. Fine electron-dense deposits, but no aggregates of stain, are seen in compact myelin, in terminating myelin loops near the nodes, in Schmidt-Lantermann clefts, and along axoplasmic filaments. Axoplasmic filaments are often noticeably stained at the center of an axon, several micrometers distant from the axolemma, which indicates diffusion of stain through the fixed axoplasm.

Ferric ion alone gives results similar to those obtained with the ferric ion-ferrocyanide combination. Myelin is consistently stained with ferric ion, but fewer nodes are well stained. Ferrocyanide also stains myelin, but nodal axolemmae are not stained with ferrocyanide alone.

These results are applicable to nodes of Ranvier in rat sciatic nerves and to the narrowest nodes (0.2-2 μm) in Sternarchus electric organ. Sternarchus electrocytes also have some very wide nodes (5-50 μm) that are known to be electrically inexcitable.[3,4] These nodes are not stained with ferric ion-ferrocyanide, either in blocks of tissue in which nearby narrow nodes are heavily stained or in teased fiber preparations in which adjacent narrow nodes of the same axon are well stained. Sternarchus nodes of transitional size (2-5 μm) are intermediate in their staining properties.

Our results indicate that there are distinct structural differences between nodal and internodal axolemmae. The possibility that there are differences in specific properties between the nodal and internodal axon membrane assumes special relevance in the context of the demyelinating diseases, since the conduction properties of affected axons will depend on the electrical characteristics of the demyelinated internodal axolemmae, as well as on those of the nodal membrane. It is known that the normal nodal membrane exhibits different properties than most other excitable membranes that have been studied, including those of invertebrate myelinated fibers and the unmyelinated terminals of amphibian neuromuscular junction. We emphasize that the present results do not allow us to comment on the electrical properties of the nodal and internodal regions of the axon membrane. Our results demonstrate, however, a chemical differentiation of the inner

surface of the axon membrane between nodes and internodes in normal peripheral nerve fibers, and between the inner surface of the axon membrane at active nodes, inactive nodes, and internodes in the Sternarchus electrocyte axons.

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15. ULTRASTRUCTURE AND PHYSIOLOGY OF CENTRAL AXONS

National Institutes of Health (Grants 5 RO1 NS12307-02 and KO4 NS00010)
Bell Laboratories (Grant)

Harvey A. Swadlow, Stephen G. Waxman

We have continued to examine the morphology and physiology of visual callosal axons in the adult rabbit. Axons in the posterior 3 millimeters of the splenium of the corpus callosum were examined by electron microscopy.[1] Unmyelinated fibers comprise approximately 45% of the fiber population. These axons range from 0.08 μm to 0.6 μm in diameter, and usually occur in clusters of at least 3-4 axons. Myelinated fibers comprise 55% of the axons in the splenium. The diameters of myelinated fibers range from 0.3 μm to 0.85 μm. Values of the ratio g (axon diameter/total fiber diameter) range from 0.64 to 0.87. In the majority of myelinated axons, the inner mesaxon and outer tongue of glial cytoplasm are located in the same quadrant. The unmyelinated gap at the nodes of Ranvier extends less than 2 μm, and an electron-dense undercoating is present, subjacent to the axon membrane at the node. Branching of fibers was not observed.

In our physiological studies, we examined the conduction properties of 75 visual callosal axons of the awake rabbit.[2,3] These axons were studied by measuring latency to antidromic activation of cell bodies following midline callosal and/or contralateral cortical stimulation. Seventy-three of 75 neurons (axon conduction velocities = 0.3-12.9 m/s) demonstrated decreases in antidromic latency and threshold to a test stimulus that followed an antecedent conditioning stimulus at appropriate intervals. Control experiments

indicated that the latency and threshold variations resulted from prior impulse conduction along the axon, and that the latency decrease reflected an increase in conduction velocity along the main axon trunk. On the basis of diameter spectra, we established criterion conduction velocities for the physiological identification of myelinated and unmyelinated axons. The supernormal phase is observed in both classes of fibers. The maximum magnitude of the latency decrease for different axons ranged from 3% to 22% of control values, while the duration was in the 18-169 ms range. The duration of the latency decrease was greater for slowly conducting axons than for fast conducting axons. Latency increases to an antidromic test stimulus occurred for as long as several minutes following a train of antidromic conditioning pulses. Antidromic latency shifts of lesser magnitude and duration were also observed in somatosensory callosal axons and in some cortico-tectal axons.

Our results indicate that a complex sequence of events (refractory period → supernormal phase → subnormal phase) follows the action potential in even unbranched central axons with a relatively simple morphology. Conduction properties of axonal trunks thus are not invariant but, on the contrary, reflect the history of previous impulse activity in the axon, as suggested by Chung et al.[4] Our experiments provide a body of normative data on central white matter axons. We intend now to examine the effects of epileptic spike activity and demyelination on central impulse conduction.

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16. STUDIES ON MORPHOGENESIS OF NERVE CELLS

National Institutes of Health (Grants 5 RO1 NS12307-02 and KO4 NS00010)

Stephen G. Waxman

Working with Dr. Mark A. Dichter of Harvard Medical School, we have begun to examine the development of specificity in neuro-glial interactions, using a tissue culture model. We have studied the development of dissociated cell cultures of chick dorsal root ganglia. Our studies have demonstrated that, despite initial disaggregation of

neurons and glial cells, an apparently normal neuro-glial relationship develops in the course of several weeks.[1] This includes a normal neuron-satellite cell relationship in addition to the development of compact myelin. We hope to use this system, which is highly accessible to experimental manipulation, as a model for studying the development of specificity in nerve cell development.

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MEETING PAPERS PRESENTED

Second European Conference on Computational Physics – Computing in Plasma Physics and Astrophysics, Max-Planck Institute for Plasma Physics, Garching, Germany

April 27-30, 1976

A. Bers, J. L. Kulp, and C. F. F. Karney, Symbolic Computation of Nonlinear Wave Interactions on MACSYMA (invited)

Optical Society of America, New England Section, Boston, Massachusetts

May 17-24, 1976

S. Ezekiel, Ultra-High Resolution Optical Spectroscopy (invited)

NICHD Conference on Communicating by Language: Implications of Basic Speech and Language Research for the School and Clinic, Elkridge, Maryland

May 23-26, 1976

K. N. Stevens, The Speech Signal

Eighth NSF Grantee-User Meeting on Optical Communications, M.I.T., Cambridge, Massachusetts

June 8-9, 1976

Papers in Proceedings

H. A. Haus, Filter Design with Cascaded Index Corrugations (pp. 58-59)

J. H. Shapiro, Propagation Characteristics of Low-Visibility Atmospheres: An Experimental Program (pp. 32-36)

1976 IEEE-MTT-S International Microwave Symposium, Cherry Hill, New Jersey

June 14-16, 1976

Papers in Proceedings

R. S. Chu, J. A. Kong, and D. L. Lee, Theory for Electro-optical Grating Modulators (pp. 24-26)

NATO Advanced Study Institute on Digital Image Processing and Analysis Meeting, Bonas, France

June 14-25, 1976

L. F. Pau, Infrared Source Classification System

2nd Symposium on Frequency Standards and Metrology, Copper Mountain, Colorado

July 5-7, 1976

L. A. Hackel, R. P. Hackel, and S. Ezekiel, Molecular Beam Stabilized Multiwatt Argon Lasers

F. Y. Wu, R. E. Grove, and S. Ezekiel, Frequency Distribution of Resonance Fluorescence in an Intense Monochromatic Field

3rd OT Optical Communication Task Force Meeting, Applications and Users Working Group, Boulder, Colorado

July 7-8, 1976

R. S. Kennedy, Optical Communication within the Atmosphere

J. I. L. A., Battelle Workshop on Highly Excited States, University of Colorado, Denver, Colorado

July 21-23, 1976

T. W. Ducas and M. L. Zimmerman, Infrared Spectroscopy of Rydberg States in Sodium

D. Kleppner, Highly Excited Atoms (invited)

5th International Conference on Atomic Physics, University of California, Berkeley, California

July 26-30, 1976

J. Apt and D. E. Pritchard, Fine Structure Changing Cross Section for Na-Ne, Ar, Kr, Xe, N_2, and CO_2

W. E. Cooke and R. R. Freeman, Measurement of the Spin-Rotational Interaction in RbKr by Molecular Beam Magnetic Resonance

T. W. Ducas and M. L. Zimmerman, Infrared Spectroscopy of Rydberg States in Sodium

R. R. Freeman and D. Kleppner, Core Polarization and Quantum Defects in High Angular Momentum States of Sodium

D. Kleppner, Highly Excited Atoms (invited)

M. G. Littman, M. L. Zimmerman, and D. Kleppner, Electric Field Ionization Rates of Selected Stark States in Sodium

W. D. Phillips and D. Kleppner, Crossed Beam Measurement of Fine Structure Changing Collision Cross Section

D. E. Pritchard and J. A. Serri, NaCs Potentials from Scattering of Polarized Atoms

Thirty-Eighth Linguistic Society of America Meeting, State University of New York, Oswego, New York

July 30 - August 1, 1976

Abstracts in Meeting Handbook

Judy A. Kegl, Ella M. Lentz, and Marie J. Philip, ASL Pronouns and Conditions on Their Use (p. 21)

Barbara Lust, Gapped Coordinate Sentences: An Examination of Their Logical Form (p. 26)

Lise Menn, The Semantics of Intonation Contour in Late Babble and Beginning Speech (English) (p. 29)

Myrl E. Solberg, Developing Phonological Systems: Nomogenesis or Individual Solutions ? (p. 35)

Gordon Research Conference on Atomic and Molecular Interactions, Wolfeboro, New Hampshire

August 9-13, 1976

S. Ezekiel, High-Resolution Studies of Atoms and Molecules (invited)

Symposium on Radiation in the Atmosphere, Garmisch-Partenkirchen, West Germany

August 19-28, 1976

P. W. Rosenkranz and D. H. Staelin, Remote Sensing of Atmospheric Temperature and Water in Storms with the Nimbus-6 Scanning Microwave Spectrometer

SPIE 20th Annual Technical Symposium, San Diego, California

August 23-27, 1976

A. L. Cassel and D. H. Staelin, Passive Microwave Radiometric Observations of the Atmosphere

S. Ezekiel, High-Resolution Tunable Laser Spectroscopy

Third Symposium on Plasma Heating in Toroidal Devices, Varenna (Como), Italy

September 6-17, 1976

A. Bers, Nonlinear Mechanism for Ion Heating by Electrostatic Waves across the Magnetic Field

A. Bers, Electron Heating in Tokamaks with RF Power at the Lower Hybrid Frequency

Second Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, Washington

September 21-23, 1976

Abstracts in Proceedings

A. G. Cook and L. M. Lidsky, The Effect of Processing and Fabrication Costs on Design Choices for Hybrid and Symbiotic Fusion Reactor Blankets (pp. 77-78)

D. G. McAleest, N. A. Uckan, E. S. Bettis, P. B. Burn, C. L. Hedrick, C. G. Lawson, R. T. Santoro, H. L. Watts, L. M. Lidsky, D. A. Ehst, A. Pant, J. S. Herring, D. L. Kaplan, and R. E. Potok, The Elmo Bumpy Torus Reactor (pp. 64-65)

D. Oliver, R. Cooper, and L. M. Lidsky, Breeding of Fissile Fuel with Linear Fusion Sources (p. 79)

International Specialist Seminar on the Impact of New Technologies in Signal Processing, Aviemore, Scotland

September 22-27, 1976

J. Allen, Digital Device Technology for Signal Processing

IEEE Electronics and Aerospace Systems Convention, Washington, D.C.

September 26-29, 1976

Papers in EASCON '76 Record

J. Allen, Special Purpose Computer Architecture for Speech Processing (p. 172-A)

D. S. K. Chan, A Novel Framework for the Description of Realization Structures for 1-D and 2-D Digital Filters (pp. 157-A – 157-H)

6th Conference on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, Germany

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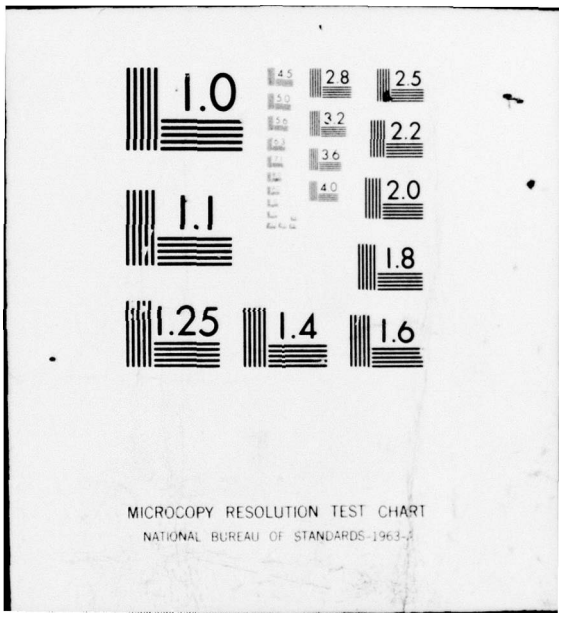
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