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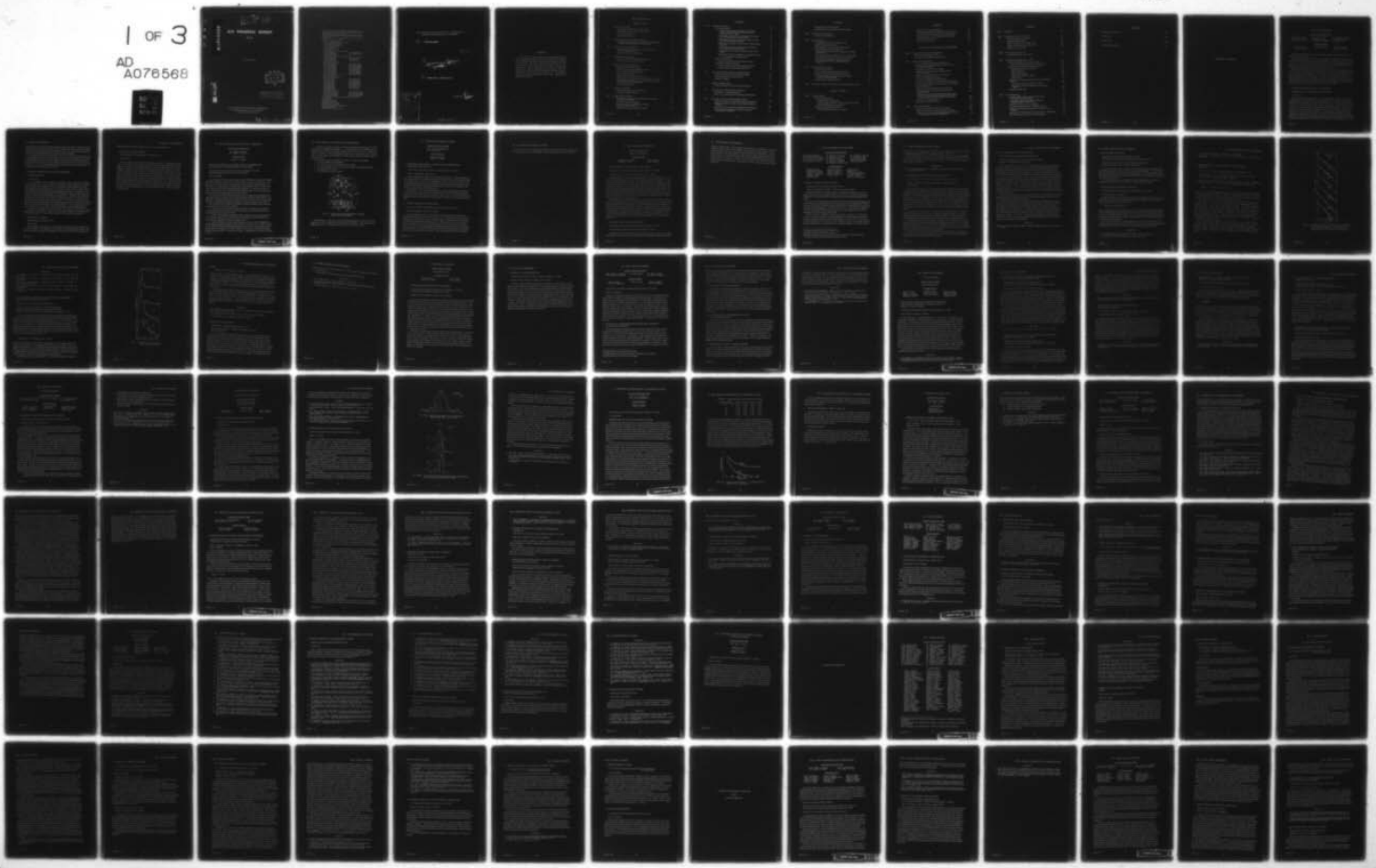

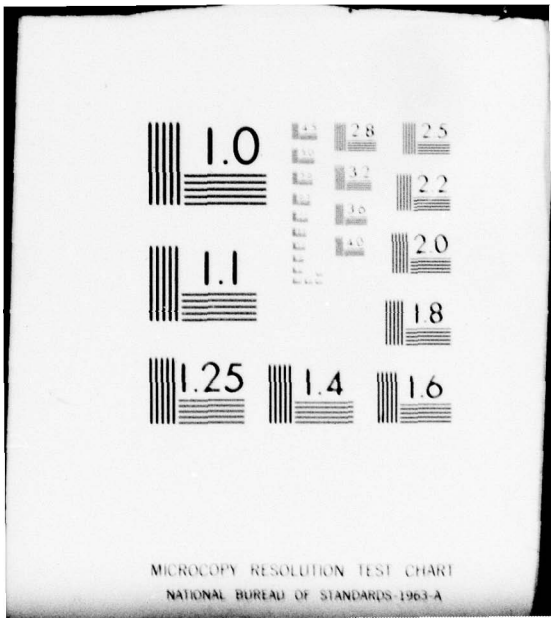
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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
RESEARCH LABORATORY OF ELECTRONICS
CAMBRIDGE, MASSACHUSETTS 02139

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The Research Laboratory of Electronics is an interdepartmental laboratory in which faculty members and graduate students from numerous academic departments conduct research.

The research in this laboratory for the year 1978 was made possible by support extended the Massachusetts Institute of Technology by the following agencies.

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J. Allen

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FOREWORD

This report, No. 121 in a series of Progress Reports issued by the Research Laboratory of Electronics, contains the customary annual statement of research objectives and summary of research for each group. The report covers the period January 1, 1978-December 31, 1978, and the source of support is indicated for each project. On the masthead of each section are listed the academic and research staff and the graduate students who participated in the work of the group during the year. The listing of personnel in the back of the book includes only members of the laboratory during 1978.

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GENERAL PHYSICS

I. MOLECULE MICROSCOPY

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Dr. Dusan G. Lysy
Dr. Carlo U. Nicola
Dr. Stanley J. Rosenthal
Dr. Peter W. Stephens
Dr. James C. Weaver
Douglas J. Ely

Graduate Students

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Jeffrey D. Macklis
Christopher Perley
Allen M. Razdow
Jeffrey G. Yorker

Our research objectives remain much as stated in RLE Progress Report No. 120. We repeat the introduction:

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

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

1. SCANNING DESORPTION MOLECULE MICROSCOPE

National Institutes of Health (Grant 1 RO1 GM23678-01)

John G. King

In connection with the development of the scanning desorption molecule microscope (SDMM) (Fig. I-2, p. 2, RLE PR No. 120, January 1978), Mr. Jeffrey G. Yorker has undertaken the development of suitable localized heaters. In order to supply the heat necessary for local desorption of molecules from our samples, we have been developing an array of microheaters called the thermal-desorption array (TDA). This device circumvents many of the problems encountered previously when electron beams were explored as a means of exciting desorption, such as insufficient intensity, the backscattering of electrons into the detector, and especially, sample damage by radiation. Furthermore, future microminiaturization of these devices will be feasible as the microelectronics industry advances. The TDA is an $n \times n$ array of diodes each of which can

be addressed by a pair of the 2n wires along the edges of the array. Diodes are needed rather than simple resistive elements so that current can be restricted to flow through only one junction. Calculations to determine the size of the region of power dissipation show that the thermal and electrical requirements are compatible.

The prototype TDA is being constructed in the M. I. T. Microelectronics Laboratory using standard integrated-circuit techniques. The prototype consists of an 8×8 array of diodes diffused into a silicon wafer substrate and addressed by aluminum leads running along the tops of the devices and heavily doped p-type stripes into the wafer below the devices. Two completed prototypes show promising electrical characteristics; the heating characteristics have yet to be tested.

2. SCANNING MICROPIPETTE MOLECULE MICROSCOPE

Health Sciences Fund

John G. King

In the development of the scanning micropipette molecule microscope (SMMM) (Fig. I-3, ibid.), Dr. Joseph A. Jarrell has established, with test patterns, the ability of the SMMM to detect differences in the concentration of helium dissolved in water. The instrument was subsequently used to examine in vitro-dissolved helium fluxes through toad and frog urinary bladder and Necturus gall bladder. No differences that could be attributed to junctional pathways were observed. Significant differences were measured in the flux through capillaries and muscle fiber. Therefore the macroscopic permeability of dissolved helium through toad bladder (corrected for boundary layers) was measured in a separate experiment as being 1×10^{-2} cm/sec. This is nearly the same as the diffusive conductance of an equivalent thickness of unstirred water, implying that this tissue presents few barriers to helium diffusion. This is consistent with the lack of differences in microscopic helium permeability through junctional pathways.

Recently the apparatus has been modified to detect fluxes of water labelled with stable isotopes, in particular, deuterium. Results and calculations to date indicate that a resolution of about 10^{-4} cm and time response of 10-20 sec may be attainable.

3. CELL SURFACE STUDIES

Health Sciences Fund (Grant 78-03)

John G. King

These studies were undertaken, and techniques of growing cells on the sample ribbon were developed. The departure of Dr. Dusan G. Lysy interrupted this project, and we are currently modifying the apparatus to increase the rate at which data can be

obtained and the flexibility with which it can be recorded and analyzed.

4. MOLECULE FLUXES IN TISSUE

National Institutes of Health (Grant 5 SO7-RR07047-13)

John G. King

We have continued the study of molecule fluxes in tissue, a collaborative project with Dr. Alvin Essig of the Department of Physiology at Boston University Medical Center. Dr. Stanley J. Rosenthal has built the molecule flux apparatus which makes possible the simultaneous measurement of CO_2 production and O_2 uptake by surviving epithelia mounted in Ussing chambers. This instrument has a time resolution on the order of one minute, which is very rapid for this type of work. Results have revealed changes in the ratio of CO_2 produced to active Na transport rates in toad urinary bladder, previously not seen. Further development should make possible the measurement of early transient metabolic phenomena in these tissues. Dr. Ying-Tung Lau has made related measurements of the basal rate of metabolism in transporting epithelia. A second molecular flux apparatus is being constructed to study the relative H_2O permeabilities of cells and tight junctions in "loose epithelia" with a spatial resolution of a few microns.

II. DEVELOPMENTAL ELECTRON OPTICS LABORATORY

Academic and Research Staff

Dr. John W. Coleman
Dr. Edward H. Jacobsen

Graduate Students

Michael R. Graham

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

Joint Services Electronics Program (Contract DAAG29-78-C-0020)
National Institutes of Health (Grant 1 RO1 GM23597)

John W. Coleman

The ultimate goal of the proposed research is the simultaneous species identification and spatial resolution of atoms of low atomic number in electron micrographs. The basis for the research is Auger electron spectroscopy coupled to high-resolution electron optics. The apparatus to accomplish this is the fixed-beam Auger electron microscope, which is now being made operationally dependable. The goal for the current year, which has been met, included final instrumental buildup, with a correction in the optical system and reengineering of the vacuum system.

The correction in the optical system was in order to bypass the undesirable focusing effects due to the structure of the specimen support (Davisson-Calbick Effect). The optics were redesigned to allow the specimen to rest at the center of a cylindrical metal electrode. Preliminary indications are that this has made focusing far less critical.

The following vacuum problems necessitated complete redesign of the housing and pumping systems of the Auger microscope:

1. Oil residues in the old vacuum system (although cryotrapped) were sufficient to cause continual microdischarges between electrodes several kV apart but spaced only millimeters away from each other.

2. These microdischarges constituted erratic changes in the optical properties of the electrostatic lenses, thus only by chance and fleetingly would all the lenses be at such value that designed-for trajectories would occur.

3. Further intolerable vacuum conditions (leaks in electrical feed-throughs and unclear diffusion pumping systems) limited vacuum to 10 minus 7 Torr, which precluded the use of the CEMA image intensifier (guarantee void for use at such values) and also made illogical the attempt to use Auger electrons to the exclusion of other secondaries (even the cleanest surface – necessary for Augers – contaminates too rapidly at 10 minus 7 Torr).

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4. With the old system, the foil lens was de facto impracticable since the electron-transparent foil contaminated rapidly, i.e., within a matter of a few minutes became electron-opaque with the accelerating voltage (20 kV) used in the AEM. Without the foil lens, of course, correction of spherical aberration is impossible, and it is just this correction which must be applied to realize the high spatial resolution which the design will allow.

A new vacuum system was designed, therefore, to enable the following:

1. Use of the CEMA image intensifier.
2. Use of the foil lens to correct spherical aberration.
3. Use of the magnetic prism energy analyzer without contaminating the faces.
4. Photography of the images.
5. Use of Augers mainly for imaging.

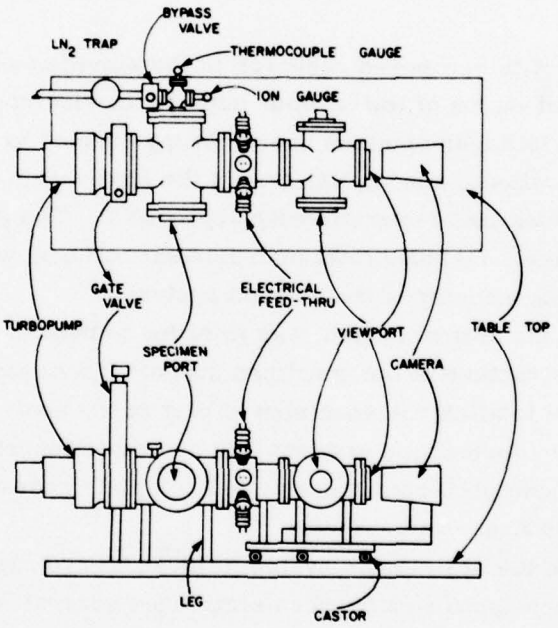

Fig. II-1. Auger electron-microscope vacuum-pumping and vacuum-housing systems.

The new vacuum system uses a copper-gasketed housing with a 100% oil-free air-suspended air-driven turbomolecular pump made by ALCATEL. This pump was nine months in delivery. A schematic of the instrument is shown in Fig. II-1.

III. SEMICONDUCTOR SURFACE STUDIES

Academic and Research Staff

Prof. John D. Joannopoulos
Dr. Eugene Mele

Graduate Students

Robert B. Laughlin
William R. Pollard

1. ELECTRONIC STRUCTURE OF HOMOPOLAR AND HETEROPOLAR SEMICONDUCTING SURFACES

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

John D. Joannopoulos, Eugene Mele

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

Specifically, we have been studying the nature of semiconductor metal interfaces. We have introduced a new ionicity scale that accounts for the remarkable covalent-to-ionic behavior of Schottky barriers with metal work functions. We are currently investigating the effects of submonolayer and monolayer coverages on Schottky-barrier functions.

2. SURFACE PHONONS IN BONDED SOLIDS

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

John D. Joannopoulos, Robert B. Laughlin

We are continuing our studies of the nature of surface phonons in bonded solids. Particular attention is focused on disordered systems with large internal voids. These materials (e.g., SiO_2) have a massive internal surface area that makes them amenable to studies with conventional phonon probes (e.g., Raman, infrared, etc.). The theory involves treating the system in terms of Bethe lattices which are attached to surface atoms in various ways and describing the potential energy of the atoms in terms of force-constant models. Local densities of states along with theoretical Raman, IR, and neutron cross sections have been calculated. These response functions have been helpful

in unraveling many of the puzzling experimental measurements on these materials. We are currently involved in investigating excitations at interfaces between Si and SiO_2.

IV. PHOTOEMISSION SPECTROSCOPY

Academic Research Staff

Prof. F. Read McFeely

Graduate Students

Michael R. McClellan
Michael J. Sayers
Neal D. Shinn
Michael Trenary

1. ANGLE-RESOLVED PHOTOEMISSION SPECTROSCOPY

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

F. Read McFeely, Michael R. McClellan, Michael J. Sayers

During the past few years we have been working to develop a highly sensitive versatile instrument to perform electron-spectroscopic experiments on surfaces. This work has been substantially completed. The instrument we have constructed is based around a 180-degree spherical-sector electrostatic electron-energy analyzer capable of rotating 360 degrees in a horizontal plane and 100 degrees in a vertical plane, thus enabling us to perform angle-resolved electron-spectroscopic measurements of all types. In addition, the incorporation of an efficient input lens system provides us with a very large accessible range of electron energies we can analyze with high transmission, thus allowing us to use the same energy analyzer in conjunction with excitation sources ranging from 2 keV down to 1 eV.

Our primary experimental effort in the coming year will be to use this system to study the orientational effect of the surface upon adsorbed molecules via angle-resolved ultraviolet photoemission spectroscopy. In order to perform these experiments in an optimum fashion polarized photons are required. In the past year we have built and tested a rotatable UV polarizer which has given us roughly 50% of theoretical intensity for He II photons generated in a discharge lamp. The use of a multichannel electron detector (currently installed in the system and being tested) will provide for us the increased sensitivity necessary to do these experiments with the reduced polarized photon flux.

2. ELECTRON-ENERGY LOSS SPECTROSCOPY

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

F. Read McFeely, Michael R. McClellan, Michael J. Sayers

In addition to the completion of our energy-analysis system, we have also designed and constructed an electron monochromator, for performing high-resolution electron-

energy loss experiments. These experiments will allow us to elucidate the vibrational properties of the molecules of the surface. We will be able to perform these experiments simultaneously with the angle-resolved photoemission experiments. At the present time this monochromator can produce a beam of usable intensity with approximately thirty-meV resolution. While we plan on a substantial effort to improve this to approximately 10 meV in the coming year, this beam is already useful for studying higher frequency vibrations, and, in particular, the study of large-momentum transfer scattering.

V. ATOMIC RESONANCE AND SCATTERING

Academic and Research Staff

Prof. Daniel Kleppner
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Robert E. Walkup
Myron L. Zimmerman

1. ATOMS IN STRONG MAGNETIC FIELDS

National Science Foundation (Grant PHY77-09155)

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

Magnetic interactions of Rydberg atoms are qualitatively different from those of tightly bound atoms. The diamagnetic interaction can not only exceed the paramagnetic interaction, it can exceed the term separation, and even the total electrostatic interaction.

We have studied the diamagnetic structure of sodium in an intermediate region where it exceeds the term separation and starts to display free-electron (Landau-like) behavior. The atoms are stepwise-excited to Rydberg states within a superconducting solenoid and are detected by field ionization. An atomic beam is used. The atoms move parallel to the field. Motional Stark effects are greatly reduced, permitting the study of states unperturbed by parity mixing or Stark shifts.

We have observed completely resolved levels in the vicinity of n = 28 at fields up to 60 kG. We have been able to account quantitatively for the diamagnetic structure by solving the secular equation for levels in the range of n = 25 to n = 31. The work has also been extended to n = 33 at 60 kG, where the energy starts to vary linearly with field, instead of quadratically, a characteristic of Landau-like behavior. We can account for

---

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‡Visiting Associate Professor from State University of New York at Stony Brook.

**Visiting Scientist from Observatoire de Paris, France.

the structure using our perturbative method based on a low-field representation, although it is apparent that this approach is reaching the limit of usefulness.

Our most recent efforts have been centered on the construction of a new apparatus which should permit us to achieve 100 kG. In addition, plans are under way for employing a swept cw dye laser instead of a pulsed dye laser, which will provide a hundredfold increase in resolution.

Publications

Myron L. Zimmerman, Jarbas C. Castro Neto, and Daniel Kleppner, Phys. Rev. Lett. 40, 1083 (1978).

2. FAR INFRARED DETECTION WITH RYDBERG ATOMS

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

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

We have detected radiation at 496 μ using Rydberg atoms and the technique of selective field ionization. Sodium atoms are prepared in the 26s state, and the incident IR radiation induces transition to the 26p state. The radiation is supplied by a methyl fluoride FIR laser. The Rydberg transition is brought into coincidence with the laser by applying a field of 27 V/cm. The transition tunes at the rate of approximately 250 MHz/(V/cm). The radiation is detected in a pulsed mode at a rate of 10 pps. The interaction time is 1.3 μsec, and the resonance linewidth is typically 1 MHz. The FIR power was measured directly by using a calibrated power meter followed by attenuators, and by observing the broadening of the resonance. The two methods agreed to within a factor of two.

The detector combines features of incoherent and coherent detection. It is fundamentally a photon-counting device and resembles an incoherent detector in having no inherent limitation on the detection area or angular aperture. On the other hand, it is narrow-banded and tunable, features usually associated with a heterodyne system.

The marginal sensitivity of the detector was taken to be the quotient of the power needed to drive the resonance and the observed signal-to-noise ratio. In our initial study the sensitivity was 3×10^{-15} watt/$\sqrt{\text{Hz}}$. The quantum efficiency was 0.1%, although this can be substantially increased. It is believed that the observed noise can be greatly reduced, and that much higher sensitivity is possible.

We have also observed resonance IR absorption at 10.8 μ and 118 μ, although we have not studied the systematics in detail. Our method should be applicable throughout the IR spectrum, and in the millimeter-wave region.

3. FIELD IONIZATION AND PHOTOIONIZATION

U.S. Department of Energy (Grant EG-77-S-02-4370)

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

We have undertaken a study of the role of nonadiabatic effects on field-ionization processes. Briefly, if a Rydberg atom is subjected to a rapidly increasing electric field, it can make transitions to other states as the electric field sweeps the energy levels through successive level anti-crossings. The ionization characteristics of the system are then dominated by the properties of these levels, rather than the initial state.

The process by which an atom "jumps" to another state as the energy levels are swept through an anti-crossing is called the Landau-Zener effect. We are studying the Landau-Zener effect in a two-part program. The first part comprises the accurate mapping of an anti-crossing in order to determine the parameters which enter the Landau-Zener theory. This is essentially completed. We have mapped a group of crossings between the $n = 18$ and $n = 19$ levels of lithium, using a cw dye laser with 30-MHz resolution. A number of the crossings appear to be good candidates for studying the Landau-Zener effect.

We have also studied the anti-crossings theoretically. Our calculations are in good agreement with the observation, and give us confidence that anti-crossings can be reliably calculated for many Rydberg systems.

We have also undertaken photoionization measurements of Rydberg atoms. Photoionization from Rydberg states is important to energy transfer in stellar atmospheres and in plasmas. Relatively little experimental work has so far been carried out on photoionization from excited species. Our initial studies are on photoionization near the continuum edge, where the cross sections vary most rapidly. We have employed a CO_2 laser to photoionize Rydberg states of sodium, and have observed both s and d states on the range $n = 12$ to $n = 20$. The experimental results are still preliminary. Nevertheless, they are in qualitative agreement with calculations that we have carried out based on the Coulomb approximations.

Publications

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(V. ATOMIC RESONANCE AND SCATTERING)

4. SPIN-POLARIZED HYDROGEN

National Science Foundation (Grant DMR 77-10084)
National Aeronautics and Space Administration (Grant NSG-1551)

Daniel Kleppner, Thomas J. Greytak, Stuart S. B. Crampton,
William D. Phillips, David A. Smith, Abel Weinrib

We have developed a source of atomic hydrogen at liquid-helium temperature, and have studied the properties of H on frozen H_2 using spin resonance. The zero-field hyperfine transition has been observed with atoms stored in a bulb coated with solid H_2. The frequency shift due to wall collisions and the transverse and longitudinal relaxation times have been measured.

The cold-hydrogen source should have a number of applications in atomic and surface physics, as well as in the production of spin-polorized hydrogen.

5. EFFICIENT ENERGY-TRANSFER PROCESSES

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Neil Smith, David E. Pritchard

Using a technique for selecting velocity based on the Doppler shift,[1,2] we have completed study of the velocity dependence of the total cross section for collisions which change the fine-structure level of Na atoms,[3]

$$Na(3P_{1/2}) + X \rightleftharpoons Na(3P_{3/2}) + X,$$

where X can be an atom or a molecule. These cross sections are typically 100 $\mathring{A}^2$, and we found that the target determined whether they increased or decreased with velocity. For some of the target atoms we studied, the velocity dependence has subsequently been measured in a crossed-beams machine – this has enabled us to show that our technique gives reliable results within 5%.

We have also completed a theoretical paper[4] in which we have been able to give a procedure based on Fourier transforms which can remove the thermal averaging inherent in this technique, as well as in several other classes of collision experiment.

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6. DETAILED STUDY OF EXCITED-STATE ENERGY-TRANSFER PROCESSES

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

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

One of the most probable inelastic collisions involving molecules is Rotational Energy Transfer (RET). We have measured rate constants for the RET process

$$Na_2^*(v, j_o) + X \rightarrow Na_2^*(v, j_o + \Delta) + X - \Delta E_r,$$

where v is the vibrational quantum number, j_o is the initial rotational quantum number, X is a rare-gas atom, and ΔE_r is the increase in rotational energy. We use a tunable dye laser to populate the desired initial level, and observe the resulting fluorescence with a monochromator to monitor the populations of the levels.

The results of our experiment with Na_2^* in collision with Xe are shown in Fig. V-1 where we plot the rate constant divided by a translational (R) and a spin (N_o) density of final states versus energy transfer. The positive ΔE_r data fall on the same line as those with negative ΔE_r due to our use of a novel spin-space factor N_o which assumes conservation of the magnetic quantum number. Furthermore, the data follow a power law[1,2] rather than the previously accepted exponential gap law.[3] We have applied this power-scaling law to other experimental and theoretical data[4] and found it to be superior to the exponential gap law in every case.

We are currently measuring the velocity dependence of the above RET process by using the Doppler shift to vary the velocity component of the excited molecule along the laser beam. To reduce the averaging due to unselected translation degrees of freedom we have developed a new deconvolution procedure.[5] We are currently measuring the velocity dependence of RET in Na_2^*-Xe collisions.

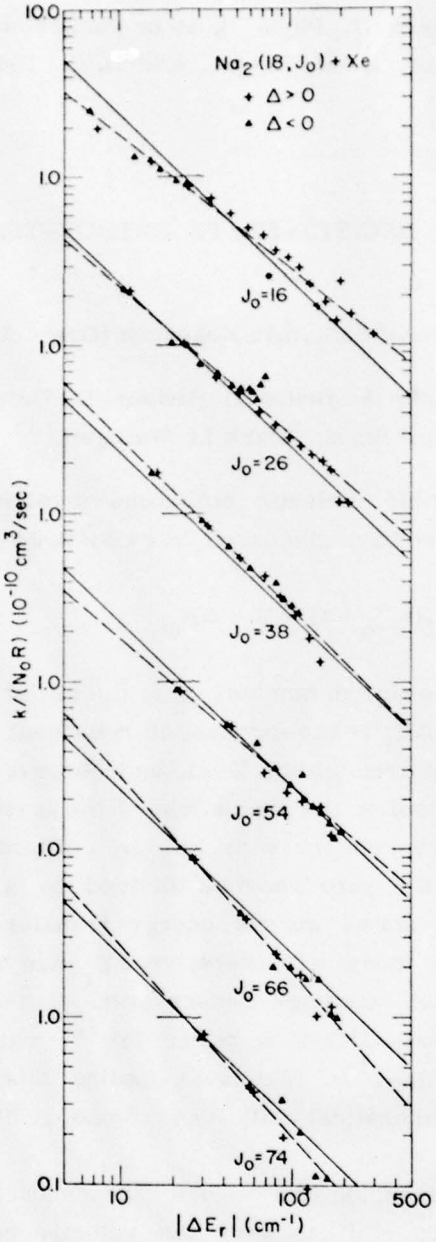

Fig. V-1. $k/(N_oR)$ versus $|\Delta E_r|$. Dashed lines are power-law fits to data for individual j_o. Solid lines are all a single power-law function which fits all data well.

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7. STATE-RESOLVED DIFFERENTIAL CROSS-SECTION MEASUREMENTS USING DOPPLER VELOCITY ANALYSIS

National Science Foundation (Grant CHE76-81750)

John A. Serri, Richard Mittleman, Alejandro Morales-Mori,
David E. Pritchard, Christopher H. Becker, James L. Kinsey
[James L. Kinsey is Professor in the Department of Chemistry, M. I. T.]

We have demonstrated a new technique for measuring inelastic differential cross sections. This method, named Angular Distribution using the Doppler Shift (ADDS) is based on the idea that atoms are excited into resonance by a laser at frequency ν only when the projection of their velocity along the laser beam, $v_\ell = v \cos \theta_{cm}$, is equal to $c(\nu-\nu_o)/\nu_o$. The frequency ν_o represents the rest-frame resonance frequency. By tuning a laser beam which travels along the relative velocity axis of two intersecting atomic beams and recording the subsequent fluorescence signal as a function of ν from one of the beams, we directly obtain the center of mass differential cross section versus $\cos \theta_{cm}$. The collision process studied was[1]

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

The first excited state of sodium ($3P_{1/2}$) was produced by a laser beam tuned to the $3S_{1/2}$ to $3P_{1/2}$ transition. A second laser beam, placed on the relative velocity axis and tuned across the $3P_{3/2}$ to 4D sodium transiton, analyzed the scattering angle of the $Na^*(P_{3/2})$ produced by the structure state-changing collisions. Figure V-2 compares our experimental results (points) with an ab initio calculation convoluted with the experimental resolution profile and the appropriate hyperfine structure.

The ADDS method is now being applied to rotational energy transfer in diatomic

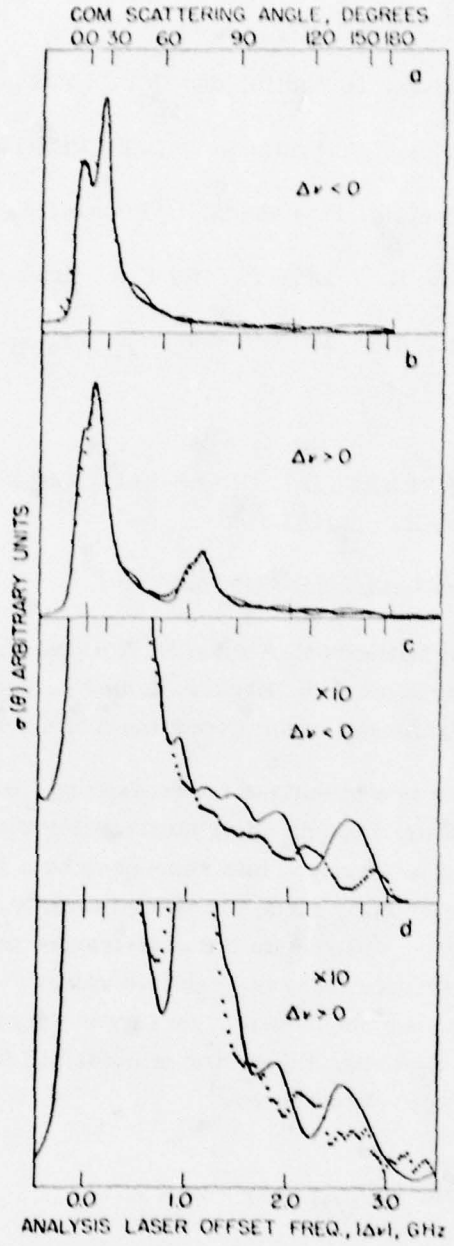

Fig. V-2. Straight lines – theoretical fit.
Points – experimental data.

sodium,

$$Na_2(V, J) + Ar \rightarrow Na_2(V, J') + Ar + \Delta E,$$

where V is the vibrational quantum number. The experiment uses two lasers, one to modulate the dimer population of the initial state (V, J) and the other to analyze the final state (V, J'). The angular distribution of the final state (V, J') resulting from inelastic collisions with the argon will be measured by fluorescence from the Doppler-tuned transition $X^1\Sigma(v, j) \rightarrow A^1\Pi(v', j \pm 1)$. Collisions which connect states (v, j) and (v, j') will then be isolated by phase detecting at the modulation frequency of the laser tuned to the (V, J) level.

These measurements will be conducted in a new crossed-beams machine which utilizes Campargue nozzle sources[3] to produce high-intensity molecular beams with narrow velocity distribution and low internal temperature. Construction is complete, and at the present time we are performing beam diagnostics on the dimers using laser-induced fluorescence. Our immediate objective is to optimize the production of rotationally cold Na_2 and to further reduce the velocity spread, currently 10% FWHM.

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8. MOLECULAR SPECTROSCOPY

National Science Foundation (Grant PHY77-09155)

Mark D. Havey, Walter P. Lapatovich, Philip E. Moskowitz,
David E. Pritchard

We are studying weakly bound diatomic molecules. The van der Waals molecule NaAr has been produced in a supersonic expansion, and laser-induced bound-bound transitions have been observed. The spectra obtained extends earlier data of Smalley and his co-workers,[1] and shows much hitherto unseen structure, particularly in the region where the excited state is close to dissociation. A long-range analysis,[2] utilizing the new data, is currently in progress. Analysis of the spectra attributable to the highest vibrational levels of the $A^2\Pi$ excited state (and comparison to spectra from NaNe) should yield information about the elusive $B^2\Sigma$ state. This would complete the experimental determination of all potentials necessary to calculate line-broadening and

atomic-collision processes for this system. This will provide a sharp test of theories for these processes.

Future plans include studying the free-bound transitions in NaHe.

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VI. INTERFACIAL CHEMISTRY

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1. PHOTOACOUSTIC SPECTROSCOPY OF SURFACES

Joint Services Electronics Program (Contract DAAG29-78-C-0020)
National Science Foundation (Grant DMR-76-80895)

Ralph H. Staley, Manfred M. Kappes, John B. Kinney

We have been working to develop a new technique, photoacoustic spectroscopy (PAS), that will be used to characterize the physical and chemical properties of solids. Heat released when light from an intensity-modulated source is absorbed produces periodic temperature and pressure changes in gas in contact with the solid; this effect can be used as a sensitive means to measure the light absorption and allows spectra to be obtained from solid samples which are otherwise difficult or impossible to study. A photoacoustic spectrometer has been purchased from Princeton Applied Research Corporation with capabilities for studies in the ultraviolet-visible-near-infrared range (200 to 1600 nm) and which allows microprocessor manipulation of the phase and magnitude data obtained from the experiment. Additional cells have been built for this instrument to allow control of the gas environment of the sample and to permit studies of liquid-solid interfaces. The first of these will be particularly useful in studies of photoaction spectra, where the observed signal arises from photochemical processes that produce or consume gas molecules.

Photoacoustic spectra have also been obtained in the infrared using a cw CO_2 laser. These experiments have provided the first demonstration of photoacoustic spectra of solids in the infrared, a capability that may well prove to be the most important application of this new technique. This promises to make it possible to obtain infrared spectra of monolayer concentrations of chemical species on the surface of single crystals. Sensitivities adequate to obtain such spectra have not been available using other techniques. Development of instrumentation to obtain photoacoustic spectra throughout the infrared is continuing.

(VI. INTERFACIAL CHEMISTRY)

2. CHEMICALLY MODIFIED SURFACES

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Ralph H. Staley, Manfred M. Kappes, John B. Kinney

Covalent bonding of organic functionalities to surfaces, in particular the Si, SiO_2 surface, is being studied as it affects the electronic properties and chemical reactivity of the surface. Three types of behavior are of particular interest: (1) Effectiveness of certain redox-active species such as ferrocene to prevent corrosion of the surface and to mediate surface redox chemistry in photoelectrochemical applications; (2) photochromic and electrochromic behavior of dyes covalently attached to semiconductor surfaces for use in display and information storage applications; (3) work function modification by covalently attached monolayers of molecules containing large internal dipole moments. Chlorosilane reagents are used to accomplish covalent attachment to the semiconductor surface. Photoacoustic spectroscopy, infrared spectroscopy, x-ray photoelectron spectroscopy (ESCA), and work-function and electrochemical measurements are being used to characterize the results.

VII. X-RAY DIFFUSE SCATTERING

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Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Robert J. Birgeneau

We have now completed construction of a two-spectrometer x-ray diffuse-scattering system based on a Rigaku 12-kW rotating-anode x-ray generator. The system is designed in such a way that one may easily tailor the instrumental resolution function to optimize studies of structure and fluctuations in a vast range of physical systems. Angular resolution of 1.8 seconds of arc and sample temperature control of 2 mK between 10 K and 500 K are available. We are currently implementing a position-sensitive detection system to allow rapid scans over a wide range of scattering angles, again with continuously variable resolution. Our current research program emphasizes structure and melting transitions both for monolayer physiadsorbed films on graphite and for layered liquid crystals. The surface experiments involve in situ high-precision vapor-pressure and surface-coverage measurements. We now discuss our individual projects.

1. MELTING AND COMMENSURATE-INCOMMENSURATE TRANSITION OF KRYPTON ON GRAPHITE

It has traditionally been assumed that only surface-sensitive probes such as low-energy electron diffraction (LEED) could be used to study monolayer surface films. However, for a variety of experimental reasons LEED is extremely limited in the information which it can provide. Accordingly, we have initiated a study of monolayer surface overlayers using x-ray scattering techniques. Our first experiments were performed on krypton physiadsorbed onto exfoliated ZYX graphite. This system is particularly interesting because the ideal krypton-krypton interatomic separation is quite close to, albeit slightly less than, a natural superlattice ($\sqrt{3} \times \sqrt{3}$) spacing provided by

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the (0001) graphite-plane substrate. We find that for less than monolayer coverage the krypton forms a commensurate $\sqrt{3} \times \sqrt{3}$ structure at all temperatures. Furthermore, for coverages greater than 0.9, the melting transition is second-order with the critical behavior of the 3-component Potts lattice gas model as predicted by theory.[1] With increasing coverage the krypton undergoes a two-step commensurate-incommensurate transition. The details of this transition are still being investigated.

2. STRUCTURE OF XENON-ON-GRAPHITE

Xenon provides an interesting contrast with krypton-on-graphite in that the solid xenon-interatomic spacing lies intermediate between the graphite (0001) $\sqrt{3} \times \sqrt{3}$ and 2×2 superlattices. We find that xenon for nearly all coverages and temperatures forms an incommensurate, floating solid hexagonal overlayer. We have carried out a detailed study of the two-dimensional solid-liquid-gas coexistence near the triple point at 99 K. Our experiments confirm that a triple point may indeed exist in two dimensions, in contrast to much theoretical speculation to the contrary. However, the 2D solid exhibits anomalous properties; in particular, the solid-structure factor varies drastically as the relative amounts of 2D solid and vapor are varied. This may reflect a fundamental instability of line interfaces in two dimensions. Work on this most interesting system is continuing.

3. NEMATIC-SMECTIC A TRANSMISSION IN BILAYER SMECTIC-LIQUID CRYSTALS

De Gennes has proposed an elegant model which establishes an isomorphism between the nematic-smectic A transition in liquid crystals and the normal metal-superconductor transition in metals. However, because the liquid-crystal interactions are short-range, one should observe true critical behavior rather than mean-field behavior as in a superconductor. We have carried out a detailed study of the mass-density critical fluctuations in three bilayer smectic-liquid crystals CBOOA, 8OCB, and 8CB.[2] In all cases both the smectic susceptibility and the longitudinal correlation length exhibit helium($d = 3$, $n = 2$)-like critical behavior as predicted by de Gennes. However, the transverse correlation length appears to diverge more weakly, probably due to the highly anisotropic elastic forces in the liquid crystal.

4. THE NATURE OF SMECTIC B LIQUID CRYSTALS

Smectic B liquid crystals constitute one of the most mysterious phases of condensed matter. These systems exhibit considerable positional order in all three dimensions, yet they have a number of liquidlike properties which distinguish them from conventional solids. No rigorous model for this phase has yet been proposed. However, an important clue may have been provided by Halperin and Nelson who show that in <u>two</u> dimensions

melting may occur in two stages with the solid first losing its positional long-range order at T_1 and its orientational order at a higher temperature T_2. The intermediate phase has been labelled "hexatic." We have proposed a model[3] in which the smectic B essentially corresponds to stacked hexatic films. We have shown that this model appears to be consistent with all available data. High-resolution x-ray experiments are now under way to test a number of the predictions of our model.

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VIII. QUANTUM ELECTRONICS

A. Laser Applications

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1. DOPPLER-FREE STIMULATED EMISSION SPECTROSCOPY AND SECONDARY-FREQUENCY STANDARDS USING AN OPTICALLY PUMPED LASER

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Shaoul Ezekiel, Stephan C. Goldstein

We have developed, in collaboration with R.W. Field and J.B. Koffend, a new Doppler-free stimulated emission spectroscopic technique using a cw optically pumped laser (OPL). The molecule under study forms the gain medium of the OPL. The technique can also be used to generate a set of laser-frequency standards covering a substantial spectral range. We have demonstrated this technique by observing narrow hyperfine structure features in an I_2 OPL with linewidths of less than 1 MHz. This allowed us to perform high-resolution spectroscopic measurements of the complete hyperfine structure of several rotational-vibrational levels in the ground electronic state of I_2. The data was fitted to obtain values for the nuclear electric quadrupole coupling constant (eQq") and the nuclear spin-rotation coupling constant (C") for v" from 0 to 83. The observed variation in eQq" may be due mainly to the spin-orbit interaction of the $X'\Sigma_g^+$ state with the O_g^+ state, both of which share the common $^3P_{3/2} + {}^2P_{3/2}$ dissociation limit. The observed nonzero values for C" are due to the perturbation of the $X'\Sigma_g^+$ state by the 1g component of the $^3\Pi_g$ state which dissociates into two $^2P_{3/2}$ iodine atoms.

In addition, the I_2 OPL laser has been actively stabilized to one of the narrow I_2 hyperfine components within 1 kHz.

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2. OBSERVATION OF NON-LORENTZIAN ABSORPTION LINE SHAPE OF A STRONGLY DRIVEN TWO-LEVEL ATOM

National Science Foundation (Grant PHY77-07156)
Joint Services Electronics Program (Contract DAAG29-78-C-0020)

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

We have conducted careful measurements of the power-broadened absorption line shape of a two-level atom in an atomic beam as a function of the intensity of the monochromatic driving field. The results showed that at low driving-field intensities, the absorption line shape was indeed Lorentzian, as expected. However, the line shape became skewed as the field intensity became much larger than the saturation intensity. This departure from Lorentzian line shape is due to atomic recoil. By allowing for atomic recoil we were able to obtain a very good fit to the observed line shape.

Our experiments were conducted on an atomic beam of Na prepared as a two-level system by optical pumping using a single-frequency σ^+-polarized cw dye laser locked to the $3\,^2S_{1/2}$ (F=2) - $3\,^2P_{3/2}$ (F=3) transition as described elsewhere.[1] A second dye laser, also σ^+-polarized, is made to interact with the two-level atoms farther down the atomic beam, and the resulting fluorescence is monitored as a function of laser frequency. This line-shape measurement was repeated for different laser intensities. To ensure uniformity of the laser intensity in the interaction region, the fluorescence detected was limited to that emitted from a small central area of the interaction region.

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3. OBSERVATION OF SUBNATURAL LINEWIDTHS USING TWO-STEP RESONANT SCATTERING IN I_2 VAPOR

National Science Foundation (Grant PHY77-07156)
Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Shaoul Ezekiel, Richard P. Hackel

We have observed linewidths narrower than the natural width using a two-step resonant scattering scheme in a folded configuration in I_2 vapor. The measured width of the lines at 5828 Å is 80 kHz, with the major contributions to the width stemming from instrumental broadening mechanisms and laser jitter in our present setup. These extremely sharp lines which, to our knowledge, are the narrowest recorded in the visible region of the spectrum,[1] have a number of important applications. In addition to

Doppler-free stimulated emission spectroscopy of thermally unpopulated levels, these narrow resonances can be used as unique high-resolution probes for the study of collisional effects on specific energy levels and as reference lines for laser-frequency standards. It should also be noted that because these reference lines, whether in atoms or molecules, can be very sharp, the frequency difference between pump and probe (or between two probes using a common pump) may be established extremely accurately. This suggests applications to spectroscopy and frequency standards in the RF/microwave/FIR regions using optical lasers.

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4. MEASUREMENT OF INERTIAL ROTATION USING A PASSIVE RING RESONATOR

U. S. Air Force – Office of Scientific Research (Grant AFOSR-3042)

Shaoul Ezekiel, Glen A. Sanders, Robert P. Schloss

The drift performance of an optical rotation sensor employing a passive ring resonator has been investigated. With a square cavity, 17 cm on a side, and a 1-mW external laser, the rms flucutation in the measurement of rotation was 0.45°/hour for an integration time of 1 second.[1] This is consistent with shot-noise-limited performance expected for the present setup. Recently we have constructed a larger resonator, 70 cm on a side, using discretely mounted components. The resonator linewidth is 200 kHz and preliminary results have demonstrated an rms drift fluctuation of about 0.15°/hour for an integration time of 1 second which is at least an order of magnitude larger than the shot-noise limit for this configuration. A thorough experimental as well as theoretical investigation of error sources is in progress.

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5. MEASUREMENT OF INERTIAL ROTATION USING A MULTITURN FIBEROPTIC SAGNAC INTERFEROMETER

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Shaoul Ezekiel, James L. Davis

Currently there is considerable interest in using a multiturn fiber Sagnac interferometer for the measurement of inertial rotation. Such a measurement is difficult to perform because the nonreciprocal phase shift (NRPS) induced in the fiber by inertial rotation is very small. For a rotation rate Ω, the NRPS $\Delta\phi$ is given by

$$\Delta\phi \approx \frac{8\pi NA}{\lambda_o c}\,\Omega, \tag{1}$$

where $\Delta\phi = \phi_{cw} - \phi_{ccw}$ is the difference between clockwise (cw) and counterclockwise (ccw) phase shifts in the fiber, A is the area enclosed by the fiber loop, N is the number of turns, λ_o is the vacuum wavelength of the light source, and c is the velocity of light. For example, if $\Omega = 7.3 \times 10^{-5}$ rad/sec (i.e., earth rotation, Ω_E), N = 1000 turns, A = 100 cm^2, and $\lambda_o = 0.6328\ \mu$, the NRPS is $\Delta\phi \approx 1.0 \times 10^{-4}$ radian. Similarly, if $\Omega = 7.3 \times 10^{-8}$ rad/sec or $10^{-3}\,\Omega_E$, then $\Delta\phi \approx 1.0 \times 10^{-7}$ radian.

We are investigating several approaches[1] to the measurement of nonreciprocal phase shift. In particular, we are examining a scheme in which different optical frequencies propagate along the clockwise and counterclockwise directions by means of acousto-optic shifters. In this way, we have achieved a nonreciprocal phase shift modulation of $\pm\pi/2$ at a rate sufficiently high for shot-noise-limited performance. In addition, this 2-frequency scheme is also used to lock the frequency difference so that operation is always at the center of the zero fringe to avoid errors due to laser intensity fluctuations. Thus, the frequency difference of the counterpropagating beams is directly proportional to rotation-induced nonreciprocal phase shift.

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6. AC STARK EFFECT IN A DOPPLER-BROADENED THREE-LEVEL SYSTEM

National Science Foundation (Grant PHY77-07156)
Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Shaoul Ezekiel, Richard P. Hackel

We are performing experiments extending our investigations of the ac Stark effect in an atomic beam to a gas cell where Doppler broadening and also collisions must be considered. The experiments so far are being performed with molecular iodine in a temperature-controlled vapor cell. The pump beam in this case is a single-frequency argon ion laser at 5145 Å interacting with the $B^3\Pi_{0^+u}$ (v' = 43, J' = 12) ← $X'\Sigma^+_g$(v" = 0, J' = 13) Doppler-broadened transition in I_2. The probe is a single-frequency dye laser tuned to the $B^3\Pi_{0^+u}$ (v' = 43, J' = 12) ← $X'\Sigma^+_g$(v" = 9, J" = 13) transition. In this way, we have a folded three-level system. The lower level of the probe transition is metastable because I_2 is homonuclear. The pump and probe beams are collinear and ac Stark-effect measurements are made for both co- and counterpropagating probe beams. The absorption/gain of the probe is measured by chopping the pump beam and synchronously detecting the probe beam. The data so far appear to be in disagreement with existing calculations.

7. MEASUREMENT OF NATURAL WIDTHS IN I_2 HYPERFINE STRUCTURE: A TEST OF HYPERFINE PREDISSOCIATION

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Shaoul Ezekiel, Robert E. Tench

We are performing high-resolution studies of hyperfine structure associated with the P(13) (0-43) transition in I_2. The primary aim is to measure the natural width of individual hyperfine components so as to separate out the radiative decay contributions to the linewidth from those due to natural and magnetic predissociation of the iodine $B^3\Pi_{o^+u}$ state. Since we have to measure widths ranging from 45 kHz to 150 kHz at about 5145 Å, we have constructed a high-resolution saturated-absorption spectrometer using stabilized argon-ion lasers. This spectrometer will also be used for studying the interaction of I_2 with intense monochromatic radiation in the presence of Doppler broadening.

VIII. QUANTUM ELECTRONICS

B. Nonlinear Phenomena

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1. PICOSECOND PULSES FROM SEMICONDUCTOR LASERS

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Clifton G. Fonstad, Hermann A. Haus

The capability of lasers to produce picosecond pulses has not been exploited by communications technology, because no compact sources of picosecond pulses are available. Laser diodes are the obvious active component for such applications, yet they have not been successfully mode-locked.

We have initiated a program for the development of sources of picosecond pulses utilizing laser diodes. A year ago we reported our first attempts at mode locking of a GaAlAs laser diode operating at 8100 Å in an external resonator by microwave modulation of the bias current. At that time we determined the effect of the modulation on the microwave spectrum of the detected optical output and found evidence of mode locking in the change of the spectrum. In the meantime, the cw train of pulses has been measured by second-harmonic generation. The pulses were as short as 23 psec at a rate of 3 GHz.[1] InGaAsP diodes operating at 1.2 and 1.3 μ, respectively, have been mode-locked.[2] The shortest pulses obtained from the 1.2-μ device were 18 psec, at a 2-GHz repetition rate.

We do not know as yet the ultimate limits on the achievable pulse lengths. Dispersion of the diode material should play a role only when pulses of the order of 1 psec are achieved.[3] We have shown[4] that the spontaneous emission significantly affects the mode locking. Further, we have observed that the free-running diodes invariably self-pulsed without an applied microwave drive, emitting pulses of the order of three times longer than those achieved with the forced mode-locking drive.[2] Future work will be concerned with the following issues:

1. Design of external resonators with flexibility for length and bandwidth adjustments. Optimization of mode-locked pulses by adjustment of these parameters.

2. Pinpointing of the mechanism of self-locking.
3. Combination of forced- and saturable-absorber mode locking, using one diode as the laser and one as the saturable absorber.
4. Exploration of means of miniaturization of the external resonator through replacement by an optical waveguide.
5. Design of broadband multiplexers and demultiplexers for the generation of 20-Gbit pulse trains.

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VIII. QUANTUM ELECTRONICS

C. Distributed Feedback Structures

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1. SURFACE ACOUSTIC WAVE GRATING RESONATOR MODES

National Science Foundation (Grant ENG77-24981)

Hermann A. Haus

The impetus for our research in grating resonators derives from their potential use in integrated optics. Present-day technology is not yet at a stage where gratings with periods of the order of 2000 Å can be easily manufactured so that ideas developed for grating resonator-filter design have to be tested in their SAW realization.

The potential of SAW filter design using grating structures is great in its own right, and problems peculiar to SAW devices have to be overcome. One of these problems is the spurious response of higher order grating resonator modes.[1]

We have launched an investigation of grating waveguide modes[2] which were shown to exhibit both lower and upper cutoff frequencies.[3] Beyond the cutoff points the modes were shown to become leaky.[3] A normal mode expansion of a SAW excited by a transducer and incident upon the entry plane of a grating waveguide includes both guided modes and leaky modes – the latter contribute to the power escaping from the guide, or the SAW resonator made up of such grating guides.

As part of the investigation of Rayleigh wave loss, bulk wave scatter by grooves[4] and more recently by posts[5] have been the subject of investigation. The latter results are useful in the design of post-support structures for semiconductor superstrates of SAW correlators.

In further support of SAW filter design, we are starting to investigate higher order effects in h/λ_r (where h is the groove depth and λ_r is the Rayleigh wavelength). The Bragg frequency of a SAW grating is a function of $(h/\lambda_r)^2$, and resonator design has incorporated this effect empirically. We have developed a variational principle which seems particularly suited for the theoretical study of second-order effects. One gratifying result was a very simple derivation of the grating reflection coefficient 2r which was obtained by a different and much lengthier method.[4]

We are extending the coupling-of-modes analysis with diffraction[2] to the study of mode patterns in metal-strip couplers. In spite of their importance, no analysis of the two-dimensional mode patterns underneath open-circuited metal strips exists today.

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2. TUNABLE OPTICAL-GRATING WAVEGUIDE FILTERS

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Clifton G. Fonstad

We have been engaged in an effort to experimentally realize aperiodic distributed feedback, or grating waveguide, optical-wavelength filters like those proposed by Professor Hermann A. Haus,[1] and already used at acoustic frequencies to design acoustic surface-wave filters. The predicted effects have now been demonstrated at optical frequencies, and a new technique for calculating the filter characteristics of a practical structure including parasitic reflections, etc., has been developed.[2,3] The potential for applying the tunable, narrow-linewidth filters produced in electrically tunable DFB is at present being assessed.

A periodic corrugation on a waveguide surface perturbs the propagation of the normal traveling modes of the waveguide. At frequencies around the Bragg frequency (the wavelength corresponding to twice the corrugation period), reflections off each periodic disturbance interfere constructively, resulting in an intense wave in the reverse direction. This is described mathematically as a periodic coupling between the forward and reverse modes. The calculated reflection spectrum of a uniform-grating waveguide is shown in Fig. VIII-1a.

Any departure from perfect uniformity of such a periodic structure introduces new features in the reflection spectrum. For example, a phase shift at the midpoint of the structure allows the transmission of wavelengths that are reflected in the uniform

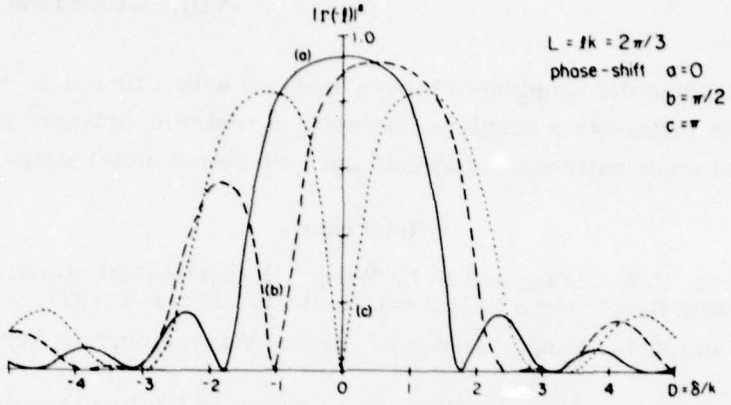

Fig. VIII-1. Reflection spectra for a waveguide with three different phase shifts. $D = (\beta - \beta_o)/k$.

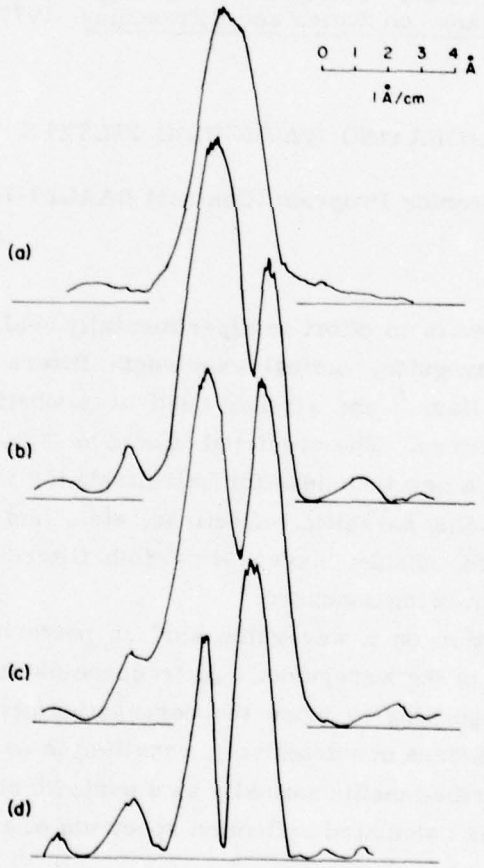

Fig. VIII-2. Three reflection spectra showing the tuning of the passband caused by gradually increasing phase shift.

structure. As illustrated in Fig. VIII-1b and 1c, this is a very narrow passband, and the position of this new passband within the normal Bragg-frequency-centered stopband is tunable by varying the magnitude of the phase shift. Such a tunable spectrum has potentially important applications as a filter, and when utilized in distributed-feedback lasers.

The above behavior can be explained by considering the structure as a Fabry-Perot cavity formed by two grating reflectors separated by a fraction of a wavelength. The new passband is then simply one of the Fabry-Perot modes. The phase shift corresponding to the separation of the two reflectors determines the position of this mode (within the broad stopband). The tuning of the mode is the consequence of the change in the mode separation due to the change in cavity length.

To obtain experimental verification of this behavior, corrugations (gratings) were produced on the surface of sputtered thin-film glass waveguides using interferometric exposure and ion-milling. A phase shift was introduced by reducing the film thickness at the center of the waveguide. This retards the beam in this region so that the beam faces the following grating section at a different phase. Reflection-spectrum measurements made on these filters using a prism coupler and specially constructed dye laser clearly demonstrate the existence and tunability of the predicted passband in optical-grating (DFB) waveguide filters (see Fig. VIII-2). The model developed also accurately fits spectra from filters containing nonuniformities and excess reflection, and provides us with a good measure of the sensitivity of the filter characteristics to practical restrictions.

The application of these concepts in electronically tunable filters and frequency-stable, low-threshold DFB laser diodes is currently under investigation.

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IX. TIME-RESOLVED SPECTROSCOPY OF CONDENSED MATTER

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Joint Services Electronics Program (Contract DAAG29-78-C-0020)

J. David Litster

1. MICROVISCOSITY IN GELS AND POLYMER SOLUTIONS

Fluorimetry has long been used as a tool to study biological molecules and much more information can be obtained when the fluorescence depolarization is studied as a function of time after a short light pulse. These tools have had much more limited applications to the study of synthetic polymers and gels. Monitoring the dichroism as a function of time induced by a mode-locked laser pulse provides as much or more information as the above techniques and permits greatly improved time resolution. Traditionally nonradiative energy transfer has been studied by measuring the fluorescence yield, but time-resolved spectroscopy can be used to measure the nonradiative lifetime directly.

We have carried out a series of experiments using the laser dye oxazine-4 as a probe of microviscosity in gels made with collagen polymers dissolved in mixtures of water and methanol. A gel is formed when the polymers become cross-linked to form a continuous network. With collagen this cross linking is due to hydrogen bonding, and thus a reversible gel-sol transition occurs around 27°C. The macroscopic viscoelastic behavior of the gel is determined by the elastic modulus of the polymer network and a frictional coefficient with the fluid medium; the latter is determined by the local viscosity of the fluid and a correlation length for polymer density fluctuations. We used the reorientation time of the dye molecules (measured by the decay of induced dichroism) as a probe of the local viscosity. Measurements of this reorientation time in solvents (without polymer) consisting of mixtures of methanol and water as a function of temperature showed the times to scale closely with the solvent viscosity calculated from the mole fractions of water and methanol and the viscosity of the pure solvents. The results of a series of experiments as a function of temperature for a series of collagen gels gave the following results. In pure water the dichroism decay at 50°C was 15% faster than one would expect from scaling the viscosity; we believe this results because the decay is a competition between reorientation and decay of the excited state of the molecules,

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Table IX-1. Ratio of dichroism decay in gel to pure solvent.

Fraction Collagen	298°K	303°K	313°K	323°K
0	1.000	1.000	1.000	1.000
2%	1.072	1.023	1.146	1.145
4%	1.174	1.178	1.281	1.296
6%	1.256	1.240	1.349	1.401
8%	1.372	1.341	1.521	1.553

and the latter is also temperature-dependent. This effect can be normalized out by taking the ratio of decay times in the gel to those in pure solvent at each temperature. Table IX-1 gives results for four different collagen gels in pure water. In this system the gel exists below 300°K. The conclusions are that the local viscosity in the gel is to a first approximation the same as that of the pure solvent. The longer decay in gels as the polymer concentration increases shows that reorientation is hindered by interaction with the polymer chains; this hindering becomes more pronounced well above the gel transition where the interaction between polymers is less important. A quantitative measure of this effect is seen in Fig. IX-1 which shows dichroism decay for oxazine dissolved in methanol in free solution (τ = 97 ps) and in the 40 Å pores of Vycor glass (τ = 129 ps); the latter dichroism does not decay to zero in 500 ps because molecules bound to the Vycor cannot reorient. The curve also provides a quantitative measure of the fraction of dye molecules bound to the Vycor (37% at 20°C).

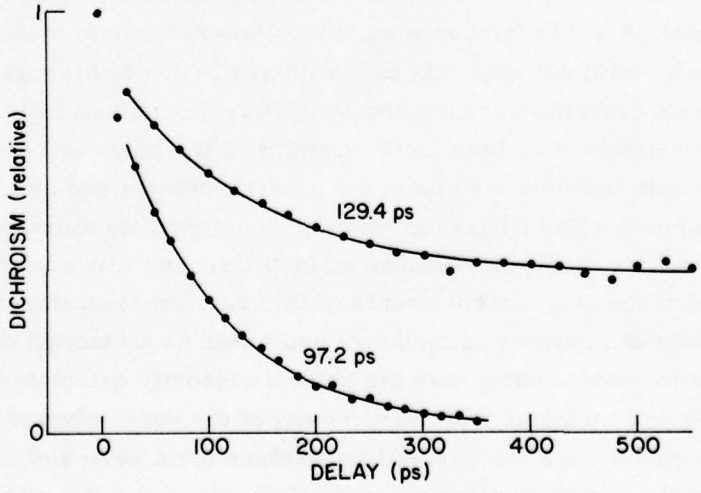

Fig. IX-1. Dichroism decay of oxazine-4 in methanol at 20°C. (Upper curve in Vycor glass.)

These preliminary results show that interesting information can be obtained about gels and polymers, and an article is in preparation. Other experiments in which dyes or fluorescence quenchers are bound to the polymers to reveal details of polymer chain motion will be carried out.

2. MOLECULAR MOTION IN CRITICAL MIXTURES

The motion of molecules in critical mixtures can, in principle, be studied by light scattering. In practice, strong quasi-elastic scattering can make the experiments difficult or nearly impossible. Time-domain spectroscopy should alleviate these problems. We have been able to measure the reorientation of nitrobenzene by means of the optical Kerr effect and are engaged in a study of the critical slowing down of orientational motion in nitrobenzene-n-hexane mixtures.

3. EQUIPMENT CHANGES

During the past year, the stability of our mode-locked laser was improved to the point where integration times of several hours are possible. The experiment is now operated by a PDP 11/03 computer which analyzes the results on-line. A real-time pulse-width measuring device was constructed to facilitate alignment. An N_2 laser-pumped amplifier is under construction to permit Kerr-effect measurements in a wider variety of materials (e.g., liquid crystals).

X. 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)

Dirk J. Muehlner, Peter A. Wolff, Kathleen Kash, Muhammad A. Khan, Roosevelt People

Studies of resonant, spin-induced, four-photon mixing in (Cd, Hg)Te are continuing. Some time ago, we reported the observation of several distinct spin resonances in our (Cd, Hg)Te sample – a result which indicated that the crystal is inhomogeneous. This experiment is now being used by the Honeywell group as an analytic technique to determine g-value and alloy composition as a function of position in (Cd, Hg)Te. In our work, we have concentrated on homogeneous portions of the (Cd, Hg)Te crystals, which show exceedingly sharp spin resonances. At higher laser powers (in the 500 W/cm^2 range) the four-photon resonances broaden and saturate in a manner similar to that observed in n-InSb. The values of the spin-relaxation times, T_1 and T_2, that we infer are comparable to those measured in InSb. Finally, at the highest laser powers the spin line splits in a quite unexpected way. We suspect that the sideband is a Rabi frequency, induced by coherent oscillation of carriers between the conduction and valence bands. Calculations to test this hypothesis are in progress.

We have made extensive studies of carrier excitation[1] – from donor levels to the conduction band – as n-Ge is irradiated by intense (10.6-μ) laser beams. In cold n-Ge crystals, the optical absorption decreases markedly (by more than a factor of 10) in the power range 100 kW-10 MW/cm^2. A kinetic model, which balances the photoionization rate from 1s levels against the rate of carrier recombination with donors, gives an excellent fit to the data. This experiment determines photoionization cross sections, the donor recombination cross section as a function of carrier temperature, and the thermalization rate of hot carriers in n-Ge.

Studies of resonant, impurity-induced, four-photon mixing in n-Ge and n-Si are continuing. During the past year, we have observed[2,3] resonances in the third-order nonlinear coefficient caused by impurity levels in Si – the resonance being at the valley-orbit splitting energy of the donor levels. To date, the impurity resonances in these

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four-photon mixing experiments have been studied by step-tuning the CO_2 lasers. More precise data can be obtained by sweeping the impurity levels with magnetic field. These experiments, which are now under way, will determine:

i. magnetic structure of donor levels in n-Ge and n-Si;

ii. precise linewidths of valley-orbit transitions;

iii. excitation transfer rates between donor levels.

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XI. MICROWAVE AND MILLIMETER WAVE TECHNIQUES

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1. FLUCTUATIONS IN NONLINEAR SYSTEMS

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Madhu S. Gupta

During the year 1978, the study of thermal fluctuations in physical systems led to the following four principal achievements:

a. Thermal Noise in Driven Nonlinear Systems

A new theorem expressing the spectrum of thermal fluctuations in terms of the phenomenological response of the system has been proved. It is more general than the so-called fluctuation-dissipation theorem, in that it applies to nonlinear systems, subjected to a stationary driving force.[1] In an attempt to understand the scope of the theorem, a considerable amount of effort was devoted to explicitly stating the assumptions inherent in the method of proof, and to exploring the necessity of those assumptions. Applications of the theorem to electron devices are presently being studied and will be published later.

b. Hot-Electron Diffusivity in Two-Valley Semiconductors

Thermal velocity fluctuations in a two-valley semiconductor were studied by an analytical random-walk model of carrier scattering. This study resulted in the calculation of the electric-field dependent longitudinal diffusivity of charge-carriers, a transport parameter of considerable importance in high-frequency semiconductor devices. The random-walk model has the novel feature that it models carrier motion in terms of two simultaneous random walks, which are coupled. The calculated results for GaAs agree well with the available experimental data on diffusivity.[2]

c. Ultimate Limits to Nonlinearity of Lossless Energy-Storage Systems

A study of the equilibrium thermal fluctuations of an extensive variable in an ideal, lossless, energy-storage system led to the hitherto unknown fact that the nonlinearity of such a physical system is thermodynamically limited. An upper and a lower bound

were established for a measure of nonlinearity of the system. The bounds were illustrated through the example of varactor nonlinear capacitors. Such bounds are of theoretical interest in studies of the fundamental limitations of physical devices.[3]

d. Fluctuations and Dissipation in Information Processing

A one-bit information storage system is modeled as a bistable equilibrium thermodynamic system, with one nonthermal, conserved extensive parameter serving as the information-bearing degree of freedom. The system is assumed to be in contact with a thermal reservoir which serves to induce randomizing fluctuations within a state but does not cause jumps between the two stable states. Such a system is shown to be necessarily nonlinear, energy-storing, and dissipative during switching.[4] Energy dissipation during a state change of the system, caused by a flow of the extensive variable, is calculated by adding the components due to the irreversibility of flow and due to the necessity of determining the state of the system prior to state change. The minimum dissipation required is approximately 2 kT per switching operation and occurs when approximately 2 bits of information is obtained about the state of the system. It is emphasized that this dissipation is not confined to the information storage system itself, and therefore the heat to be removed from the system may be lower.

e. Microwave Devices

Two other papers, describing the work of the previous year, were prepared for publication during this year.[5, 6]

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2. THE M.I.T. THREE-ELEMENT MICROWAVE INTERFEROMETER

National Science Foundation (Grant AST77-26896)

Bernard F. Burke, Barry R. Allen, J. Antonio Garcia-Barreto,
Perry E. Greenfield, Charles L. Bennett, Charles R. Lawrence

The M.I.T. aperture-synthesis microwave interferometer consists of two fixed and one movable 5.5-meter paraboloids suitable for wavelengths as short as 7 mm. The antenna separations are east-west, and range between 9 and 300 meters. At the current operating frequency of 22 GHz, these correspond to spacings between 680 and 23,000 wavelengths.

The 22-GHz radiometers are conventional regulated ambient-temperature diode mixers fed by circular polarizers. The bandwidth is 75 MHz, and the double-sideband noise temperature is approximately 600 K. The IFs are sampled at 150 MHz by ECL comparators, and are correlated and summed in eight parallel streams at 18.75 MHz in a three-level scheme. Digital delays between 6.7 and 853.3 ns in 6.7-ns steps are accomplished by multiplexers and latches at 150 MHz and by shift registers clocked at 18.75 MHz. Additional cable delays of 0.83, 1.67, and 3.33 ns are used to keep the system response within 1 percent of optimal. A Nova 820 minicomputer controls the pointing of the antennas, steps the delays, interrogates the correlators, performs a real-time fit to the fringes, and writes the results on magnetic tape.

The interferometer has recently been brought into operating condition, and we are beginning to take data toward aperture synthesis. Panel adjustments in two of the dishes have resulted in substantial increases in antenna efficiency, which we now measure to be approximately 0.50. The antenna pointing scheme has been revised. Corrections for azimuth zero-point, gear-ratio, and collimation error and for zenith gear-ratio and collimation error are now made by real-time computer evaluation of empirically determined correction formulae. This replaces a table lookup procedure which resulted in unacceptably large pointing discontinuities at some positions in the sky. Further improvements in the operating system which are under way include extension of its unmanned operating capability to permit an arbitrarily long sequence of sources to be observed automatically.

The processing of visibility data from the interferometer will be accomplished by a combination of M.I.T. and NRAO programs on the M.I.T. IBM/370 computer. The M.I.T. software performs minor corrections related to the real-time fringe fitting. The NRAO-VLA package (kindly provided by Dr. Eric Greisen) has been modified for our site, antenna configuration, and computer. This package of programs is especially well suited to our system since, like the VLA, we have alt-az mounted dishes and employ circular polarizers. Adaptation of these programs is being completed, and debugging is beginning. Preliminary working versions of the M.I.T. programs exist in

Fortran, but these will be translated into PL/I for compatibility with the VLA package. This development has value for other programs as well, since we are making extensive VLA studies, and will be doing much of the processing in-home eventually.

Our first goal is to produce a high-quality map of the supernova remnant Cassiopeia A. One year ago, as we began this project, a number of subtle flaws in the system were uncovered, and we are confident that they are now all fixed. During the summer of 1978, a study of Saturn and its rings was made, and we derived an upper limit of 25° for the apparent brightness temperature of the map. Amplitude stability of the system was clearly a problem in these measurements, which would otherwise have produced a more interesting measurement. During the fall and winter of 1978 the problems were grappled with, and the system is ready to go. We built circularly polarized feeds for the system, which makes the separation of total-power distribution and linear-polarization distribution far more tractable for strongly polarized sources such as Cas A.

Calibration data are currently being taken with the system. The phase stability of the system has always been good (3° repeatability day-to-day), and the synthesis of Cas A should proceed during the summer and fall of 1979. A total-power map will first be derived, followed by a polarization map. The resolution of the maps will be comparable to that of the best studies made at longer wavelengths. By studying the degree of polarization at the shorter wavelength, compared to the more depolarized and Faraday-rotated longer wavelength studies, we should be able to make a detailed study of magnetic-field strength and geometry in the remnant. We also plan to map the compact H II region DR21, which requires relatively few interferometer spacings for a complete map.

The next step in the interferometer work will be to change the frequency to 43 GHz. While we could continue working at 22 GHz, we have developed a high-quality cooled mixer for 43 GHz that is described in our new NSF research proposal. Millimeter-wave interferometry is a largely unexplored field, and while some interesting work will remain at 22 GHz, many of the more attractive possibilities will be better studied by the VLA. (Cas A is not a practical VLA target, and is much better suited to our small system.)

In view of our greatly improved system noise temperature at 43 GHz, a change in observing frequency at the close of the Cas A synthesis work is indicated. At the same time, we are developing a 100-channel crosscorrelator that should also be ready for use in early 1980. Studies of SiO radiation will be made with the system, but continuum and other line sources will also be studied.

There is a philosophical point that should be made concerning the interferometer. If we chose to make it the major focus of our observing program, concentrating our five graduate students, three engineers, and one or two postdoctoral graduates on the project, it would proceed at a far more rapid pace. It would not then be a small project, however, and the major thrust of our graduate student training and research program

would be drastically changed. As it now stands, the interferometer project represents an incremental cost to the program of about $70,000 per year, since the engineering force is also used for other developmental programs, such as building new front ends and observing hardware for VLBI experiments. Most of the hardware in recent years has come from M. I. T. private funds, and the result has been to provide a unique training ground for students. Our graduate students have always been in high demand, since they are familiar with hardware and software, and are experienced in the use of major national facilities. The interferometer gives a truly effective introduction to the real world of instruments, without which there would be no observing. It thus justifies its existence both as a teaching tool and as a driver for new research. We have developed the fastest correlator presently in use in radio astronomy, and future state-of-the-art developments will continue.

XII. MICROWAVE DEVICES EMPLOYING MAGNETIC WAVES

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Prof. Robert L. Kyhl
Dr. Aryeh Platzker
Dale A. Zeskind

Graduate Students

Peter N. Horowitz
Leslie M. Itano
Daniel D. Stancil
Nickolas P. Vlannes

1. MAGNETIC-GRADIENT LOCALIZED MAGNETOSTATIC RESONANCES

Joint Services Electronics Program (Contract DAAG29-78-C-0020)
National Science Foundation (Grant ENG76-18359)

Peter N. Horowitz, Frederic R. Morgenthaler, Robert L. Kyhl, Dale A. Zeskind

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

We have now solved and presented in an invited paper,[1] at the 1978 Intermag Conference held in Florence, Italy during May 1978, the eigenvalue problem governing two-dimensional magnetostatic mode propagation in thin ferrite disks when the dc magnetic field, H_z, is normal to the plane and varies radially as

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

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

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

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by the magnitude of the dc gradient. All of the $B \neq 0$ modes have nonzero volume divergence of the small-dignal RF magnetization. For the gradient-bound modes the divergence is very large at or near the track.

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

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

John J. Cooley[2] completed his study of bound modes in thick single YIG disks, and on September 12, 1977 submitted a thesis entitled "Magnetostatic Modes Bound by dc H-Field Gradients" in partial fulfillment of the requirements for the degrees of Master of Science and Electrical Engineer. A summary of his thesis follows:

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

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

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

finding the eigenmodes of a general circularly symmetric internal-field profile was discussed and a computer algorithm implemented. The computer-generated eigenmodes are ϕ-directed and bound to circular tracks of constant radii. Families of eigenfrequencies which vary linearly with applied dc magnetic field at the rate of 2.8 MHz/Oe exhibit multiple degeneracies which suggests the possibility of multiplets. The widths of the experimentally observed modes spectra (approximately 1.5-2.0 GHz) agree qualitatively with computer-generated mode spectra.

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1. F. R. Morgenthaler, "Bound Magnetostatic Waves Controlled by Field Gradients in YIG Single Crystals and Epitaxial Films," IEEE Transactions on Magnetics, Vol. MAG-14, pp. 806-810, September 1978.

2. J. J. Cooley, "Magnetostatic Modes Bound by dc H-Field gradients," S. M. and E. E. Thesis, Department of Electrical Engineering and Computer Science, M. I. T., September 1977.

2. MAGNETIC RESONANCE IN THIN FILMS CONTAINING MAGNETIC BUBBLES

National Science Foundation (Grant ENG76-18359)

Frederic R. Morgenthaler

The abstract of a paper[1] presented at the 24th Conference on Magnetism and Magnetic Materials, Cleveland, Ohio, November 14-17, 1978 follows:

We have recently discussed magnetostatic modes in a normally magnetized, thin-film disk that are bound to "virtual-surfaces" created by the presence of a radial dc-field gradient; the frequency and polarization of such modes was found to be a sensitive function of the gradient. We now employ a similar method of analysis to study two-dimensional resonance modes in a thin film containing a single magnetic bubble. When the thickness of the bubble-domain wall is ignored, and there is no applied gradient, the spectrum, as expected, contains single-bubble resonances coupled to disk resonances. However, actual domain walls contain large anisotropy field gradients due to the often complex spin-reversal pattern. Such gradients will affect the mode polarization within the wall and the effective boundary conditions acting across the wall may be significantly altered for those resonances coupled to exchange modes within the domain wall. The related but simpler problem of RF exchange modes generated at a plane "virtual-surface" within a single-domain region is studied in detail.

References

1. F. R. Morgenthaler, "Two-Dimensional Magnetostatic Resonances in a Thin-Film Disk Containing a Magnetic Bubble," presented at the 1978 Conference on Magnetism and Magnetic Materials, Cleveland, Ohio, November 14-17, 1978.

3. OPTICAL DETECTION OF LOCALIZED MAGNETOSTATIC RESONANCES

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Nickolas P. Vlannes, Frederic R. Morgenthaler

The doctoral thesis of Nickolas P. Vlannes, now in the initial phase, will deal with optical detection of localized magnetostatic resonances in thin LPE films of yttrium iron garnet (YIG).

The experiments will make use of our existing Spectra Physics 125 laser tuned to 1.15 μm and new optical detectors capable of responding to approximately 2-GHz modulation rates. A new optical table has been installed and the microwave portions of the setup are currently being planned.

4. VARIABLE-SPEED MAGNETOSTATIC MODES IN UNIFORM OR NONUNIFORM DC H FIELDS

Joint Services Electronics Program (Contract DAAG29-78-C-0020)
National Science Foundation (Grant ENG76-18359)

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

The S. M. thesis of Peter N. Horowitz[1] concerned the control of magnetostatic surface-wave group velocity on a sandwich structure composed of two ferrite rectangular slab crystals separated by an adjustable air gap. This geometry, suggested by Tsutsumi, is a valuable one in which to study fundamental wave properties and material constants. The thesis also contains preliminary results of magnetic wave propagation in thin films immersed in nonuniform magnetic fields. The abstract follows:

Magnetostatic modes of bulk rectangular slabs and thin films of single-crystal yttrium iron garnet (YIG) are studied both theoretically and experimentally. Delay times of up to 300 nsec (a group velocity as slow as 7.6×10^{-4} c) are reported for magnetostatic surface waves propagating along a structure composed of two 1-mm × 5-mm × 7-mm slabs of YIG separated by an adjustable air gap (3 to 15 mils) between two of the 5-mm × 7-mm faces and magnetized normal to the 1-mm × 5-mm faces. High-quality thin films (5 microns thick) of YIG are transversely magnetized and

nonreciprocal magnetostatic surface waves with delay times of up to 280 nsec are observed with integrated-circuit microstripline antennas spaced 0.1 inch apart. The cutoff dc H fields of these modes are measured and found to be close to theoretical values. Surface modes for a transversely magnetized thin film are again shown to exist for only certain angles, $\theta \leq \cos^{-1}[(\omega_o/(\omega_o+\omega_M))^{1/2}]$, between the plane of the film and the internal dc H field.

Two pole pieces were made to create a spatially nonuniform dc H field of the form A + Bx normal to the plane of the film. Gradients of from 110 to 145 Oe/mm were tried but only weak coupling resulted. With only the bottom pole piece in place (an in-plane component of the dc magnetization is expected), strong coupling was observed to nonreciprocal modes. Delay times of up to 320 nsec along 0.1 inch of YIG film are observed.

References

1. P. N. Horowitz, "Variable Speed Magnetostatic Modes in Uniform or Nonuniform dc H Fields," S. M. and E. E. Thesis, Department of Electrical Engineering and Computer Science, M. I. T., September 1978.

5. MAGNETOELASTIC YIG DELAY LINES

Joint Services Electronics Program (Contract DAAG29-78-C-0020)
National Science Foundation (Grant ENG76-18359)

Aryeh Platzker, Leslie M. Itano, Frederic R. Morgenthaler

An overview of our recent work[1] on magnetic field synthesis procedures for magnetostatic and magnetoelastic devices was given in an invited paper at the 1978 International Symposium on Circuits and Systems in New York, May, 1978. The abstract follows:

Certain types of magnetostatic and/or magnetoelastic devices require nonuniform dc bias fields of sufficient strength to locally saturate the active ferrite element.

We here review a synthesis procedure for cylindrically symmetric geometries that allows prespecification of the field on the symmetry axis or on a plane perpendicular to it.

The method is then applied to the cases of both a thin-film disk magnetized normally to its plane and microwave magnetoelastic delay line designed for linear-frequency dispersion over wide bandwidths.

Finally, we report construction details and test data on an actual packaged device having greatly improved characteristics. Measured parameters for two-port operation at S-band over a 1-GHz bandwidth include a linear dispersion factor D = 0.3 nsec/MHz

and an insertion loss (untuned) of 27-30 dB.

References

1. F. R. Morgenthaler and A. Platzker, "Magnetic Field Synthesis Procedures for Magnetostatic and Magnetoelastic Devices," Proceedings of the IEEE International Symposium on Circuits and Systems, New York, May 17-19, 1978, p. 574.

6. MAGNETOSTATIC ENERGY OF STRIPE DOMAIN PATTERNS

National Science Foundation (Grant ENG76-18359)

James H. Spreen, Frederic R. Morgenthaler

Results of the doctoral thesis[1] research of James H. Spreen were presented at the 1977 Conference on Magnetism and Magnetic Materials in Minneapolis,[2] and have been published in the Journal of Applied Physics (September 1978).[2]

References

1. J. H. Spreen, "Magnetic Domain Wall Motion Studied Using Optical Diffraction," *Ph. D. Thesis, Department of Electrical Engineering and Computer Science*, M. I. T., June 1977.

2. J. H. Spreen and F. R. Morgenthaler, "Magnetostatic Energy of Stripe Domain Patterns," presented at the 1977 Conference on Magnetism and Magnetic Materials, Minneapolis, Minnesota, November 8-11, 1977; published in J. Appl. Phys. 49, 1590-1591 (1978).

XIII. MICROWAVE THERMOGRAPHY

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Graduate Students

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1. MICROWAVE THERMOGRAPHY

National Institutes of Health (Grant 5 ROl GM20370)

Alan H. Barrett, Philip C. Myers

We have continued to develop and evaluate microwave radiometers for clinical detection of breast cancer. In collaboration with Dr. N. L. Sadowsky of Faulkner Hospital we have examined more than 70 women with breast cancer confirmed by biopsy and more than 5000 normal women, using a 3.3 GHz radiometer. We also examined more than 25 women with breast cancer and more than 1000 normal women, using a 1.3 GHz radiometer. A simple quantitative criterion of detection relies mainly on temperature asymmetry between the right and left breasts. With this criterion, observation at each frequency gives detection of about 70% of the cancers and a "false alarm" rate of about 30%. Each of these rates is similar to the corresponding detection rate of infrared thermography on the same set of patients. When the 3-GHz and infrared data are combined, the resulting cancer detection rate exceeds 90%. If microwave and infrared examinations are used as a zero-risk first-pass screen, and if mammography is used only as a follow-up of positive cases, then the resulting detection rate is about 90% and the false alarm rate can be about 15%. These results are the same as those of a program of mammography screening alone, but the number of women exposed to x-rays is reduced by more than half. Thus the combined use of safe methods such as microwave and infrared examinations for breast cancer screening appears to be a distinct possibility.

Our equipment development and testing work has continued. We have completed and installed in Faulkner Hospital 6-GHz tissue-matched antennas, a 6-GHz low-noise radiometer, and a microprocessor-based data handler. Data reduction is done in real time and a hard copy of the microwave results becomes a part of the patient's records.

XIV. RADIO ASTRONOMY

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Prof. David H. Staelin
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1. LONG-BASELINE ASTROMETRIC INTERFEROMETER

National Science Foundation (Grant AST77-06052)

Michael Shao, David H. Staelin

This year the one-inch interferometer facility was completed and transported to the Mt. Wilson Observatory in California, where initial experiments were performed. This system has a baseline of ~2 meters and tracks Polaris. The purpose of the system is to demonstrate the basic concept of two-color fringe tracking, which should eventually enable relative stellar positions to be measured with $\sim 10^{-4}$ arc-sec accuracy. Such accuracy is sufficient to detect any Jovian planets orbiting nearby stars.[1]

These initial experiments have been successful. Using one-half inch apertures Polaris was tracked continuously with 2 arc-sec seeing, and intermittently with 3.5 arc-sec seeing.

Future work will include two-color tracking experiments with a 10-meter baseline, and use of siderostats so that stars other than Polaris can be observed. Such experiments would be a prelude to establishment of a permanent four-inch observatory capable of measuring positions of 10^{th}-magnitude stars.

References

1. M. Shao and D.H. Staelin, "Long-Baseline Optical Interferometer for Astrometry," J. Opt. Soc. Am. 67, 81-86 (1977).

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2. CONTROLLED THIN-FILM ANTENNA

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

David H. Staelin, James R. Melcher

The use of a scanning electron beam for rapidly manipulating the charge distribution on a thin membrane is being studied as a method for precisely controlling the shape of very large (30- to 1000-m) reflector antennas in space.[1]

The work progressed on three fronts in 1978. First, the theoretical effort has focused on the issues of electrostatic instabilities and algorithms for control. Second, to test these theories a 1-meter square membrane has been stretched on a frame between plates, the potentials of which are controlled at nine points independently. To date the basic modes have been observed, together with their stability and cross coupling. Also, the 1, 1 mode has been biased to instability and then controlled. Third, an apparatus is nearly constructed which will enable the front and back-side secondary-emission characteristics of various metals and insulators to be studied as a function of beam energy and surface contaminants.

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1. J. Lang, J. Gersh, and D. H. Staelin, "Electrostatically Controlled Wire-Mesh Antenna," Electronics Letters 14, 665-666 (1978).

3. SCANNING MICROWAVE SPECTROMETER EXPERIMENT

National Aeronautics and Space Administration (Contract NAS5-21980)

David H. Staelin, Philip W. Rosenkranz

The five-channel Scanning Microwave Spectrometer (SCAMS) yielded 10 months of almost continuous data from the Nimbus-6 satellite, launched in June, 1975.[1]

Analysis of Typhoon June (1975) has shown that passive microwave soundings can yield wind information in two ways, by virtue of the enhanced surface emissivity due to foam and rough seas, and by means of the observed horizontal temperature gradients which are related to winds by the thermal wind equation.[2] These studies also demonstrated that such soundings can yield reasonable water vapor and liquid water estimates in these intense storms.[2]

Kalman filtering was applied successfully to the problem of temperature profile retrievals; the rms errors were reduced by as much as ~50 percent, with moderate improvements being more typical.[3]

Snow and ice observations have been analyzed at some length, and three manuscripts

are now in preparation.

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3. W. H. Ledsham and D. H. Staelin, "An Extended Kalman-Bucy Filter for Atmospheric Temperature Profile Retrieval with a Passive Microwave Sounder," J. Appl. Meteorol. 17, 1023-1033 (1978).

4. TIROS-N SATELLITE MICROWAVE SOUNDER

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

David H. Staelin, Philip W. Rosenkranz

The first Tiros-N Satellite was launched October 13, 1978, and the second unit is scheduled for launch in 1979; these operational weather satellites each incorporate four-channel passive microwave spectrometers operating in the 50-58 GHz band. The resulting microwave maps of atmospheric temperature profiles complement the maps by the other spacecraft sensors. This research program focuses on development of an improved understanding of the limits to performance of these microwave sensors and the development of high-performance estimation procedures appropriate for handling the effects of precipitation, clouds, and the surface, as well as the nonlinear, non-Gaussian, and nonstationary character of the statistics.

Initial analysis of the data has revealed that the instrument performance is excellent. Software to analyze the scientific results is now being prepared.

5. SCANNING MULTICHANNEL MICROWAVE RADIOMETER (SMMR) EXPERIMENT

National Aeronautics and Space Administration (Contract NAS5-22929)

David H. Staelin, Philip W. Rosenkranz

The two SMMR passive microwave instruments were launched June 26, 1978 on the Seasat satellite, and October 24, 1978 on the Nimbus-7 satellite. The Nimbus-7 SMMR scans the earth over a ~780-km swath with resolutions of ~20-150 km, depending on frequency. The instruments view the earth at a constant incidence angle of 50 degrees, at two orthogonal linear polarizations and five frequencies: 6.6, 10.7, 18, 21, and 37 GHz.

Parameters that can be mapped for the first time by this instrument include sea surface temperature and roughness, and certain snow, rain, ice, and humidity parameters. The effort to develop improved geophysical analysis techniques centers on the development of improved physical models for the phenomena and improved estimation techniques that appropriately reflect the nonlinear and nonstationary character of the problem.

One of the critical issues in the data interpretation process arises from the frequency-dependent angular resolution of the sensors. An approach to this problem has been developed and described.[1] This procedure takes proper account, in a least-squares sense, of the three-dimensional statistical behavior of the physical phenomenon and of the frequency-dependent character of the sensor.

References

1. P.W. Rosenkranz, "Inversion of Data from Diffraction-Limited Multiwavelength Remote Sensors. I. Linear Case," Radio Sci. 13, 1003-1010 (1978).

6. METEOROLOGICAL REMOTE SENSING NEAR 2-mm WAVELENGTH

National Aeronautics and Space Administration (Contract NAS5-23677)

David H. Staelin, Philip W. Rosenkranz

The 118-GHz radiometer system was operated aboard the CV-990 aircraft for the Summer Microwave Hurricane Program (SMHP) during the summer and fall of 1978. Brightness temperatures were measured looking downward at clear atmosphere and rain cells and also upward at rain cells.

The clear air data were inverted using a linear statistical method of multidimensional regression. The inferred temperature profile was compared with the profile measured by a dropsonde released from the aircraft. Agreement between the two profiles was within the expected error in the retrieval procedure, ~1 K. This is the first temperature profile retrieval to be obtained using the 118-GHz oxygen line.

7. MICROWAVE SPECTROSCOPY OF THE INTERSTELLAR MEDIUM

National Science Foundation (Grant AST77-12960)

Alan H. Barrett, Philip C. Myers

During the past year our studies of atomic and molecular interstellar gas clouds have continued, with observations of microwave transitions of HI, CO, CS, NH_3, H_2CO, and HC_5N, toward Bok globules, dark clouds, molecular clouds associated with HII

regions, and globular clusters. We have used radio telescopes of the National Radio Astronomy Observatory in Green Bank, West Virginia, and at Kitt Peak, Arizona; National Astronomy and Ionosphere Center in Arecibo, Puerto Rico; Millimeter Wave Observatory, Fort Davis, Texas; and of M.I.T. Haystack Observatory.

Observations have been made of HC_5N, NH_3, and CO emission from a number of small dense clouds in Taurus which form a streamer. The NH_3 emission was found to exhibit a wide range of intensity variation from cloud to cloud, by a factor of ~10. The velocity width is very small, typically ~0.5 km s^{-1}. The HC_5N emission was detected only in one cloud, TMC-2, where the width is extremely narrow, ~0.2 km s^{-1}. The CO observations indicate that the dense clouds have temperature 10-15 K. In TMC-2, the small size (~0.1 pc) and linewidth of the HC_5N region suggest that this dense clump may be a nearly stable prestellar condensation.

8. RADIO ASTRONOMY STUDIES OF INTERSTELLAR MASERS, THE INTERGALACTIC MEDIUM, AND EXTRAGALACTIC SOURCES

National Science Foundation (Grant AST77-26896)

Bernard F. Burke, Robert C. Walker, Aubrey D. Haschick, Thomas S. Giuffrida, J. Antonio Garcia-Barreto

The principal aims of this research have centered on the properties of the interstellar medium. In our own galaxy, the emphasis was on the properties of interstellar masers, which are closely related to stars in their earliest stages of formation. The extragalactic studies concentrated on the properties of the interstellar gas in Seyfert galaxies and in the intracluster medium in clusters of galaxies.

The maser work emphasized the use of VLBI methods to map the maser complexes, which consist of clusters of individual spot sources, each at its own velocity. As part of his Ph.D. thesis, Robert C. Walker showed that the apparent size of a given spot is a strongly varying function of the observing frequency within the line. Near the line center, the apparent size is smaller than in the wings of the line, and no model is in full agreement with the data. A saturated maser model is closer to the data, however, than an unsaturated model. A study of the OH maser in W3OH, the observations having been taken two years previously in a 7-station VLBI experiment, finally neared completion. Aubrey D. Haschick, working with M. Reid of the NRAO, produced a detailed map of the region that strongly suggests multiple Zeeman pairs. Some work remains to be done on the enormous quantity of data that had to be reduced, but the principal task is now complete.

A discovery was made in the W3OH water maser of a strongly time-varying line that was followed through its entire development, and three VLBI experiments were

performed to clarify the results. The H_2O complex is in the form of a well-defined arc, plus a few outlying sources. One of the sources in the arc came up from a low intensity over a one-week period, and then declined over the following month. The light curve appears to be fitted accurately by a simple phenomenological theory, but the implication is that a large amount of pump energy, 10^{40} ergs or more, had to be released within one or two days. Star-formation processes may well involve such unexpected irregularities, but the current state of cosmogonic models lacks predictive power fur such irregular phenomena, which may be caused by magnetic-field merging.

The study of the intracluster medium resulted in stringent upper limits to the quantity of neutral hydrogen inside clusters of galaxies. A total of 15 nearby clusters were studied by looking for hydrogen absorption lines against background radio sources. The observed upper limits on the density are several orders of magnitude below the density needed to bind the clusters or close the universe.

Work with the Very Large Array (VLA) of the NRAO in Socorro, New Mexico has begun, and several programs have been carried out that were designed, in part, to help with development of the equipment. The x-ray source associated with the galaxy NGC 2110 was identified quickly, and the coincidence of the radio source with the nucleus of the galaxy was established. The source has a 3 arc-second size and a normal radio spectrum.

The extensive program on hydrogen absorption lines in galaxies was completed by Aubrey D. Haschick in his Ph.D. thesis. Several examples of absorption lines in quasar/galaxy pairs were studied, absorption lines in Seyfert galaxies were discovered, and an unusual example of an absorption line in the radio source 2C178 was also discovered. Absorption lines in Seyfert galaxies appear to be a moderately common phenomenon.

The microwave aperture-synthesis interferometer was completed during the report year. The "debugging" operations are proceeding, and useful observations will be expected after approximately one year of engineering studies. At the same time, we are developing a cooled 7-mm mixer that should be useful for interferometric observations.

XV. ELECTRODYNAMICS OF MEDIA

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1. ELECTROMAGNETIC WAVES

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Jin Au Kong

Electromagnetic waves are studied with applications to remote sensing of the earth, geophysical subsurface probing and communication with a dipole antenna, microstrip antennas, and beam diffraction by periodic structures. We also studied acoustic waves in geophysical exploration. Papers on research in the past year which have been published, accepted for publication, submitted for publication, or presented at meetings are listed in the references.[1-14] Second-order coupled-mode equations have been developed to treat diffraction of plane waves as well as beams by periodic structures.[1-3] Geophysical probing and communication with dipole antennas has been studied for half-space and two-layer media.[4-6] Microstrip antennas are being studied.[7] Extensive work has been done in the field of active and passive microwave remote sensing.[8-22] The use of acoustic waves in geophysical exploration has been investigated.[23-24]

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2. REMOTE SENSING WITH ELECTROMAGNETIC WAVES

National Science Foundation (Grant ENG76-01654)

Jin Au Kong

Active sensing with dipole antennas has been studied[1-6] for both monochromatic and pulse excitations. Extensive work has been accomplished on theoretical modelling and data interpretation for passive microwave remote sensing with radiometers.[7-22] Active remote sensing with radars has also been investigated.[23-26]

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3. ACTIVE AND PASSIVE MICROWAVE REMOTE SENSING

National Aeronautics and Space Administration (Contract NAS5-24139)

Jin Au Kong

In active microwave remote sensing radiative transfer theory[1-2] has been applied and derived from the wave theory. Energy conservation and asymptotic solution for the reflectivity of a very rough surface are being studied.[3-4] In passive remote sensing theoretical modeling, experimentation, and data matching have been extensively investigated and conclusive results are being documented.[5-11]

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4. PREDICTION OF BACKSCATTER AND EMISSIVITY OF SNOW AT MILLIMETER WAVELENGTHS

U. S. Air Force – Eglin (Contract F08635-78-C-0115)

Jin Au Kong

Radiative transfer theory has been applied to the active remote sensing of half-space random media.[1] The validity of the radiative transfer theory was justified by a rigorous wave theoretical approach.[2] Energy conservation and asymptotic solutions for remote sensing of rough surfaces are being considered.[3-4] Passive microwave remote sensing of snow fields has been extensively investigated.[5-10]

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5. ACOUSTIC-WAVE PROPAGATION STUDIES

Schlumberger Doll Research Center

Jin Au Kong, Leung Tsang

Transient solutions due to a line source in a slab medium have been obtained with a modified modal theory applying the technique of double deformation.[1,2] Asymptotic solutions for the first compressional head wave arrival in a fluid-filled borehole are also being investigated.[3]

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XVI. ELECTRONIC PROPERTIES OF CHARGED CENTERS IN SiO_2-LIKE GLASSES

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Joseph W. Orenstein

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Marc A. Kastner

We have demonstrated that vacuum-ultraviolet excitation of pure silicon dioxide causes luminescence. We believe that the luminescence centers are intrinsic defects. Excitation and luminescence spectra have been measured for suprasil (containing about 10^3 ppm OH) and suprasil W (much lower OH concentration). Since the spectra and quantum efficiency are the same, OH is not important in the luminescence process. The luminescence has a large Stokes shift: the excitation band is approximately 0.8 eV wide, centered at 7.6 eV; the luminescence is approximately 1.5 eV wide, centered at about 4 eV. A 7.6-eV optical absorption band is known to be enhanced by neutron damage, strongly suggesting that it arises from an intrinsic defect. Neutron irradiation of samples to enhance the luminescence is now under way.

PLASMA DYNAMICS

XVII. PLASMA DYNAMICS

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XVII. PLASMA DYNAMICS

A. Basic Plasma Research

1. NONLINEAR WAVE INTERACTIONS

National Science Foundation (Grants ENG77-00340)

Abraham Bers, Kwok C. Ko, Vladimir B. Krapchev, Kim S. Theilhaber, Hossein Baghei, Abhay K. Ram, Thomas M. O'Neil

This research group concerns itself with theoretical studies of large-amplitude waves in a plasma. Thus it impacts on problems of wave propagation, plasma heating, and turbulence in plasmas. The following is a brief summary of accomplishments:

(a) We have completed our study of the nonlinear evolution in space-time of three interacting wavepackets, including the effects of dephasing due to inhomogeneity in the medium. This problem appears in many branches of physics and engineering, and not just in plasma physics. Two comprehensive papers on this work are now completed and scheduled to appear in Reviews of Modern Physics this spring.[1,2]

(b) We have initiated a new kinetic (Vlasov) description of ponderomotive effects in a plasma, and were able to solve some simple problems to all orders in the electric field. These results are particularly applicable to intense laser-plasma interactions, and they predict a new mechanism for the generation of magnetic fields in such interactions.[3-6]

(c) We have achieved a detailed understanding of self-modulation for electrostatic waves in a plasma, including the effects of plasma inhomogeneity. These results are of importance to wave propagation and RF heating of plasmas.[7]

(d) We have completed our study of the linear evolution of the three-wave interaction in a finite-width pump, including the effects of three-dimensional geometry and inhomogeneity.[8] In addition, we have completed the study of the nonlinear evolution of the convective quasi-mode parametric interaction in two and three dimensions.[9] This, like the three-wave problem, is also a universal nonlinear wave-interaction problem. Unlike the three-wave problem which is a second-order wave-wave interaction, the quasi-mode interaction is a third-order interaction (like self-modulation) describing the nonlinear coupling of waves through scattering off of particles.

In the past two years, three Ph.D. theses were completed (A. H. Reiman, J. L. Kulp, and C. C. F. Karney; the last two shared support from DOE). Two postdoctoral research associates (Drs. A. Sen and G. L. Johnston) completed their two-year stay. One foreign postdoctoral research associate (Dr. G. Leclert, University of Nancy, France) spent one year with us, and another one (Dr. M. E. Villalon, University of Madrid, Spain) is currently with us; both are supported primarily by their governments. This year, Professor T. M. O'Neil of the University of California at San Diego, is spending his sabbatical within our group.

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2. RENORMALIZATION METHODS IN PLASMA TURBULENCE THEORY

National Science Foundation (Grant ENG77-00340)

Thomas H. Dupree

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

(XVII. PLASMA DYNAMICS)

3. INTENSE RELATIVISTIC ELECTRON BEAMS

National Science Foundation (Grant ENG77-00340)
U.S. Department of Energy (Contract EY-76-S-02-2766)
U.S. Air Force – Office of Scientific Research (Grant AFOSR-77-3143)

George Bekefi

Three areas of research are now being studied, making use of our pulsed high-voltage facilities, Nereus (voltage 500 kV, current 70 kA, pulse duration 30 nsec) and Pulserad 110A (voltage 1.5 MV, current 20 kA, pulse duration 30 nsec).

Magnetron Design

We are continuing with our studies of the relativistic electron-beam magnetron. These studies include optimization of magnetron design, studies of its frequency spectra, and scaling with voltage and magnetic field. The experimental program goes hand-in-hand with a particle-in-cell computer code developed by us in collaboration with Dr. Adam Drobot at the Naval Research Laboratory.

Free Electron Laser

Experimental and theoretical works are in progress on a novel free-electron laser. In this device the low-frequency pump wave is a spatially periodic, quasi-static electric field obtained by rippling the wall of the drift tube containing the relativistic electron beam.

Reflex Diode

We are studying the dynamics of the electrons in the reflex diode. This diode is comprised of a pinch cathode and a thin-foil anode. The system is immersed in a strong axial magnetic field of 10-20 kG.

XVII. PLASMA DYNAMICS

B. Plasma Research Related to Fusion

1. PHYSICS OF HIGH-TEMPERATURE PLASMAS

U.S. Department of Energy (Contracts ET-78-C-01-3019
and ET-78-S-02-4681)

Bruno Coppi

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

Relevant theoretical and experimental contributions have been presented at national and international conferences or published in professional journals. The primary focus has been on the experimental effort involving the Alcator A and C devices. 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, high current and particle densities and relatively low impurity concentration, have made it one of the most successful confinement experiments in terms of achieving the highest known values of the confinement parameter "$n\tau$" and of realizing a sequence of plasma regimes of basic physical interest. In particular, during 1978 a series of experiments carried out with record low values of the so-called "safety factor" has led to regimes with relatively high plasma currents and modest magnetic fields where the confinement time is improved in comparison to that obtained at the higher values of the "safety factor" that characterize the conventional operation of most toroidal confinement devices.

Experiments on the injection of microwaves at the lower hybrid frequency, which for the system adopted on Alcator A is 2.45 GHz, have been undertaken systematically at power levels of approximately 100 kW. One of the most striking observable effects has been the enhancement of the rate of fusion-neutron emission in deuterium plasmas, by approximately a factor of 30 when compared to the case where there is no injection of microwave power. Therefore it has been possible to verify the dependence of

microwave penetration and energy deposition on different macroscopic parameters, such as the magnetic field, the particle density, and the plasma current.

The Alcator C device was formally dedicated in April 1978, and is now operating with well-confined plasmas and plasma currents of approximately 300 kA. We recall that the reference design value of the total plasma current is 1 megampere and that one of the objectives of Alcator C is to achieve values of the confinement parameter $n\tau$ around 10^{14} sec/cm^3.

A major program on microwave heating of Alcator C was undertaken with the goal of realizing a system for injection of up to 4 megawatts at a frequency of 4.6 GHz. This is in the range of the lower hybrid frequency for the values of the plasma density that are expected to be realized. A parallel program of heating at the ion cyclotron frequency has also been undertaken. The objectives of these efforts are to be able to raise the maximum temperature of plasmas with peak densities of approximately 10^{15} particle/cm^3 above 2 keV and to study their basic confinement properties in conditions where the effectiveness of ohmic heating begins to degrade. The experimental program is integrated with a theoretical effort for the numerical simulation of the plasma regimes that we hope to obtain.

A series of experiments carried out on the FT device at Frascati and on the PLT machine at Princeton have confirmed and extended the results that had been obtained on the Alcator A device since 1974 concerning the nature of the diffusion coefficient for the electron thermal-energy loss. This was, in fact, one of the bases for the transport model and codes that have been developed as a part of our program, and that have been used both to predict the performance of Alcator C and to formulate a research program on α-particle heating by the realization of a series of compact devices. These are generally called Ignitors or Alphators, and represent the natural evolution of the Alcator program into a generation of high particle density, relatively small-dimension fusion reactors. A design study of an Alcator D device along the same line is being undertaken.

The Rector experiment, which was originally developed to study the confinement properties of toroidal plasmas with elongated cross sections, was moved to new and more appropriate quarters. Regular plasma operation has restarted with a series of new diagnostic systems. Remarkable results, in terms of improved equilibrium and stability conditions, have been obtained by converting the basic axisymmetric magnetic configuration of Rector into a Stellarator-like configuration with helical symmetry. A novel distribution of coils has been adopted for this and, given its favorable construction characteristics, we expect that a series of higher performance experiments will evolve from this.

As is traditional with our mode of operation, we have maintained a system of close collaborations with national and overseas institutions for both our theoretical and experimental programs.

2. DYNAMICS OF TOROIDAL DISCHARGES

U.S. Department of Energy (Contract ET-78-S-02-4682)

James E. McCune, Daniel E. Hastings, George M. Svolos

a. Drift Modes in Tori

George M. Svolos, James E. McCune

Our study is focused on the analysis of drift modes and other related low-frequency modes in low-collisionality, "banana" regime, large toroidal systems.

In our approach we will make use of an inertial drift kinetic equation with appropriate choices for the relevant physical parameters of the problem. Insofar as a straight cylinder, even with a helical field, is not the true natural limit of a toroidal magnetic field configuration, toroidal effects are included from the outset.

The systematic study of the cross-flux eigenvalue problem, the effects of shear on the stability of the modes, their localization and the toroidal effects are the central parts of this research. In addition, special attention is given to nonlinear turbulent electron behavior. In particular, we examine the effects that nonlinear stochastic cross-flux electron diffusion close to mode rational surfaces may have on the stability properties and ultimate fate of these modes.

b. Drift Modes in Tandem Mirror Systems

Daniel E. Hastings, James E. McCune

The central cell plasma in the tandem mirror is expected to be high-beta. Hastings (FY '79) developed a general formalism to describe small fluctuations in the high-beta plasma including finite ion Larmor radius effects and has since then set up the corresponding radial eigenmode problem. This has been solved in a WKB sense giving (in the no-shear case) the so-called 'local' approximation. Work in this area is now directed to writing computer programs to numerically locate and track the various low-frequency drift waves as beta is increased.

A complete study of low-frequency drift waves (universal drift mode, temperature-gradient drift mode, etc.) will be made available with the important high-beta physics included.

3. RF HEATING AND NONLINEAR WAVES IN TOROIDAL PLASMAS

U.S. Department of Energy (Contract ET-78-S-02-4682)

Abraham Bers, Kwok C. Ko, Vladimir B. Krapchev, John L. Kulp, Jr., Kim S. Theilhaber, Maria Elena Villalon, Thomas M. O'Neil

The general objective of this research is to explore the use of externally applied electromagnetic power (generically, "RF power") for the supplementary heating and confining of toroidal plasmas. Particular studies are being carried out to determine the heating of tokamak plasmas with microwave power in the lower hybrid range of frequencies, with the results applied to current experiments on Alcator A and Doublet II-A, as well as to experiments in the near future on Versator II and Alcator C.

Our studies have continued to focus on problems relevant to lower hybrid heating of tokamak plasmas in general, and to understanding the recent results of lower hybrid heating on Alcator A in particular. The two most prominent results from Alcator A are the observed nonlinear effects in the coupling of the RF power and the strong ion heating observed in a narrow range of plasma densities.

We have recently pointed out that at the plasma edge ponderomotive effects parallel to $\overline{B}_o$, coupled with the nonlinear bunching of the electrons there, can explain the experimentally observed nonlinear effects in the external coupling of lower hybrid energy to the plasma, as seen, for example, in Petula, JFT II, and Alcator A.[1] The ponderomotive force in the direction of $\overline{B}_o$ produces plasma density modifications in that direction that are independent of the phasing of the waveguides. In addition, the applied electric fields at the edge are such that the electron bunching is nonlinear; thus one finds that $(\omega_B/\omega) = (k_{\parallel} v_{tr}/\omega) = (v_{ind}/v_{ph})^{1/2} \sim 0.3$. This, together with the ponderomotive rippling of the plasma surface, leads to a shift of the applied $k_{\parallel}$-spectrum to larger $k_{\parallel}$ by a factor of 2-3, which is consistent with observations of heating and CO_2 laser scattering in Alcator A.[2,3]

In relation to the observed ion heating in Alcator A there exist three possible mechanisms: (a) by the parametrically excited waves; (b) by stochastic heating of the lower hybrid wave or its parametrically excited waves; (c) by linear ion-cyclotron harmonic damping of the lower hybrid wave or its parametrically excited waves. (Enhanced collisional damping at mode conversion can no longer be relied upon.[4]) The theory of stochastic heating by lower-hybrid waves is by now relatively well advanced.[5] In the recent past we have concentrated on understanding the possible relevance of linear ion-cyclotron-harmonic damping in an inhomogeneous magnetic field, and the nonlinear heating aspects of quasi-mode parametric excitations. The first requires $(k_{\perp}\rho_i)^2 \gtrsim (\omega/\Omega_i)$ which can only be satisfied near or beyond wave conversion occurring at the

center of the plasma. At the large field amplitudes of interest, however, and with the above condition satisfied, stochastic heating is effective and linear theory is not appropriate. The relevance of parametric excitations in ion heating is less clear. Parametrically excited spectra are observed in all tokamak heating experiments utilizing externally applied power in the lower hybrid range of frequencies. These are detected, however, at the plasma wall, and hence can not necessarily be assumed to occur in the plasma where the heating occurs. In the recent past, we have undertaken a detailed study of the nonlinear (heating) aspects of the quasi-mode parametric excitation in an inhomogeneous plasma. This parametric excitation is a prominent one since it is nonresonant, and it has a low threshold. In the past it was thought that the lower frequency sideband (also a lower hybrid wave) is mainly excited by scattering of the pump (the applied lower hybrid wave) off the electrons.[6] We have recently shown that for the parameters of Alcator A (but also, in fact, for any tokamak-type plasma) the dominant scattering is off the ions by Doppler-shifted ion-cyclotron-harmonic resonance of the low-frequency fields.[7] This may explain the ion-cyclotron-harmonic structure which one observes on the sideband signal at low frequencies.[2,8] Furthermore, nonlinearly, the quasi-mode excitation may be strong near the edge of the plasma. In that case, the pump depletes mainly to the sideband which propagates farther into the plasma but in a different direction, and has a wave conversion point that is farther out in the density gradient. Ion heating can then occur near wave conversion of the sideband by either linear ion-cyclotron-harmonic damping or induced stochastic ion motion, as before. A small fraction of the pump power (ω_{LF}/ω_s), where LF ≡ low frequency, and s ≡ sideband, goes directly to the ions via the low-frequency fields of the quasi mode.

Two projects have been completed. The first was related to current generation by RF fields.[9] The second involves a study of group velocity rays in toroidal geometry. The results of the latter have been written up in the Ph.D. thesis of John L. Kulp.[10] As a result of this work, we now have a sophisticated (symbolic and numeric) computer program and display for following RF energy propagation in a toroidal plasma, including all of the linear effects due to plasma and magnetic-field inhomogeneity, and toroidal geometry. The most important new result is the discovery that the applied $n_{||} = (ck_{||}/\omega)$ can be <u>reduced</u> by as much as 30-50% when $\omega \sim \omega_{LH}$ and $(\omega_{pe}/\Omega_e) \gtrsim 1$. This can have important consequences, especially in electron heating which is sensitive to $k_{||}$.

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4. NONLINEAR THEORY OF TRAPPED-PARTICLE INSTABILITIES

U. S. Department of Energy (Contract ET-78-S-02-4682)

Thomas H. Dupree, David J. Tetreault

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

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

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

5. TOKAMAK RESEARCH: RF HEATING AND CURRENT DRIVE

U. S. Department of Energy (Grant EG-77-G-01-4107 and
Contract ET-78-S-02-4714)

George Bekefi, Miklos Porkolab, Kuo-in Chen, Stanley C. Luckhardt

Wide-ranging experimental investigations involving injection of high RF power levels are in progress or planned for the near future on the Versator II Tokamak. To accommodate these experiments, Versator II has been upgraded in toroidal field strength from 8 to 15 kG. This project was completed in late 1978, and after initial studies of plasma equilibrium in the upgraded machine, improved discharge parameters now achieved include plasma currents of 30-50 kA, central densities of $2\text{-}3 \times 10^{13}$ cm and pulse durations of 20-40 ms.

Currently, first RF injection experiments were initiated at the lower hybrid frequency using up to 150 kW of power at 800 MHz from an RF system supplied by the Princeton Plasma Physics Laboratory. In these experiments lower hybrid waves are injected with a phased array of waveguides (grill) designed to produce a favorable power spectrum of injected waves for heating ions or modifying the electron-velocity distribution so that a net toroidal current is driven. This later effect, investigated theoretically by Fisch and Bers,[1,2] could lead to the possibility of achieving a steady-state fusion reactor driven by microwave power.

In a second series of experiments to begin in late 1979, microwave power will be injected into the torus at the electron-cyclotron frequency. For this purpose, the newly developed gyrotron microwave generator will be supplied by the Naval Research Laboratory; the NRL gyrotron will allow ECRH experiments to be carried out at significant power levels in the range of 100-200 kW at a frequency of 35 GHz.

In support of the basic physics experiments, a large number of plasma diagnostic experiments are available or in preparation. These include: vacuum ultraviolet spectroscopy, 90-GHz microwave scattering, first-harmonic electron-cyclotron emission measurement, 35-GHz microwave interferometry, charge-exchange neutral-atom energy analysis, and ruby laser Thompson scattering.

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6. MIRROR-CONFINED PLASMAS

U. S. Department of Energy (Contracts ET-78-S-02-4886 and ET-78-S-02-4690)

Louis D. Smullin

We have two systems in operation, Constance I and II. Constance I is devoted, this year, to the study of electron-cyclotron-resonance-heating (ECRH) as a means of damping the drift-cyclotron-loss-cone (DCLC) instability that limits the lifetime of highly ionized mirror-confined plasmas. This problem is being studied by M. E. Mauel.

Constance II is a larger version of Constance I. When completed (about June 1979) it will be used to compare DCLC stabilization by ECRH with stabilization by electron-beam plasma interaction (a technique demonstrated last year on Constance I). K. Rettman is the engineer in charge of building Constance II.

The target plasma we are attempting to stabilize is produced by the self-trapping of a plasma stream emitted from a plasma gun located outside the mirror region. Although this is an effective technique used by others before us, virtually nothing is known about the trapping mechanism nor about the detailed characteristics of the plasma stream. This problem is being studied by J. P. Rymer.

7. NEUTRAL BEAM RESEARCH

U. S. Department of Energy (Contract ET-78-S-02-4690)

Louis D. Smullin

High-current, negative ion (H^- or D^-) sources are needed to produce the high-energy ($\gtrsim$300-keV) neutral beams needed for heating of tokamak reactors. The Dimov magnetron source has been shown to be capable of emitting $\gtrsim$1 amp of H^-. Peter Kenyon has been studying the high pressure ($\rho \approx 0.5$ T) magnetron discharge that characterizes these devices. His particular interest is to understand the noisy (turbulent) behavior of the discharge; he is comparing experimental results with a linear theoretical model of the onset of a drift instability driven by radial gradients of density and electrostatic potential.

COMMUNICATION SCIENCES
AND
ENGINEERING

XVIII. 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 NGL 22-009-013)
Joint Services Electronics Program (Contract DAAG29-78-C-0020)

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

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

During the past year, a series of papers which resolve many of the questions concerning the propagation and detection of quantum fields have been prepared and published by Professor Shapiro and Dr. Yuen.[1-3] Also, in his doctoral research, Mr. Curlander has shown that, for digital communication with error probability as a performance measure, the optimum quantum receiver for either pure coherent states or pure two-photon coherent states is not markedly superior to the performance that can be achieved with homodyning. This resolves a question that has persisted for some time.

The other work in this area has been the design of an experiment to verify that two-photon coherent states can be produced. These states are interesting for communication because they allow the total quantum noise required by the uncertainty principle to

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be divided unequally between the quadrature components of the field, thereby permitting marked improvement in the attainable performance. The experiment has been designed and a means of performing it is now being sought.

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2. IMPROVED LOW-VISIBILITY COMMUNICATION

National Science Foundation (Grant ENG78-21603)

U. S. Army Research Office – Durham (Contract DAAG29-77-C-0048)

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 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 initial goal in the program has been to experimentally determine the magnitudes of key propagation parameters so that a useful theoretical model of the propagation can be developed through judicious approximation. Earlier measurements at wavelengths of 0.69 μm and 2.06 μm over our 13-km propagation path have now been augmented with measurements at wavelengths of 0.25 μ, 0.27 μm, 0.53 μm, and 1.06 μm.[1] Also, a series of measurements in fog were made over a 1000-ft path at a wavelength of 0.25 μm in Lubec, Me.[2] During the coming year we will make further fog measurements in Eastport, Me., and will begin to supplement our 13-km observations with measurements over a path of approximately 4 or 5 km. We also expect to increasingly shift our attention from the collection of data to the development of a useful multiple scatter propagation model.

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XIX. DIGITAL SIGNAL PROCESSING

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The Digital Signal Processing Group is carrying out research in the general area of digital signal processing with applications to speech, image, and geophysical data processing. In addition to specific projects being carried out on campus, there is close interaction both with Lincoln Laboratory and with the Woods Hole Oceanographic Institution.

In the area of speech processing, over the past several years the Digital Signal Processing Group has been working on the development of systems for bandwidth compression of speech, parametric modeling of speech using pole-zero models, and enhancement of degraded speech. Our work in the speech area is currently heading toward an increasing involvement with the problem of enhancing degraded speech and a related problem, that of the development of algorithms for robust speech compression in the presence of additive noise.

In a related area the methods of speech compression using linear predictive encoding are being applied to the compression of data recorded in ocean-bottom seismometers. These methods are being tested with data provided by the Woods Hole Oceanographic Institution.

The areas of image and geophysical data processing in general both involve the processing of multidimensional signals. The theoretical projects in 2-D signal processing include filter design (e.g., 2-D all-pass design to match phase response), the synthesis of good 2-D filter implementations, 2-D spectrum analysis, and 2-D deconvolution. We have been pursuing a number of projects specifically related to geophysical data processing. We are applying some of the filter design results to seismic-wave migration by implementing a program on our MAP processor. Another project, which has been carried out in collaboration with the Woods Hole Oceanographic Institution, is the development of an algorithm for data processing to measure the acoustic reflection coefficient from the ocean bottom. Out of this work has come a Hankel transform algorithm which has potential applications to a number of other problems. Another problem area is that of velocity analysis on array data. The specific application that we are

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considering is that of velocity analysis on well logging data. We are also pursuing a number of other problems associated with the analysis of well logging data, including the development of techniques for event detection. In another application of velocity analysis, we have applied adaptive array processing to measure the reverberation of acoustic signals in the Arctic Ocean, as well as the phase velocity of the seismic paths within the seabed. Acoustic imaging from a submersible often generates an image dominated by strong highlights because of the specular reflections introduced by the relatively long wavelengths. We are working on an adaptive array processing method to suppress the deleterious effects of these highlights in the image.

There are also a number of projects related to image processing that we are currently pursuing. The work on image processing is being carried out in collaboration with Lincoln Laboratory, and we are in the process of defining a research program which would involve close collaboration between our group and Lincoln Laboratory. Projects that we are contemplating include enhancement of degraded images, and reconstruction of images from phase-only information. In both the context of image processing and array processing, we are also beginning to explore such topics as high resolution, multidimensional spectral estimation, and two-dimensional short-space signal processing.

1. LINEAR PREDICTIVE ENCODING OF SEISMIC DATA

National Science Foundation Fellowship

Thomas E. Bordley, Arthur B. Baggeroer

If marine seismic traces are stored in their original digital form, large quantities of data storage are necessary because of the broad dynamic range of these signals. Since these signals are not sample waveforms of a white noise process, it is known that the data can be presented more efficiently (e.g., via entropy encoding). Thus, ocean-bottom seismometers with their limited available storage are artificially constrained in the number of signals which they can record, if the incoming data are simply stored without processing. Since the retrieval of these sensors is difficult and expensive, it is of significant interest to determine a processing scheme suitable for use by these minicomputer-controlled seismometers. This research examines the effectiveness of Linear Predictive Encoding (LPE) in reducing the amount of storage required for data gathered in ocean-bottom seismology.

The essence of this technique is to characterize a waveform in terms of the parameters of a stationary rational digital model, i.e., as the output of a reverberative system, and then to store the parameters of this system and a correction signal instead of storing the original signal. The rationale behind this approach is that if a signal is sufficiently predictable in terms of the model, the energy in the error signal will be

much less than the energy in the original signal. Thus, the total number of bits required to represent the signal as an error signal and a set of parameters will be much less than needed to represent the waveform directly.

At present, we are engaged in empirically testing this technique on data supplied through Dr. Graham M. Purdy of the Woods Hole Oceanographic Institution.

2. IMPLEMENTATION OF MULTIDIMENSIONAL DISCRETE SYSTEMS FOR SIGNAL PROCESSING

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

David S. K. Chan, James H. McClellan

This research has established a "state-space" representation for studying the implementation of a general class of multidimensional discrete systems. This formulation extends to cases other than the first-quadrant causal filters that are usually studied. Using this framework, the minimization of coefficient sensitivity and round-off noise under structure transformations can be studied. The analog network technique known as continuously equivalent networks has been adapted to the multidimensional realization problem. Work is progressing on the realization algorithm to improve its performance, especially for the two-dimensional case.

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3. EVENT DETECTION IN SONIC WELL LOGGING

National Science Foundation (Grant ENG76-24117)

Webster P. Dove, Alan V. Oppenheim

Oil wells are analyzed by acoustically testing at many places along their depth, from which a sound velocity profile can be developed. For each test a pulse of sound is generated at the bottom of a 13 meter long test probe and received at four microphones spaced at one meter intervals at the top of the probe.

The signal received at each microphone is the sum of many overlapping dispersed pulses, each of which has travelled a different path. To find the velocities in the paths

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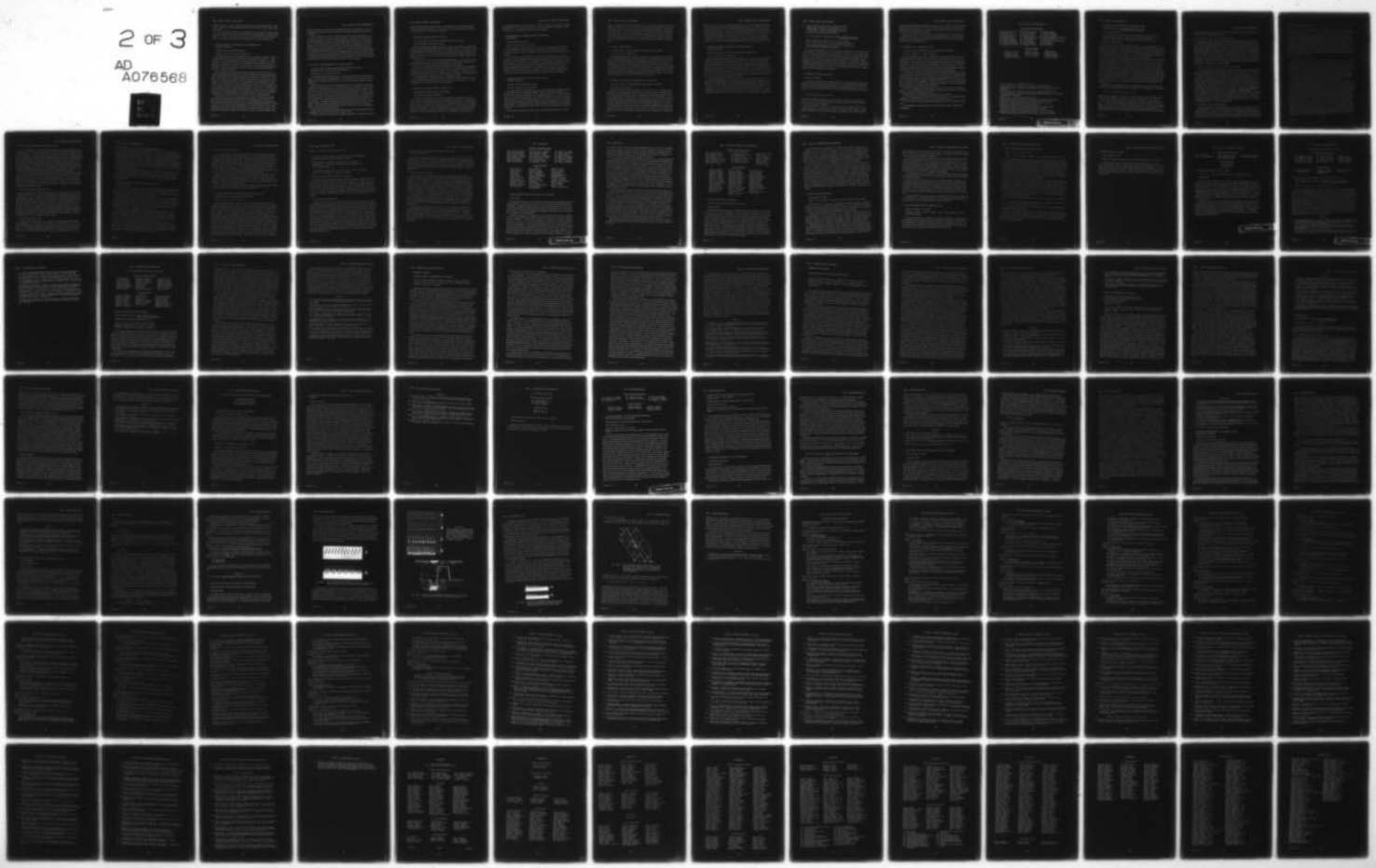

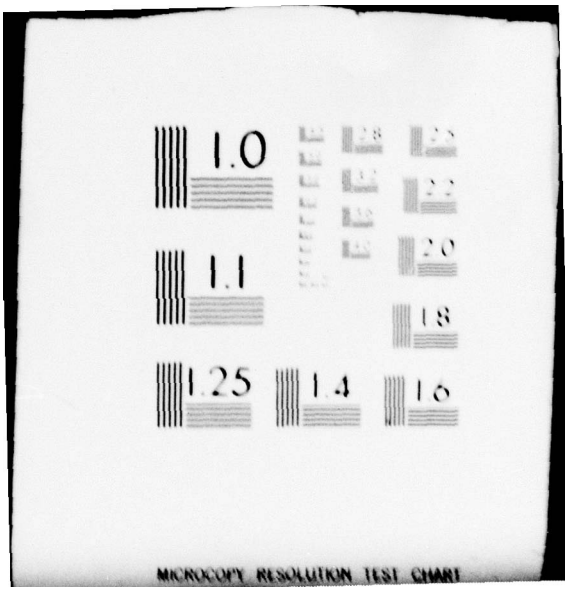
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of interest the arrival time of each related pulse must be determined accurately. That requires a method of reducing the dispersion of the pulses so they become distinct separate arrivals.

To do this signal processing, we are using Recursive Least Squares prediction (the covariance method) to cancel the filtering effect of the different paths. Then the arrival time of the first and second pulses (which are the ones of interest) should be apparent either in the output of the predictor or the behavior of the predictor coefficients.

4. ADAPTIVE ARRAY PROCESSING FOR HIGH-RESOLUTION ACOUSTIC IMAGING

National Science Foundation Fellowship

Gregory L. Duckworth, Arthur B. Baggeroer

Determination of the internal structure of a medium opaque or ill-suited to electromagnetic radiation is a problem encountered in many different applications. High-resolution visualization of underwater objects through turbid seawater is the problem currently being dealt with; however, other applications include real-time viewing of internal movements of the human body without x-ray's potentially harmful effects, nondestructive testing of metallic and low x-ray contrast objects, and determination of the earth's subsurface structure.

Because of their analogous behavior to electromagnetic radiation with respect to reflection, diffraction, and refraction, but differing attenuation and physiological properties, short wavelength acoustic pressure waves can be used to perform the above tasks, but with a new set of inherent advantages and difficulties. For example, in the context of the undersea environment, acoustic imaging has an advantage over optical imaging in that the attenuation of the acoustic-pressure waves is dependent primarily on the temporal frequency, and relatively independent of the density of suspended solids, whereas light is subject to intense backscattering from cloudy water. A result of this is that the "range-to-reverberation" limit is larger for acoustic imaging, and although absorption at wavelengths adequate for reasonable resolution is high, we can theoretically increase the illuminating power and obtain the desired range capabilities.

The problems with acoustic imaging stem from the need to keep the wavelengths long enough for adequate range, SNR, and power consumption, and short enough for good resolution and small receiver apertures. These considerations ultimately lead to systems with small numerical apertures with the diffraction field undersampled in space and hence, poor resolution and aliasing problems. Resolution seems to be the most problematic issue since the large point-spread function generated by classical (Fresnel transform) processing is subject to tremendous amounts of sidelobe leakage from

specular reflections. Typically a great deal of specularity is encountered since the illuminating wavelengths are large compared to the surface roughness of the objects to be imaged.

These problems lead us to the thrust of the current research – application of the "Maximum Likelihood" technique of spectral analysis to adaptive array processing of the diffraction-pattern samples. It has been found that the adaptive point-spread function of a system incorporating this technique yields better resolution for distributed objects as long as care is taken in estimation of the spatial-covariance function. The subtlety involves making the spatial covariance look like it was formed by reflections from statistically independent incremental areas. The work also involves determination of the statistics of the estimators when an inadequate number of data vectors are used to ensure that the spatial-covariance matrix is distributed in a complex Wishart manner. Two-dimensional arrays that are optimized in some sense for good resolution and aliasing reduction with the minimum number of sensors are also examined.

5. DESIGN OF TWO-DIMENSIONAL ALL-PASS FILTERS

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

David B. Harris, James H. McClellan

The objective of this research project is to develop methods for designing all-pass filters with specified phase characteristics. Little previous work has been done on the design of phase functions, particularly in two dimensions, since the problem is highly nonlinear.

Several applications for two-dimensional phase-only filters await the development of satisfactory design techniques. The most important is in simulation of acoustic-wave propagation. In a two-dimensional spatial geometry involving depth and lateral offset, the wave field recorded (for all time and offset) at a particular depth is related to the wave field at another depth by a two-dimensional filtering operation. The implied filter is specified by one of two solutions to the two-dimensional acoustic-wave equation. The filter characteristic is all-pass with the phase given by the dispersion relation of the wave equation. A broadband digital filter approximation to this ideal response is being sought to enable numerical extrapolation of measured wave fields from one depth to another. Wave-field extrapolation of this sort is an integral part of the wave-equation method of seismic time-section migration.

Another possible application of all-pass filter design is phase compensation of two-dimensional recursive filters designed for magnitude only.

Recently, progress in design of all-pass has been obtained. A method whereby the

phase-design problem is transformed to a more tractable 2-D spectral-factorization problem has been used effectively. And a new form of 2-D linear prediction has been developed to perform the spectral factorization.

6. TIME-SCALE MODIFICATION OF SPEECH

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

Samuel Holtzman, Michael R. Portnoff

We have implemented an analysis-synthesis system on our PDP-11 computer that performs uniform-rate speed transformations on speech signals. The problem of spectral degradation and introduction of noise, which usually occur in similar systems, are not found in this one. This is because the system performs the transformations in the frequency domain by means of the discrete short-time Fourier transform rather than in the time domain.

In order to achieve an even more natural-sounding result, we are at present introducing nonuniformities into the speed transformations to incorporate a dependency of the system on local features of the speech signal being transformed.

Our work has been directed toward the development of an algorithm to automatically segment the speech signal into a sequence of passages for which an expected level of degradation, caused by uniform time-scaling, can be determined. The purpose of segmenting the signal in this manner is to allow the degree of local time-scale modification to be decreased whenever the expected level of degradation is high.

The algorithm uses a statistical analysis of the speech signal to determine a level of local quasi-stationarity which, based on our model of speech production, is highly correlated with the expected level of local degradation.

7. PARAMETER ESTIMATION FROM SEISMIC DATA

Schlumberger-Doll Research Center Fellowship

Andrew Kurkjian, Alan V. Oppenheim

The purpose of this research is to develop signal processing for a borehole (oil well) sonic tool which takes into account more physics than is found in a simple nondispersive model. The problem is to estimate certain parameters of the rock surrounding the borehole from signals received at an array of sensors in the borehole. The actual physics of the situation is very complicated due to the variety of seismic-wave phenomena which are present. Aside from compressional and shear wavelets, the pressure field also contains a water (tube, mud) wave, a head (lateral, conical) wave, a

pseudo-Rayleigh wave, and a Stoneley wave. This work will examine the physical nature of these seismic waves and then develop processing to estimate the parameters of interest from the received signals based on this physical nature.

8. PERFORMANCE OF MAXIMUM ENTROPY SPECTRAL ESTIMATORS

Hertz Foundation Fellowship

Steven W. Lang, James H. McClellan

Many problems in estimation can be considered as the estimation of some feature of a power spectrum. The development of new methods of spectral estimation, such as various "maximum entropy" techniques, gives us new tools with which to attack such problems.

This research is concerned with an analysis of the performance of various maximum entropy spectral estimators when the random process being observed is composed of sinusoids in additive noise. In particular, the problem of estimating the sinusoid frequencies is considered. This problem is interesting and important in its own right; the measurement of Doppler shifts in radar or the search for periodicities in geophysical data might be so modeled. It also points up some differences between various "maximum entropy" spectral estimators. Thus, the results obtained should provide some insight into the performance of these estimators in other situations.

9. PARAMETRIC MODELLING OF THE LUNGS FROM ACOUSTIC SIGNALS

National Science Foundation Fellowship

David C. LeDoux, James H. McClellan

This is part of a project attempting to develop new diagnostic techniques for detecting pulmonary disease in infants and children. In these techniques, a sound wave is injected into the patient's respiratory system through the mouth. The sound is reflected from various points within the lungs, and the reflected signal is recorded as it emerges from the mouth. If we model the lung as a linear time-invariant system, we can determine its transfer function (frequency response or impulse response) from the input and output signals. This transfer function contains information about the air passages within the lungs and can hopefully be used to detect such problems as blocked or constricted airways.

Since the air passages in the lungs form a branching network of tubes, we would

expect the frequency response to exhibit dips due to resonances of single tubes and combinations of tubes. This is, in fact, what is observed from actual data. However, the human lung contains several million tubes and the frequency response is correspondingly complicated. The object of this research is to apply the techniques of pole-zero modeling to represent the dominant features of the frequency response by a small number of parameters (poles and zeros). It is hoped that some future workers might be able to use the parameters as a basis for differentiating between healthy and diseased lungs.

10. SPEECH ENHANCEMENT

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

Jae S. Lim, Alan V. Oppenheim

Degraded speech occurs in a variety of contexts, and its enhancement is desirable for many practical applications. In our past research on this problem, we have developed several systems for enhancement and bandwidth compression of noisy speech by attempting to estimate the parameters of a specific underlying speech model based on the Maximum A Posteriori (MAP) estimation procedure. When the systems were implemented and applied to real speech data, they performed well as enhancement and potential bandwidth compression systems of noisy speech at various S/N ratios. Our future research in this area will include investigation of methods to improve our current speech-enhancement systems and development of new systems.

11. MAXIMUM LIKELIHOOD ESTIMATION WITH NOISY DATA

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

Bruce Musicus, Jae S. Lim

Maximum Likelihood (ML) Estimation is a powerful tool for estimating model parameters or signals from observed system output. Not only does it yield estimates with nice theoretical properties, but the estimates are also easily calculated for many useful signal models. Unfortunately, when both the parameters of the system as well as the system output must be estimated from observations corrupted by noise, Maximum Likelihood Estimation usually requires a difficult nonlinear optimization. Three different ML approaches have been proposed for estimating the signal and parameters of a system from noisy observations. We have found iterative algorithms for solving each of the three problems, which effectively decouple the uncertainty in the parameter and signal values, thus simplifying the calculation required. When applied to a particular

pole-zero model, all three algorithms iterate back and forth between linearly filtering the observations to estimate the signal and fitting parameters to the signal estimate by solving linear equations. The theoretical properties of the algorithms, their relationship to methods previously proposed by Lim, and their application to a variety of signal models have been studied. Testing of the algorithm's performance on real data has just begun, and results are not yet available. However, because of their conceptual and algorithmic simplicity, as well as their solid theoretical basis, these algorithms promise to be a useful tool for signal and parameter estimation in the presence of noise.

12. WINOGRAD FOURIER TRANSFORM ALGORITHM (WFTA) IMPLEMENTATION

National Aeronautics and Space Administration (Grant NSG-5157)

Syed H. Nawab, James H. McClellan

Bounds on the minimum number of data transfers (i.e., loads, stores, and copies) required by WFTA and FFT programs have been derived. The analysis is applicable to those general-purpose computers with at least 4 general processor registers (e.g., the IBM 370, PDP-11, etc.). It was shown that the 1008-point WFTA requires about 21% more data transfers than the 1024-point radix-4 FFT; on the other hand, the 120-point WFTA has about the same number of data transfers as the mixed-radix (4×4×4×2) version of the 128-point FFT and 22% fewer than the radix-2 version. Finally, comparisons of the "total" program execution times (multiplications, additions, and data transfers, but not indexing or permutations) were made.

Arithmetic concurrences, such as those found in special-purpose fast Fourier transforms (FFT) hardware, were surveyed and categorized. Similar structures were then derived for the Winograd Fourier transform algorithm (WFTA). Relative time-efficiency plots were obtained for the 1024-point radix-4 FFT and the 1008-point WFTA as a function of the number of real arithmic operations executable in parallel. This comparison showed that the relative time efficiency of the two algorithms in sequential computations generally carries over to cases where arithmic parallelism is exploited.

13. EVALUATION OF CIRCULARLY SYMMETRIC TWO-DIMENSIONAL FOURIER TRANSFORMS AND ITS APPLICATION TO THE MEASUREMENT OF OCEAN-BOTTOM REFLECTION COEFFICIENTS

U. S. Navy – Office of Naval Research (Contracts N00014-75-C-0951 and N00014-77-C-0196)

Alan V. Oppenheim, George V. Frisk, David R. Martinez

[G. V. Frisk is with the Woods Hole Oceanographic Institution.]

[D. R. Martinez is with the M. I. T.-W. H. O. I. Joint Program in Oceanography/Oceanographic Engineering.]

In a variety of applications the need arises for the evaluation of the two-dimensional Fourier transform of circularly symmetric functions. Because of the circular symmetry, the two-dimensional Fourier transform reduces to the Fourier-Bessel or Hankel transform. This research considers a method for evaluating this transform using the "projection-slice" theorem for multidimensional transforms. The method is applied specifically to the measurement of the plane-wave reflection coefficient of a horizontally stratified ocean bottom using the fact that, for a point source, the bottom-reflected field and the plane-wave reflection coefficient are circularly symmetric and are related through a two-dimensional Fourier transform.

14. SHORT-TIME FOURIER ANALYSIS

Michael R. Portnoff

Short-time Fourier analysis is based on the notion of a multidimensional representation for a one-dimensional signal. Specifically, a one-dimensional time signal, $x(t)$, is represented by a two-dimensional function of time and frequency, $X(t, \omega)$, called a short-time Fourier transform (STFT). In its simplest form, the STFT $X(t, \omega)$ is defined as

$$X(t, \omega) = \int_{-\infty}^{\infty} x(\tau)\, w(t - \tau)\, e^{-j\omega\tau}\, d\tau,$$

where $w(t)$ is a window function that is, in some sense, narrow in time or frequency, or both. In its more general form, the STFT is defined using a window that is allowed to depend on both time and frequency.

Short-time Fourier analysis is particularly useful for studying "slowly time-varying" phenomena such as speech, music, and other acoustic signals, because rapidly varying local features appear as functions of frequency in the STFT, whereas

slowly-varying global features appear as functions of time. Thus, the STFT is a formal mathematical description for our notion of a "time-varying spectrum." Furthermore, short-time Fourier analysis is, in many ways, analogous to the acoustic processing performed by the human auditory system.

At present, short-time Fourier analysis is not well understood. The objective of our research, therefore, is to develop a better understanding of this method of signal analysis, both by investigating the mathematical properties of the STFT and studying the STFT for specific signal models.

15. ESTIMATION OF UNWRAPPED PHASE

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

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

The unwrapped phase estimation problem for discrete-time sequences was first encountered in the development of a mixed-phase homomorphic vocoder, where the smooth-phase estimate of the vocal-tract impulse response led to harsh-sounding synthetic speech. The sensitivity of the unwrapped-phase envelope to time-domain perturbations was observed to be greater than that of the log-magnitude spectrum. These observations initiated a number of questions and answers in magnitude/phase properties and relations, which are common to numerous areas of signal processing.

In particular, a theoretical framework was developed for unwrapped-phase estimation from harmonic spectra (voiced speech) through smoothing real and imaginary spectral components. Short-time homomorphic analysis and a short-time harmonic model have led to pitch-adaptive duration and alignment requirements on time-domain windowing. The underlying phase envelope is consequently preserved so that cepstral windowing can be applied. The result is a mixed-phase homomorphic vocoder of somewhat higher quality than its minimum-phase counterpart.

In addition, two alternative mixed-phase vocoders were considered: the first is based on linear interpolation of complex harmonic peaks, and the second on Lim's homomorphic spectral-root deconvolution scheme.

Current research encompasses the following three major topics:

(1) A general framework of phase estimation for a number of signal-processing applications, including speech, seismic, and oceanographic problems.

(2) More reliable methods of obtaining unwrapped phase from sampled and random data.

(3) Investigation of magnitude/phase relations and their relative sensitivities to perturbations.

XX. SPEECH COMMUNICATION

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(XX. SPEECH COMMUNICATION)

1. STUDIES OF SPEECH PRODUCTION AND PERCEPTION

National Institutes of Health (Grant 2 ROI NS04332 and
Training Grant 5 T32 NS07040)

C. J. LeBel Fellowships

Sheila E. Blumstein, Bertrand Delgutte, Morris Halle, William L. Henke, Samuel J. Keyser, Dennis H. Klatt, Ralph N. Ohde, Colin Painter, Joseph S. Perkell, David B. Pisoni, Kenneth N. Stevens, Victor W. Zue

a. Segmental Aspects of Speech

Our research on the segmental aspects of speech is examining the acoustic, perceptual, and articulatory correlates of the phonetic features that classify speech sounds in language. The objectives of the work are to determine how the human perceptual and articulatory systems place constraints on the selection of an inventory of phonetic features, and to utilize evidence from speech acoustics, auditory perception, speech production, and phonology to work toward a revised inventory of features.

We have completed several studies of the acoustical properties and of the perception of place of articulation for stop consonants in English, and these studies have suggested that the listener samples the speech signal in the vicinity of points in time when there is a rapid change in the spectrum, and classifies the sound in these regions in terms of certain gross characteristics of the short-time spectrum. Further work in this area is investigating the acoustic correlates and the phonological evidence for features that differentiate among coronal consonants (i. e., consonants produced with the tongue blade) that have been traditionally classified in terms of different places of articulation in different languages. We have also begun to examine the acoustic bases for the categorization of consonants as voiced or voiceless, with the aim of finding an integrated acoustic property that applies over a variety of phonetic contexts and consonantal manners of articulation.

Research on the laryngeal features is continuing with a laryngeal fiberscope study of what the vocal folds are doing during the production of the following set of consonants:

$\underset{\circ}{b}$, p^h, p, b, $p^?$, ph, $b^{\text{ɦ}}$, ?b, ɓ, kp, gb, p'.

Each of these consonants is recorded in carrier sentences before the eight primary cardinal vowels. This is a follow-up on an acoustic study using the same data set.

As a continuation of our study of the articulatory correlates of certain vowel features, we have run two preliminary palatographic experiments to explore the notion that patterns of tongue-to-maxilla contact are invariant correlates of "vowel height" features. Results from six speakers with differently-shaped palatal vaults suggest that such invariant patterns may not exist on the palatal surfaces and that further study is necessary

to determine whether there is some other basis for postulating invariant articulatory correlates for the vowel height features.

b. Acoustic Study of the F_o Contours of Cantonese Tone

As part of our research directed toward a better understanding of the behavior of the larynx and the features underlying it, we have examined the fundamental-frequency (F_o) contours of the nine Cantonese tones. The data were collected from two native speakers of the Canton dialect. The corpus was designed such that the effects of sentence intonation were minimized and modifications of tone contours by adjacent consonants were counterbalanced. In addition to the F_o contours of the nine tones, durational data were also obtained. From the production data that we have collected, we were able to obtain average F_o contours for all the tones. We are currently in the process of synthesizing simple consonant-vowel syllables with the averaged tone contours for perceptual experiments. One aim of the study is to gain some insight into whether these contours are perceived and produced in a quantal manner.

c. Study of the Phonological Processes in American English

The goal of this part of our research is to provide, through acoustic studies, quantitative information on the variation of the properties of speech sounds in context. Whenever the variations appear to be systematic, either for all speakers or for a subset of the speakers, rules are proposed to describe such phonological variations. Over the past year we have conducted a study of the acoustic effect of a phonological process commonly known as palatalization. In particular, we investigated the effect of palatal consonants (/$\overset{y}{s}$, $\overset{y}{z}$, y/) on the adjacent alveolar fricatives (/s, z/). Our results indicate that the palatalization of alveolar fricatives occurs much more readily and completely when the palatal consonant precedes the alveolar fricative (e.g., this ship, gas shortage) than when it follows the alveolar fricative (e.g., Irish setter, tunafish sandwich). The observed difference in acoustic data can be accounted for by several hypotheses, ranging from explanations that are based on the relationship between anticipatory and perseveratory articulation to those that are more motivated by considerations of the underlying articulatory constraints. We are currently exploring these hypotheses by examining additional acoustic as well as physiological data.

d. Experiments on Spectrogram Reading

Several spectrogram reading experiments were conducted over the past year. The experiments were designed to determine the amount of phonetic information that is contained in the speech signal or, more specifically, in a spectrographic representation of the speech signal. The task involved identifying the phonetic content of an unknown utterance only from a visual examination of the speech spectrogram. In the first experiment,

the subject attempted to phonetically label spectrograms of normal and anomalous English utterances as well as words in a known carrier phrase. The results, when compared with the transcriptions of three phoneticians who listened to the utterances, indicated an overall agreement of better than 85% on the sentences, and 93% for words in a carrier phrase. Subsequent experiments were designed to see how fast spectrogram reading can be accomplished and to what extent such a procedure can be taught. The general conclusions from these experiments were that there exists a great deal of phonetic information in the acoustic signal, and that a spectrographic display captures a substantial amount of such information. Furthermore, spectrogram reading is often based on the application of explicit rules, and thus can be taught efficiently. Preliminary data from these experiments also suggest that spectrogram reading can probably be done in 30-40 times real-time.

e. A New Model of Lexical Access

During speech perception, how does the perceptual apparatus generate lexical hypotheses "bottom-up" from direct analysis of the input acoustic waveform? The conventional point of view is that the process proceeds logically in stages, where the peripheral auditory system first performs a spectral analysis of the input, and then a set of property detectors extracts relevant properties from this neural spectrogram and generates a phonetic transcription (in the form of a feature matrix in which the columns denote segments and the rows denote distinctive features). The phonetic representation may be errorful and incomplete, but it forms the basis for a search of the lexicon for candidate word hypotheses through an analysis-by-synthesis procedure.

Examination of the strategies employed in the construction of several computer-based speech-understanding systems has suggested that the analysis-by-synthesis model is seriously suboptimal in a computational sense. The knowledge contained in the verification component should be applied earlier in the recognition process so that phonological and lexical constraints of the language can be used to reduce the alternatives and thus reduce errors. All of the knowledge that is embodied in the generative rules of the verification component can be precompiled into a representation that is ideal for direct bottom-up lexical hypothesis formation without post-verification. Phonetic segmentation and labeling decisions need not be made during lexical search, since the decoding network can be made to represent directly the acoustic manifestations of words and word sequences. We intend to pursue these theoretical arguments and ask whether the speech perception apparatus might have evolved in such a way as to take advantage of these strategies. The first objective will be to program a computer simulation of these algorithms in order to establish their potential for accurate decoding of acoustic data. These efforts should lead to refinements in the theory and perhaps lead to new kinds of perceptual tests of competing theories of speech perception.

f. Prediction of Segmental Duration in English Sentences

A set of rules has been developed for the prediction of segmental durations in any English sentence. The input representation for a sentence is a string of symbols drawn from an inventory of 52 phonemes, three alternative stress markers, morpheme boundary, word boundary, and eight syntactic structure distinctions. Eleven durational rules are applied to predict acoustic durations (in ms) of phonetic segments derived from this abstract representation. The rules are intended to quantify many of the larger rule-governed changes in duration that are associated with syntactic environment, segmental position within a word, stress, and phonetic context. The effects of different rules are combined multiplicatively (subject to an incompressibility constraint). The rule system is offered as a first start toward more sophisticated and powerful algorithms.

An objective evaluation of the rules has been performed in which durational predictions have been compared with durations measured in new paragraphs read by the author. Results indicate that the rules account for 84% of the variance in measured segmental durations. Perceptual evaluation of speech synthesized using rule-governed durations indicates that both naturalness ratings and intelligibility of sentences synthesized using these rules are comparable to results using sentences synthesized with durations obtained from a natural recording.

g. Perceptual Interpretation of Durational Cues

The concept of a lexically-based perceptual strategy has been extended to the interpretation of durational cues. Many factors influence the duration of phonetic segments in an utterance. How is it possible to determine whether a particular segment has been lengthened due to syntactic, stress, or phonetic factors? We argue that the answer lies in the specification of expected durations for segments in the representation for each word of the lexicon. Then the lexical search strategy can include durational criteria to select among lexical candidates without unraveling phonetic causality, and, simultaneously, it can look for certain kinds of segmental lengthening and shortening patterns (relative to the word under consideration) that indicate particular syntactic structures. We plan to look in detail at the kinds of rule-durational systems proposed for English to determine the relative advantages of this viewpoint.

h. Analysis of Speech Error Data

A corpus of over 8000 speech errors collected by Merrill Garrett and Stefanie Shattuck-Hufnagel has been examined for evidence concerning the active use of distinctive features and markedness concepts during early stages of the speech production process. The results of our analyses support the view that, when segmental speech errors occur, individual distinctive feature values of segments rarely, if ever, move

about independently. It is entire phonetic segments that move.

Our analyses also indicate that markedness plays no role in the determination of which intrusion consonants are selected in an error. There is no measurable response bias toward a favored set of intrusion consonants. The relative frequency with which a consonant functions as an intrusion in a segmental speech error is statistically indistinguishable from the relative frequency with which it participates as the intended segment. In addition, error frequencies for different consonants are highly correlated with frequency of occurrence in content words in English, suggesting that errors are based on confusions with segments in similar positions in other words which are being manipulated during sentence planning.

Finally, there are more palatalization errors involving alveolar obstruents, particularly [s] → [š], [t] → [č], than one might expect by chance. These errors appear to be caused by the misapplication of a familiar palatalization rule of English, because normal application of the rule (to, for example, the [s] of "this shirt") would not be counted as an error.

i. Electrophysiological Investigation of Peripheral Processes in Speech Perception

Electrophysiological studies of the coding of speechlike sounds in the auditory nerve have been conducted in collaboration with the Eaton-Peabody Laboratory of Auditory Physiology. Single-unit recordings from the auditory nerve of anesthetized cats were obtained using the methods described in 1965 by Kiang et al.

Tone-burst stimuli were used to study the characteristics of short-term adaptation. Over a wide range of stimulus conditions, the time course of firing rate after the onset of a tone burst can be described as a superposition of a rapidly and slowly decaying component with time constants of a few msec and a few tens of msec, respectively. These results are likely to be relevant to the coding of certain characteristics of the onsets that occur in speech (e.g., abruptness, voice-onset time).

Fibers which have been adapted by a tone burst of adequate frequency and level respond with a decreased firing rate to the onset of a second tone burst occurring up to 100-250 msec after the offset of the adapting stimulus. This "forward-masking" effect suggests that the spectral content of previous stimulation may affect the way the spectrum of an onset is coded in the distribution of firing rate across fibers.

Single-formant synthetic stimuli were used to study the coding of certain vowel characteristics. Information about formant frequency is present in the discharge pattern of fibers with a characteristic frequency close to the formant frequency. At levels typical of speech, information about fundamental frequency is present in the firing pattern of fibers over a wide range of characteristic frequencies.

j. Physiology of Speech Production

A preliminary experiment has been performed to test the idea that the articulators assume a "speech posture" which is different from rest and from which articulatory movements may be made most efficiently. Initial electromyographic (EMG) and cineradiographic data suggest that while there may be such a speech posture, its nature (in terms of whether it is expressed as the position of a structure, its configuration, or the tension of certain muscles) may depend on the particular articulatory structure as well as a number of other factors. A great deal of additional analysis is needed.

Two EMG and movement studies aimed at gaining an understanding of coarticulation strategies have been run, and these data are currently being analyzed.

Studies on reducing dosages in radiographic pellet-tracking experiments suggest that dosages may be reduced by using: the lowest possible cine-frame rate, 16-mm film size, high-speed recording film (Kodak 2474), or videotape. While videotape requires the lowest possible dose at 60 frames per second, frame-by-frame analysis thus far seems to be less accurate than with cine.

We are continuing to build up our physiological data-gathering and analysis facilities, and we expect to be close to completion by the end of this year.

2. SYNTACTIC-TO-PHONETIC CODING IN SPEECH PRODUCTION

National Institutes of Health (Grant 5 ROI NS13028)

William E. Cooper, John M. Sorensen

The speech wave contains a number of characteristics that reflect the speaker's structural representation and processing of syntactic constituents. A theory of syntactic-to-phonetic coding has been developed in order to account for a variety of experimental results obtained in the recent years of this project. The structural component of the theory contains a metric of syntactic boundary strengths to account for the presence and rank magnitude of syntactic influences on speech timing, fundamental frequency (F_0), and the application of cross-word phonetic conditioning rules. The processing component of the theory includes constraints on the speaker's on-line planning and execution. In addition to theory development, experimental studies have been conducted on fundamental-frequency patterns to obtain more information about the following F_0 attributes: (a) the form and domain of F_0 declination in declarative utterances, (b) the influence of syntactic boundaries on the application of cross-word F_0 conditioning effects, and (c) the influence of speaking rate, utterance and constituent length, and parenthetical expressions on the form and domain of F_0 declination. These experimental studies have been conducted primarily with native speakers of English. Two related studies have been completed for

Japanese in collaboration with Kazuhiko Yorifuji.

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

National Institutes of Health (Training Grant 5 T32 NS07040)
National Science Foundation (Grants BNS76-80278 and BNS77-26871)
C.J. LeBel Fellowship

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

a. Speech and Sound Production by Infants and Children

Measurements of various parts of the vocal tract of children at different ages have been stored in a computer data base and fitted with growth curves. These curves are used to specify the dimensions of a static model to simulate the midsagittal outline of the vocal tract at various stages of development. The model will be further developed to include generation of area functions, formant frequencies, and speech waveforms for use in the exploration of the phonetic capabilities of children and the relationship between children's articulatory configurations for different vowels and the configurations used by adults.

b. Acoustic Analysis of Infant Cries

The aim of this project is to describe statistically the properties of cries elicited from infants who are a few days old, and to specify the way in which the cries of infants known to have particular pathologies differ from the cries of normal infants. Twenty-odd parameters of the cries of a large number of infants have been measured and assembled into a data base. These parameters include temporal properties of the cries, modes of vocal-fold vibration, formant frequencies, presence of nasalization, fundamental frequency, etc. Statistical analysis of the data for normal infants and for subgroups characterized by particular pathologies is proceeding. A model of infant cry production has been developed based on the acoustic theory of speech normally used for adult sound production, but modified by some physiological and anatomical hypotheses for neonates. The most important hypothesis deals with the control strategies involved in cry production. It is assumed that neonates tend to control their muscles (especially in the larynx) in a quantal fashion, thereby helping to explain most of the observed unique acoustic phenomena found in the cry.

c. Pitch and Marked Voice Quality in Parent-Child Discourse: Acoustics and Semantics

We have been analyzing speech from recordings of 16 parent-child conversations; the children were aged 2 to 5, and the conversations took place in a semistructured laboratory playroom setting. For the parents we have found some semantically determined regularities in the pitch ranges used in successive clauses (within and across speakers) and some regularities in the use of certain marked voice qualities (falsetto, creaky voice, singing voice).

d. Speech Production by the Deaf

This area of research involves the application of acoustic theory and analysis to the study of problems commonly encountered in the speech of the profoundly deaf. One ongoing project is concerned with comparing the effects of segmental variables (such as vowel height, consonantal context, and vowel nasalization) on fundamental-frequency control in the speech of deaf and normal-hearing children and adolescents. Preliminary results suggest that certain inadequate modes of vocal-fold vibration may be maximally sensitive to such segmental variables and, furthermore, may be associated with the erratic pitch and breathy or falsetto voice quality characteristics of many deaf speakers.

In another project, a systematic study has been made of the kinds of anomalies that are present in the speech of deaf children when they concatenate words. These anomalies include pausing (with or without inspiration), glottalization, and errors in articulation of word-initial and word-final consonants. The data suggest a lack of awareness of many deaf children of how to produce phrasal units that encompass sequences of several words.

An attempt has also been made to describe the speech-production capabilities of ten adventitiously deafened adults. The most common segmental errors made by these speakers involved the production of the sibilant consonants /s/ and /$\check{s}$/. Inadequate velopharyngeal control at both the segmental and suprasegmental levels was also frequent. The best predictors of speech errors among the ten subjects appeared to be lack of hearing-aid use which, in turn, seemed related to the type and severity of a speaker's hearing loss.

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National Institute of Mental Health (Grant 5 PO1 MH13390)

Morris Halle

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

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

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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 pharses and utterances he has not previously encountered. To account for these two sets of facts, we must assume that in learning a language a child makes correct inferences about the structural principles that govern his language on the basis of very limited exposure to the actual sentences and utterances. In other words, we must assume that with regard to matters of language a child is uniquely capable of jumping to the correct conclusions in the overwhelming majority of instances, and it is the task of the student of language to explain how this might be possible.

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

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

XXII. COGNITIVE INFORMATION PROCESSING

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1. NATURAL LANGUAGE PROCESSING

National Science Foundation (Grant SED76-81985)

Jonathan Allen

The objectives of this project are changing from research in text-to-speech conversion for English to speech recognition. For over ten years, a unified set of research projects has focused on the construction of a comprehensive text-to-speech system and it is now felt that this work has reached a level of maturity and quality (of the output speech) so that the resulting system can be successfully exploited in a variety of applications, including computer-aided instruction, reading machines for the blind, and general-purpose computer output devices. There is a wide variety of capability contained in the system, including morphological analysis, letter-to-sound and lexical stress rules, parsing, timing, and pitch determination, phonological adjustment rules, and phonemic synthesis leading to the final output speech waveform. The several algorithms treating the constraints due to these domains have been developed to a high level of performance, and have been comprehensively tested.

We are now turning to a complete documentation of the system, in the form of a monograph, as well as a short course which will make the results available to the general public. There is, however, a continuing concern with practical electronic implementation, and we are utilizing techniques for custom integrated circuit design to construct devices for the high-data-rate signal-processing algorithms. We believe that the entire system can be implemented, using state-of-the-art electronic technology, in the space of a small book, and at a cost appropriate to a wide range of systems.

As the text-to-speech work is completed, we are preparing to start a major project in speech recognition. We feel that it is possible to recognize individual segments and words at a much higher level of accuracy than is now done. The approach centers around the recognition of syllable peaks, and the selective focusing on relevant cues rather than straightforward template matching. This approach requires a careful determination of the way in which cues integrate to form a percept, and the conditions which determine the subset of cues being used in particular environments. In order to collect the large amount of data needed, a computer-based "phonetician's assistant" to provide for efficient interactive examination of distributional phenomena will be developed. New techniques for syllabically anchored lexical lookup will also be developed, although current plans do not provide for initial emphasis on the heavy use of syntactic and semantic constraints.

2. DIGITAL WIREPHOTO SYSTEM

Associated Press (Grant)

Donald E. Troxel, William F. Schreiber, Richard S. Damon, John N. Ratzel

Since August 1970, we have been developing a news picture (Wirephoto) distribution system that is entirely new for the Associated Press. It is being 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.

Pictures are 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 (300-megabyte disk). The input may be a picture from the AP network, from a local analog transmitter, or from magnetic tape, 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 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 routines to be integrated easily, and we plan to keep incorporating additional picture-processing routines into the system.

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

The Associated Press has now installed the computer-based image processing system in New York City. It is initially being used to coordinate the newsphoto transmissions between the domestic and international Wirephoto networks.

3. DATA PROCESSING FOR THE GRAPHIC ARTS

Providence Gravure, Inc. (Grant)

William F. Schreiber, Donald E. Troxel, Leonard Picard, Malik M. A. Khan, Frank Tze-pu Chang

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

4. IMAGE PROCESSING FOR THE GRAPHIC ARTS

Taylor Publishing Company (Grant)

Donald E. Troxel, William F. Schreiber, Phuong-Quan Hoang, Neil M. Eisman

Taylor Publishing Company is developing a computer-based system for producing printing plates for yearbooks and similar publications. This type of printing is characterized by a very large number of different pages, most containing many pictures, and by small runs compared with most other publishing. Thus the cost of plate preparation is a high proportion of the total production cost. The purpose of the MIT project is the development of an improved system for the input and processing of the graphical elements – pictures and other nontypographical matter – to be included in the final pages. The improved system is to feature lower cost, higher speed, and no loss of quality through the application of interactive computer techniques.

The work to be done at MIT consists of the design of a scanner station and its operating system. Physically, the station, which itself will be a satellite of the Taylor Publishing Company's publishing system, comprises a small computer with associated peripherals. These include a picture display, full-frame memory, disk memory, tablet and Autokon scanner. The operating system will permit the station operator, sitting in front of the computer console, to perform, interactively, the following operations:

1. Receive layout instructions for each page, from the central system, including location and size of graphical elements.

2. Scan pictures into the system using parameters derived from the layout information.

3. View scanned pictures on the display and perform aesthetic corrections, if required. View entire page on display to verify layout.

4. Organize graphical data in local memory as required by page layout and initiate data transfer to the central system.

The novel features of this system revolve around the use of a small computer, in combination with a graphics arts quality laser scanner and some special-purpose digital hardware, to permit input of graphic elements, aesthetic corrections, and the organization of data for each page according to layout information, all on an interactive basis, and in a cost-effective manner.

5. DIGITAL COLOR TV CODING

Sony Corporation (Grant)

William F. Schreiber, Donald E. Troxel, Robert R. Buckley, Geoffrey J. Bunza

The object of this research is to produce commercial quality color TV pictures using a data rate low enough to facilitate applications at present nonfeasible or too expensive. The technique uses separate coding of luminance and chrominance components, with previously developed monochrome coding methods being applied to luminance. Initial work has been done by computer simulation. Design of a real-time (hardware) coder is under way.

XXIII. CUSTOM INTEGRATED CIRCUITS

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1. CUSTOM INTEGRATED CIRCUIT DESIGN

U.S. Air Force – Office of Scientific Research (Grant AFOSR-78-3593)

Jonathan Allen

In this project the objectives are to derive the mask specifications for a custom integrated circuit from an initial algorithmic specification. Currently, the target technology is NMOS using conservative design rules. Two projects center around the specification of algorithms. In one, the algorithm is expressed in terms of a hardware design language and then manipulated through various space-time alternatives to derive a resulting algorithm with the desired performance. In the other, the algorithm is replaced by a formal constraint representation which separates the competence of the algorithm from its performance. An appropriate performance strategy can then be erected on the competence base.

Another project is devoted to the study of placement and routing for subcomponents in an integrated circuit layout. We are also studying techniques for artwork analysis so that equivalent circuits can be derived from the mask geometry. Finally, we are building a computer facility, oriented around the Artificial Intelligence Laboratory LISP machine, including high-quality color and black-and-white graphics. The ultimate objective is to bring together the results of the various projects in this area to form a unified interactive design system.

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XXIV. COMMUNICATIONS BIOPHYSICS

A. Signal Transmission in the Auditory System

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1. BASIC AND CLINICAL STUDIES OF THE AUDITORY SYSTEM

National Institutes of Health (Grants 5 PO1 NS13126 and 5 KO4 NS00113, and Training Grant 5 T32 NS07047)

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

Research on signal transmission in the ear and auditory nervous system continues jointly with the Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary. The mechano-electric transduction system of the inner ear has been investigated through studies of the mechanical responses of the basilar membrane,[6] the intracellular responses in the receptor organ,[1] and the chemical environment of the inner ear.[7] Characteristics of auditory nerve-fiber responses to acoustic stimuli have been described in normal[2-4] and in pathological[5] ears. The expanding clinical use of compound action potentials from the auditory nerve for diagnostic purposes has made it important to determine how these responses are related to responses of nerve fibers from different regions of the inner ear.[8,9] An anatomical study has led to a description of the organization of the "feedback" system from the brain stem to the inner ear, which is substantially different from the previous conceptions.[10]

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XXIV. COMMUNICATIONS BIOPHYSICS

B. Auditory Psychophysics and Aids for the Deaf

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1. INTENSITY PERCEPTION AND LOUDNESS

National Institutes of Health (Grant 5 RO1 NS11153 and
Training Grant 1 T32 NS07099)
National Science Foundation (Grant BNS77-16861)

Louis D. Braida, Sheila M. Chase, H. Steven Colburn, Nathaniel I. Durlach, Adrian J. M. Houtsma, Mary S. Florentine, Charlotte M. Reed, Rosalie M. Uchanski

This research continues to be concerned with the development of a unified, quantitative theory of intensity perception and loudness, and involves the construction and integration of models of sensory processes, short-term memory, perceptual context effects, and decision making, as well as extensive psychophysical experimentation. During the past year, work has been conducted in four areas: (i) the relation of intensity resolution to auditory-nerve firing patterns, (ii) the relation of intensity discrimination to loudness matching, (iii) the dependence of intensity identification on stimulus presentation frequency, and (iv) intensity resolution and loudness in listeners with hearing impairments.

(i) A study of the relation between intensity discrimination and the coding of intensity in auditory-nerve firing patterns has been initiated using an approach introduced by Siebert[1,2] that is based on optimum processing of average-rate information on

auditory-nerve fibers. Recent research results in both psychoacoustics and auditory physiology now differ sufficiently from older ideas that it appears worth while to rework Siebert's formulation. For example, psychoacoustic studies[3] indicate that Weber's Law does not hold for tones at intensities above roughly 40 dB SPL, but rather that intensity resolution improves systematically above this level. In addition, recent physiological data differ, for example, from the description of rate-intensity functions and threshold distributions used by Siebert. Unfortunately, initial indications are that performance predicted by optimum use of average-rate information on auditory-nerve fibers is very sensitive to details of the auditory-nerve description, and that the available physiological data are not sufficiently complete to specify these details. During the coming year we plan to prepare a discussion of this work for publication.

(ii) According to a recent extension of our theory of intensity perception,[4] two stimuli are matched in loudness if and only if their intensities divide the respective dynamic ranges proportionally in terms of just-noticeable differences. To test this prediction we have conducted a series of intensity discrimination and loudness-matching experiments using a common set of listeners with normal hearing. Data were obtained over essentially the entire dynamic range for three types of sound stimuli: 1000-Hz tone in quiet, 1000-Hz tone partially masked by a two-octave wide noise band, and spectrally flat wide-band noise. Of the five listeners tested, only three produced results that had sufficient internal consistency to be useful for testing the prediction. For these three subjects, the data and theory were found to be reasonably consistent. Furthermore, these data were found to be strongly inconsistent with predictions based on Fechner's classical theory. Further details of this research have been submitted for publication.[5]

(iii) Identification experiments using 13 tone-pulse stimuli (1000 Hz, 500 msec) spaced by equal decibel increments from 48 to 90 dB SPL were conducted under three different presentation probability conditions: EQ, in which all stimuli were equally likely; MF, in which the middle intensity was presented on roughly 1/3 of the trials; and EF, in which each of the two extreme intensities was presented on roughly 1/5 of the trials. No correct response feedback was provided. The results were analyzed in terms of sensitivity and bias in accordance with the preliminary theory of intensity resolution[6] using a maximum-likelihood procedure.[7] The listeners generally shifted their decision criteria for MF and EF conditions in the directions required to increase correct identification performance, but no significant changes in sensitivity were observed relative to the EQ condition. These results are consistent with the predictions of the preliminary theory of intensity resolution and the results of Lippmann[7] on the effects of payoff variation, but are at variance with those of Cuddy[8] on the effects of presentation probability variation on tone-frequency identification. Further details of these results are available in Bugnacki.[9]

(iv) Experiments currently under way with hearing-impaired listeners are concerned with the measurement of basic intensity resolution over the dynamic range of selected pure-tone frequencies, and with the determination of loudness matches at a given frequency between the normal ear and the impaired ear (for listeners with unilateral impairments) or between different frequencies in the same ear (for listeners with high-frequency loss). In addition, we are beginning a series of measurements of the variability of loudness comparisons between the normal ear and the impaired ear in order to obtain a quantitative measure of signal distortion in the impaired ear. This program includes listeners with a wide variety of type and severity of hearing loss, and is undertaken both to provide insights into the perceptual abnormalities associated with hearing impairments and to check the validity of our theoretical models. During the coming year we plan to prepare the results of these measurements for publication.

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2. BINAURAL HEARING

National Institutes of Health (Grant 5 ROl NS10916)

H. Steven Colburn, Nathaniel I. Durlach, Kaigham J. Gabriel, Rudolph G. Hausler, Yoshiko Ito, Allen W. Mills, Peter J. Moss, William M. Siebert, Ronald A. Siegel, Carl L. Thompson

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

In one project, we have completed two binaural detection experiments with pseudo-random noise maskers to examine the relative contributions to the variability of the decision variable from the randomness of the stimulus (external noise) and from the stochastic nature of the internal processing (internal noise).[6] The first experiment compares detection performance measured in a two-interval, temporal forced-choice paradigm for two conditions: the same noise waveforms in both intervals of a trial versus statistically independent samples of noise in the two intervals of a trial. The second, one-interval, experiment compares performance differences among ten samples of noise waveforms, each used for about 1000 trials. Two interaural configurations were studied. In the first, the stimuli at the two ears were identical. In the second, the target tone was inverted at one ear, although the noises at the two ears were identical. In the first configuration (NOSO), internal noise dominates external noise, and in the second (NOSπ), the variance of the external noise is comparable to the variance of the internal noise. These results are surprising to us and will be pursued further with additional experiments.

In a second project, we are testing binaural hearing models that use subjective lateral position as the sole decision variable.[7] We measured the just-noticeable difference (jnd) in interaural time delay for several values of the reference interaural time delay for tone stimuli.[8] We concentrated our research in the region between one-fourth and one-half the period of the tone because the model predicts very large jnds in this region. Our results and our subjects' reports of their impressions cast serious doubt on the validity of the position model. We found no large interaural time jnds, even for values of interaural time delay for which the position model predicts the largest jnds. Furthermore, the subjects report that the perceived lateral position of a binaural tone is not a single, well-defined image as assumed by the position model, and that cues other than lateral position are often used in interaural time discrimination for large time

delays when the position-based cue is not helpful.

In a third project, we are investigating the effect of a masking noise on interaural time discrimination. The jnd in interaural time delay for a narrow-band noise signal was measured for several different interaural conditions of a wide-band masking noise. The narrow-band signal is a 1/3-octave Gaussian noise band centered at 500 Hz with an overall level of approximately 56 dB SPL, the same at each ear. The masking signal is a Gaussian noise including frequencies from 250 Hz to 1500 Hz, also presented at an overall level of 56 dB SPL. The interaural conditions of the masker include the interaurally identical case (NO), the interaurally inverted case ($N\pi$), and the interaurally uncorrelated case (NU). We also used maskers with an interaural delay of τ = 100 μs ($N\tau$), with an interaural attenuation of α dB ($N\alpha$), or with both delay and attenuation ($N\tau, \alpha$), where α is realized by attenuating one ear and is chosen to center the masker when both τ and α are present. Several relations held consistently for all four subjects. First, the masked jnds were always larger than the jnds measured with no masking. Second, the progression of increasing difficulty (increasing jnds) was NO, NU, and $N\pi$. Note that this progression is exactly opposite to that expected from detectability results. Third, the $N\tau, \alpha$ case is more difficult than $N\tau$ or $N\alpha$. Note that this is consistent with the notion that the jnd task is easier when the lateral positions of the masker and target are separated within the perceptual space; however, this notion was not applicable consistently for the rest of the conditions measured. We are continuing to test some of these conditions.

In a fourth project, we are investigating the jnd in the interaural correlation of Gaussian noise. We are measuring the dependence of the jnd on bandwidth at two reference correlations, +1 and 0. Gaussian noise waveforms with eight different bandwidths from 3 Hz to 4500 Hz were synthesized with the narrow-band cases centered at 500 Hz. For seven of the bandwidths, waveforms were synthesized via sums of random-amplitude, random-phase cosines, one every three Hertz. For the 4.5-kHz low-pass case, waveforms were generated from Gaussian-distributed random numbers. At each bandwidth, waveforms were randomly chosen for each representation from an available set of 64 waveforms. In measurements so far, jnds from a reference correlation of +1 have been determined for three subjects. The jnds obtained are about 0.04 for the wide-band waveforms (greater than 1/3 octave) and decrease to 0.004 for the narrow-band waveforms (less than 1/3 octave). These results, together with results from a reference correlation of zero, will enable us to answer questions about the spectral characteristics of our correlation processors and help us to interpret binaural detection performance for narrow-band stimuli.

In a fifth project, we are investigating the discrimination of interaural time delay of the envelopes (onset and offset) of tone-burst stimuli. We are measuring the jnd in the interaural delay of the envelope with no ongoing delay. This jnd has been determined

for three rise times (5, 50, and 150 ms) and two frequencies (500 and 4000 Hz) for four subjects at 74 dB SPL. Also, the level dependence of the jnd at 500 Hz was measured for two of the subjects. The jnds are a few hundred microseconds for all subjects at 4000 Hz, with only a slight dependence on the rise time. At 500 Hz, except for one subject, jnds increase from a few hundred microseconds to about a millisecond when the rise time increases from 5 ms to 150 ms. One subject shows exceptional results at 500 Hz; his jnds are 2 ms, 20 ms, and 35 ms for the three rise times measured. (His audiogram was normal and the results were repeatable.) For the two subjects tested at various levels, the measurements show very large increases in the jnd as the level decreases. For example, the jnd at 14 dB SPL is 90 ms. The jnd is approximately inversely proportional to the pressure in dynes/cm^2 for low and moderate levels and asymptotes to a constant value at high levels.

In a sixth project, conducted in cooperation with the Eaton-Peabody Laboratory of the Massachusetts Eye and Ear Infirmary, we have made relatively crude but reliable measurements of spatial resolution and interaural discrimination in a number of persons with hearing impairments and in a group with multiple sclerosis, in addition to a normal control group. Measurements include: the minimum audible angle (MAA) in the vertical median plane, the MAA in the horizontal plane at eight reference locations around the head, the jnd in interaural time delay, and the jnd in interaural amplitude ratio. The standard stimulus was a pair of broadband (250 Hz-10 kHz) noise bursts of one-sec duration separated by one second, although additional measurements with other stimuli were occasionally performed. Subjects with several types of hearing impairments were used, including unilateral and bilateral conductive losses, bilaterally symmetric sensorineural losses, unilateral Meniere-type losses, acoustic neuromas (all surgically confirmed vestibular schwannomas), and unilateral dead ears. The bilateral senorineural group was divided into two categories according to their performances on speech-discrimination tests. Results were relatively uniform within each category with the exception of the acoustic neuroma category, which showed large intersubject differences in all measurements. Results are generally consistent with the notion that there are separate processors for interaural timing information, interaural level information, and spectral information. Each of these types of information can be interfered with separately. For example, conductive losses, which degrade all three types of information, resulted in the poorest performance, and subjects with bilateral sensorineural losses and poor speech-discrimination performance showed poor use of spectral information (as reflected in the vertical MAA and the horizontal MAA on the sides) but relatively normal use of time and intensity information (as reflected in the jnds and the horizontal MAA ahead or behind). In subjects with multiple sclerosis and with audiometrically normal hearing, it was found that the ability to use each of the types of information could be compromised independently.

A seventh project is concerned with more careful measurements of binaural interaction in individuals with well-defined hearing losses of various types. Much of our work to date has been concerned with the development of a set of programs which permits the measurement of jnds for either time or intensity. One program constructs sets of narrow-band noise waveforms with specified bandwidths, center frequencies, and relative delays. The others control experiments in a very flexible way, including the option of substantial interaction between the experimenter and the subject. The experimenter can, for example, present stimuli at equal SPL to the two ears, preset the attenuation to each ear, or present the stimuli under subject control for ABLB or "centering" adjustment. Using the selected signal levels, the experimenter can test sensitivity to either interaural time or interaural intensity. The experimenter can choose to present a set of stimuli at a selected level, in which case the program displays the cumulative percent correct after each trial and a summary of the run including d' at the end of each block of trials. Alternatively, he can select a "PEST" adaptive procedure to obtain an estimate of the jnd, or he can elect to present single trials at selected stimulus parameters so that he can train the subject and/or make a subjective estimate of the jnd. The program is now being used in an extensive study of a subject with a suspected acoustic neuroma. Since this subject is available only a short time before surgery, the flexibility of the program has proved very helpful and the interactive features have been especially important by allowing efficient selection of parameters.

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3. HEARING AID RESEARCH

National Institutes of Health (Grant 5 ROI NS12846)

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This research is concerned with the development of improved speech-reception aids for persons suffering from hearing loss and of fundamental understanding on the limitations of such aids. During the past year, our work in this area has continued to focus on the problem of matching speech to residual auditory function. The work in this area is directed toward improved signal-processing schemes for people with sensorineural impairments, and includes the study of linear amplification, amplitude compression, and frequency lowering.

Our research on linear amplification is concerned with modelling the dependence of speech-reception performance on the speech materials, the background interference, the listener, and the linear-amplification system. Initial work on this project focused on the extent to which Articulation Theory[1-5] can be used to predict the dependence of word intelligibility on frequency-gain characteristics and presentation level for listeners with specified audiometric configurations. In general, the theory was found to yield relatively good predictions for a group of listeners with steeply sloping, high-frequency hearing loss, although it was necessary to assign a single number, the proficiency factor, to each listener in order to derate performance relative to that for listeners with normal hearing. Further details of these results are available in Dugal.[6] Future work on this project will be concerned with evaluating the theory for listeners with a wider variety of audiometric configurations, with the determination of optimum linear-amplification systems for specified configurations, and with the development of a model for the proficiency factor.

Research on amplitude compression for listeners with reduced dynamic range has been primarily concerned with obtaining further insight into the negative results obtained in our initial study of the effects of multiband amplitude compression on speech intelligibility for persons with sensorineural losses.[7] We have duplicated the critical portions of our initial study on listeners with normal hearing, employing spectrally shaped noise to simulate the losses (in terms of elevated threshold, reduced dynamic range, and recruitment) of the listeners with genuine impairments tested in the initial study. Roughly speaking, the results of this study show that, although the normals with simulated losses

generally obtained higher scores than the impaired listeners, the relative performance of the various signal-processing transformations tested was independent of whether the loss was genuine or simulated. Specifically, the results for the normals, like the results for the impaired, showed no advantage for compression over linear amplification with appropriate high-frequency emphasis. Further details of these results are available in DeGennaro.[8]

Our research on frequency lowering for listeners with negligible hearing at high frequencies employs a pitch-synchronous time-dilation technique with warping of short-term spectra[9] and has included three major projects: (i) a study of the effects of training on the perception of frequency-lowered consonants, (ii) a study of the effects of lowering and warping parameters on the discriminability of frequency-lowered consonants, and (iii) a study of the perception of frequency-lowered vowels.

(i) Naive listeners with normal hearing were trained to identify a set of 72-CV nonsense syllables processed by frequency lowering or low-pass filtering to bandwidths of 1000 and 1667 Hz. Pre- and post-training identification tests indicated that, although substantial increases in performance occurred for both processing conditions, greater improvements were obtained for the frequency-lowered condition. In the post-training tests, subjects were generally better able to identify the filtered materials than the lowered materials, but achieved higher scores for the 1667-Hz bandwidth condition in a noisy background when frequency lowering was used. Analysis of identification errors suggests that the relatively good performance obtained in quiet-background tests for the filtered materials may have been due to weak low-frequency cues less resistant to additive noise than the recoded high-frequency cues introduced by frequency lowering.

(ii) Discriminability measurements were made on 89 pairs of consonants (in CV nonsense syllables), including contrasts of voicing, manner, and place, for a variety of lowering, warping, and filtering conditions. In general, for a given bandwidth, overall performance for lowering was roughly equivalent to that for filtering for those warping conditions which left low-frequency components relatively intact. Warping conditions which altered low-frequency components (such as linear lowering – proportional frequency reduction) resulted in overall performance inferior to that for low-pass filtering. The ranking of the various processing conditions on the phonetic contrast categories of voicing and manner was similar to that for overall performance, although the discriminability of specific types of manner contrasts was different for filtering and lowering. For example, for contrasts of affricates with plosives and fricatives, performance was better for lowering than for filtering, while for contrasts of nasals with semivowels the opposite was true. Performance on place contrasts, which was generally inferior to that for voicing and manner contrasts for all processing conditions, exhibited the same characteristic. For example, higher performance was obtained on filtered materials for place contrasts within semivowel and nasal sounds, but on lowered materials for

place contrasts of fricative sounds. The results of this discrimination experiment are roughly similar to the consonant identification experiment described above.

(iii) Discrimination and identification tests of filtered and lowered vowels in /b/-V-/t/ contexts were conducted using naive normal-hearing listeners. Discriminability was found to be high for materials processed to a 1000-Hz bandwidth either by low-pass filtering or lowering with warping adjusted to minimize change in low-frequency elements. The naive listeners used in this study were, however, able to achieve much higher identification scores for the 1000-Hz bandwidth condition on the filtered materials than on lowered materials. Furthermore, both warped lowering by a factor of 5 and linear lowering by a factor of 2 yielded similar overall performance – although different patterns of errors – in this test. In general, the confusions exhibited by the listeners used in this study tended to relate to changes in formant frequency induced by frequency lowering: features related to first-formant frequency were better perceived than those related to second-formant frequency for the warped-lowering condition (which altered high frequencies proportionally more than low frequencies), while both types of features were degraded for linear lowering (which lowers all frequencies the same relative amount). Further details of this study are available in Picheny.[10]

In general, the results obtained in our initial studies of both amplitude compression and frequency lowering have been disappointingly negative. In future work, we plan to conduct further analytical studies to achieve basic understanding of the results obtained and to develop insight into fundamental limitations on these techniques. We believe that such efforts are essential. Not only may further study lead to results which are more positive, but also it is extremely difficult to build on such results unless they are clearly understood.

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4. TACTILE COMMUNICATION OF SPEECH

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The goal of this project is to develop tactile speech communication aids for the deaf and deaf-blind. Our research has been directed toward evaluating two basic types of tactile communication systems, one based on spectral displays of the speech waveform and the other based on the natural articulatory display present on the face during speech.

The spectral displays have been realized using an Optacon transducer system interfaced to a PDP-11 computer.[1,2] In these displays, frequency is coded in the 24 rows of the transducer while either amplitude or time is coded in the six columns. At present, subjects with normal sight and hearing are evaluating these displays with respect to discrimination and identification of short speech segments. One study has concerned the ability of subjects to identify a set of 12 consonants in CV nonsense syllables spoken by four speakers. An Optacon-based tactile display (spectral amplitude versus frequency) was compared to a visual analog driven by the same information. After training, the users of the tactile display performed much as listeners at a -12 dB S/N ratio, while the users of the visual display were equivalent to listeners at a -6 dB S/N ratio. For both displays performance was best on the feature voicing and poorest on place, which was most degraded by the use of multiple talker and vowel contexts. Additional details are available in Mook.[3] The second study concerned the discriminability of vowels (in isolation as well as /b/-V-/t/ contexts) displayed on the Optacon in amplitude-frequency and time-frequency modes. In general, very similar results were obtained on the two systems, although average scores were slightly higher for the amplitude-frequency

display. An analysis of results in terms of articulatory features indicated that the most salient cues were concerned with vowel amplitude, duration, and first-formant frequency, with less importance associated with the separation between first- and second-formant frequencies. Further details are available in Clements.[4]

Research on articulatory displays of speech has focused on the Tadoma method of speechreading. We are studying the performance of both deaf-blind individuals highly trained in the Tadoma method[5] and also inexperienced subjects.[6] Current work with an experienced Tadoma user is directed toward (a) increasing our understanding of the cues involved in speech perception through Tadoma by determining how error patterns for consonants and vowels change as a function of hand position; (b) exploring linguistic competence using standardized language tests as well as tests designed to examine more specific linguistic features; and (c) analyzing the subject's speech production through measurements of durational, prosodic, and articulatory aspects of speech recordings. Work with normal subjects[6, 7] (in which blindfolds and masking noise are used to eliminate visual and auditory cues) includes testing the ability of these subjects to discriminate speech elements, to learn to identify isolated phonetic units, and to learn to decode words in isolation and in connected speech.

Although it is already evident that the speech reception performance of certain experienced Tadoma users is substantially superior to the performance that has been achieved with artificial tactile displays, the reasons for this are not yet clear. It is possible that superiority arises because the experienced users have unusual tactile or cognitive abilities, the display itself is inherently advantageous (because it is a rich, multidimensional display and/or a display that is directly related to the speech-production process) or the opportunity afforded these experienced users to learn the Tadoma display greatly exceeds that afforded those subjects who were trained on artificial displays. A major portion of our research program is concerned with determining the extent to which each of these factors contributes to Tadoma's superiority.

Our future work will include comparative studies of Tadoma and various spectral displays using subjects with comparable amounts of training on the different displays. In addition, we plan to develop a "Synthetic Tadoma System" for use as a research tool. This system will involve a sensor array to be placed on the talker's face and an "artificial face" to be used as a display. Aspects of this display will be varied to determine their effects on speech-perception performance. Work is also in progress to build a new transducer system for spectral tactile displays. This device (modelled after a device developed by Sherrick at Princeton University) will consist of a rectangular array of piezoelectric bimorph vibrators appreciably larger in area than the Optacon. We are currently investigating such issues as the size and density of the vibrators in the array, appropriate interface hardware, and control algorithms.

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5. MUSICAL PITCH

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The overall objective of this research is to gain understanding of the auditory processes that underlie musical-pitch sensations arising from complex stimuli. Research effort has been devoted to three projects.

a. Pitch Perception of Harmonic Tone Complexes

Musical-interval identification experiments were conducted using dichotic two-tone complexes of frequencies nf_o and $(n+m)f_o$, where f_o is the fundamental (note) frequency, n is a random integer between 1 and 10, and m is a fixed integer between 1 and 4. The results of these experiments were compared with theoretical results derived from three modern pitch theories. The optimum-processor theory[1] was used to derive best and worst performance bounds by computer simulation, where best performance is obtained if the range of expected fundamental frequencies is known to the processor, and worst performance results if the processor scans the entire fundamental frequency range. The virtual pitch theory[2] and the pattern-transformation theory[3] were augmented with additional specific assumptions which made it possible to derive quantitative performance bounds predicted for our experiments. It was shown that the predictions of the

optimum-processor and virtual pitch theories are very similar and quite different from predictions made by the pattern-transformation theory. The former two are much better supported by the data than the latter one.[4] Significant discrepancies between data and all theories were found in some instances, however, which seem to indicate the presence of a so-called "analytic" pitch mode in which the listener fails to hear the pitch of the missing fundamental, but, instead, hears pitches of individual tone components. This hearing mode is not included in any of the current theories, but is found to have significant effects on pitch or melody recognition data obtained with complex tones.

b. Pitch Perception of Amplitude-Modulated Noise

We are conducting a theoretical analysis of pitch perception of amplitude-modulated noise. In an earlier experimental study[5] it was shown that if white noise is first low-pass filtered (cutoff frequency f_{co}) and subsequently modulated (100% AM) with a periodic signal (sine, square, or pulse) of fundamental frequency f_o, the sound evokes a pitch sensation of f_o when $f_{co} \ll f_o$. When f_{co} approaches f_o, there is no measurable pitch sensation for the pulse-modulated noise, but for the sine- and square-wave modulated noise, the pitch sensation increases again with increasing noise bandwidth. Traditionally, amplitude-modulated noise has been regarded as being devoid of spectral clues, and all pitch properties of these signals were therefore explained by temporal auditory processing. We are currently doing quantitative investigation of a pitch theory recently suggested by Pierce et al.[6] in which pitch clues are extracted from the short-term power spectrum. This formal model is similar to the classical "energy-detector model" in that it comprises a bank of parallel filters, square-law devices, and "leaky" integrators. It differs in the sense that it does not look at the temporal variation of the energy at each channel, but looks at any instant of time across all channel outputs, performing a running "spectral" autocorrelation. Qualitatively the theory can account for the experimental results described above.[5] Quantitative details are still being worked out.

c. Binaural Diplacusis

We have completed two projects concerned with the study of binaural diplacusis, the phenomenon in which a pure tone evokes a different pitch when presented to one ear compared to the other. In persons with normal hearing, the pitch differences in binaural diplacusis are very small; in pathological cases, however, this pitch difference can be large (e.g., 10%), and is often found at frequencies where the detection threshold curve shows abrupt changes. In one project, monaural and binaural pitch matches were made to the cubic difference tone (CDT) $2f_1 - f_2$ by a subject who showed a significant amount of diplacusis over some frequency range. This range was made to coincide with either the CDT or with the primary tones. These experiments shed some light on the question of whether or not the CDT is coupled to the basilar membrane at the characteristic place

of the CDT frequency.[7] In another project, the effect of intensity on binaural diplacusis was investigated. Results from preliminary experiments seem to indicate that, at any given frequency, the diplacusis function of intensity is given by the difference between the monaural pitch-intensity functions measured at that frequency for the two ears.

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XXIV. COMMUNICATIONS BIOPHYSICS

C. Transduction Mechanisms in Lateral Line and Vestibular Organs

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National Institutes of Health (Grant 2 ROl NS11080)

Lawrence S. Frishkopf, Charles M. Oman

Our overall objective is to understand the changes that occur in receptor cells of the phylogenetically related auditory, vestibular, and lateral-line systems in response to mechanical stimuli. Under investigation are the processes of mechanical-to-electrical transduction, membrane depolarization, synaptic transmission, and neural excitation in hair-cell organs. The two organ systems that we are studying were chosen because of their relative accessibility and simplicity: free-standing lateral-line organs in amphibians and elasmobranch vestibular organs.

Goals during the past year have been (1) to characterize the mechanical properties and motion of hair-cell cilia in response to controlled mechanical stimuli; and (2) to estimate through theoretical models the magnitude of cupula motion in semicircular canals of different species during normal head movements.

1. MECHANICAL PROPERTIES OF HAIR-CELL CILIA

Lawrence S. Frishkopf, Richard D. Kunin

The mechanical properties of hair-cell cilia may determine, in part, the frequency response of hair-cell organs, particularly of auditory organs. Certain frequency-related properties such as sharpness of neural tuning, tone-on-tone interactions, and nonlinear response characteristics are not well accounted for by observed basilar membrane motion, leading to a postulated second stage of filtering. It is possible that the hair-cell cilia which couple the overlying tectoral membrane to the hair cells within the organ of Corti may be the site of such nonlinear processes.

With this in mind, we have begun to study the motion of hair-cell cilia in the isolated crista of the semicircular canal of the skate using the Nomarski interference contrast microscope. Fine probes have been used to contact and displace cilia in order to observe their mechanical properties. Stereocilia appear to be stiff and brittle whereas kinocilia are flexible and may, under appropriate conditions, "beat" spontaneously. Rapid return of the stereocilia after displacement suggests a high-frequency response characteristic. Results are preliminary.

2. THEORETICAL MODEL FOR SEMICIRCULAR CUPULA MOTION

Charles M. Oman

In 1972, Oman and Young theoretically estimated the magnitude of human semicircular canal cupula motion. To provide a basis for comparison of our more recent experimental results on cupula motion in the skate (Oman, Frishkopf, and Goldstein, 1979) with the observations of McLaren and Hillman (1976) in the frog, a mathematical model for semicircular canal fluid flow was developed which specifically accounts for intercanal and interspecies differences in the large radius and cross-section shape of the membranous duct. Body temperature dependent differences in endolymph viscosity were also taken into account. Differences in the length and width of the utricle were included by extending an analytical approach originally suggested by Van Buskirk (1977) to a more general case. The analysis shows that the canal short time constant (associated with the development of steady flow in the canal duct) is probably a factor of four shorter than some previous estimates. The short time constant should be significantly influenced by the ellipticity of the duct cross section, but independent of utricular shape. The volume of endolymph displaced during cupula deformation is expected to be proportional to the short time constant of endolymph flow, and also to the length of the utricular segment. Cupula volume displacement, however, is normally relatively independent of utricular cross-sectional area. Based on estimates of cupula area in different species, cupula midpoint displacement for a swinging door or shearing mode displacement of the cupula, in millimicrons per degree per second of head velocity, is estimated to be 15-20 in man; 20-40 in the frog; and 85-300 in the skate. The range in these estimates results directly from known differences between the horizontal, anterior, and posterior canal morphology.

To interpret the above results, it is necessary to estimate the dynamic range of head angular velocities. The latter is poorly known, except in man. In the human, although head velocities not uncommonly exceed 1000 degrees per second, most normal head motions involve stimuli in the range from 2-200 degrees/second in yaw. It seems likely, therefore, that most head movements in man are associated with cupula displacements below the range of light microscopy. Although it may be possible to visualize cupula motion in animals using large stimuli (cf. McLaren and Hillman, 1976; McLaren, 1977; Oman, Frishkopf, and Goldstein, 1976), such results should be interpreted cautiously, particularly since the bending mode of cupula deformation is likely to be amplitude-dependent.

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XXIV. COMMUNICATIONS BIOPHYSICS

D. Biomedical Engineering

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National Institutes of Health (Training Grant 5 T32 GM07301)

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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 a training grant from the National Institutes of Health.

XXV. NEUROPHYSIOLOGY

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1. A CENTRAL PATHWAY OF THE INFRARED SYSTEM OF THE RATTLESNAKE, Crotalus viridis

National Institutes of Health (Training Grant 5 TOl EY00090)

Bell Laboratories (Grant)

Edward R. Gruberg, Eric A. Newman

[Eric A. Newman is with the Eye Research Institute, Retina Foundation, Boston, Mass.]

We have traced a pathway of the infrared system in the rattlesnake from the nucleus of the lateral descending trigeminal tract (LTTD, the primary infrared nucleus) to the tectum. This pathway links the LTTD and the intermediate tectal neuropil, where previous electrophysiological studies have demonstrated infrared responses. Following HRP injections into the intermediate layers of the tectum, the Mesulam benzidine blue method revealed a group of large (25-40 μ) cells on the ventrolateral margin of the contralateral medulla, filled by retrograde transport. This nucleus, which is distinct from the primary trigeminal nuclei, we have provisionally named "nucleus R". Its rostral boundary is immediately posterior of the Vth root entry, and its caudal boundary is posterior to the point of closure of the fourth ventricle. The axons from the nucleus R decussate in the ventral medulla, turn rostral in a ventral bundle, and in the tegmentum proceed dorsolaterally to the tectum. Extracellular microelectrode recordings made from the region of the nucleus R show that units are driven by infrared but not by visual or tactile stimuli. Electrolytic lesions made by the recording electrodes confirm that the units are in the nucleus R. Following HRP injection into the nucleus R, cells in the ipsilateral LTTD are heavily stained due to retrograde transport. The axons of nucleus R cells are also stained in these experiments (by anterograde transport), with terminal branches in intermediate tectal layers. The axons follow the same nucleus R-tectal pathway seen following tectal HRP injections. These experiments show that an infrared pathway in the rattlesnake proceeds from the LTTD to the ipsilateral nucleus R and thence to the contralateral tectum.

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2. CONNECTIONS OF THE TECTUM OF THE RATTLESNAKE, *Crotalus viridis*: AN HRP STUDY

National Institutes of Health (Training Grant 5 TO1 EY00090)

Bell Laboratories (Grant)

Edward R. Gruberg, Eric A. Newman

[Eric A. Newman is with the Eye Research Institute, Retina Foundation, Boston, Mass.]

This research has been done in collaboration with E. Kicliter, Department of Anatomy and Laboratory of Neurobiology, University of Puerto Rico, and P. H. Hartline and L. Kass, Eye Research Institute, Retina Foundation, Boston, Mass.

We have studied the connections of the tectum of the rattlesnake by tectal application of horseradish peroxidase. The tectum receives bilateral input from nucleus lentiformis mesencephali, posterolateral tegmental nuclei, anterior tegmental nuclei, and periventricular nuclei; ipsilateral input from nucleus geniculatus pretectalis, and lateral geniculate nucleus pars dorsalis; and contralateral input from dorsolateral posterior tegmental nucleus and the previously undescribed nucleus reticularis caloris (RC). RC is located on the ventrolateral surface of the medulla and consists of large cells 25-40 μ in diameter. Efferent projections from the tectum can be traced to the ipsilateral nucleus lentiformis mesencephali, the ipsilateral lateral geniculate region, anterior tegmental region, and wide bilateral area of the neuropil of the ventral tegmentum and ventral medulla. We have not found any direct tectal projections from the sensory trigeminal nuclei including the nucleus of the lateral descending trigeminal tract (LTTD). We suggest that in the rattlesnake RC is the intermediate link connecting LTTD to the tectum.

3. VOLUMETRIC THEORY OF COLOR CONSTANCY

Bell Laboratories (Grant)

Michael H. Brill

In previous papers[1,2] we presented a design for a trichromatic photosensing device with an analog of color constancy: For a particular class of illuminants, object spectral reflectances, and spectral sensitivities (tristimulus functions in a particular basis) of the device, we proved the illuminant invariance of any ratio of tristimulus volumes generated by triads of object colors. In that work, it was assumed that the illuminant energy spectrum is a linear combination of three known functions of wavelength.

We recently showed[3] that a single, different assumption is sufficient to assure the

illuminant-invariance of tristimulus volume ratios – it is enough that object spectral reflectances be linear combinations of three known functions of wavelength.

Reflectance spectra for natural, nonmetallic objects (see Ref. 4) are smoothly varying and generally have, at most, two maxima in the human visible-wavelength range; this suggests that such spectra may be reasonably represented by an expansion in terms of three basis functions over this range.

Although the present assumption constrains the object reflectance spectra more heavily than in the previous paper, it allows almost complete freedom for the possible illuminants. For example, it gives illuminant invariance when tungsten lights are replaced by the prime-color lights developed by W. A. Thornton (Ref. 5), which have just three spectral lines but are marketed for their high efficiency and color-rendering capability. (One must insure only that the illuminant does not render all object colors coplanar in tristimulus space, as it would if it consisted of one or two spectral lines – or more generally, if det [A] = 0 in the treatment that follows; in such cases, a volume ratio cannot be defined.) Thus the present invariance occurs under conditions like those under which color constancy obtains for human vision – a feature that vindicates and transcends our original intention of designing an illuminant-invariant object-color recognizer.

The mathematical invariance is readily shown as follows: Let the device's tristimulus functions be $q_j(\lambda)$ $(j = 1, 2, 3)$, the illuminant energy spectrum be $I(\lambda)$, and the reflectance spectrum of the i^{th} object be $r_i(\lambda) = \sum_{k=1}^{3} B_{ik} u_k(\lambda)$. Here, it is assumed that all reflectance spectra in nature differ only in their B-parameters. Then the linear filtrate (tristimulus value) for the i^{th} object due to the j^{th} tristimulus function is

$$Q_{ij} = \int I(\lambda)\, r_i(\lambda)\, q_j(\lambda)\, d\lambda = \sum_{k=1}^{3} B_{ik} \int I(\lambda)\, q_j(\lambda)\, u_k(\lambda)\, d\lambda \equiv \sum_{k=1}^{3} B_{ik} A_{kj}.$$

Given three objects i, this equation can be written in the square-matrix form [Q] = [B][A]. Here [B] depends on the reflectance spectra but not on the illuminant. [A] depends on the illuminant, and on the tristimulus and reflectance-basis functions, but not on the reflectance parameters.

The volume of the parallelepiped in tristimulus space generated by these three objects is det [Q] = det [A] det [B]. Another parallelepiped from three other objects under the same light will have a volume given by det [Q'] = det [A] det [B']. The ratio of these volumes is det [Q]/det [Q'] = det [B]/det [B'], which is manifestly illuminant-invariant.

Previously[1, 2] we restricted the illuminant spectrum to be an expansion in three basis functions; this did not free the reflectance spectra to the extent the reciprocal arrangement did for the illuminant spectrum in the present formation. Clearly,

reflectance and illuminant spectra do not play symmetric roles in the volumetric approach to color constancy. The present assumption solves the problem of color constancy when looking through a nonturbid colored medium of variable thickness, which is important, for example, for the survival of underwater creatures and fishing landdwellers. In the previous work, we assumed that the illuminant spectrum is a linear combination of three known functions, and is thereby defined as "smoothly varying." If two spectra satisfy this assumption, however, in general their product will not. Thus varying the thickness of water through which one looks must cause departures from the stated assumption of those papers.

With the present assumption, an otter fishing in varying depths of water could get depth-independent reflectance information from tristimulus volume ratios – so long as the reflectance spectra in its environment were well-behaved in the sense described above. Even through turbid water, reflectance information can be obtained from ratios of volumes produced by tristimulus-vector differences; the differencing operation removes dependence on added light reflected directly from the turbid medium.

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4. PERCEPTION AND THE OBSERVER IN RELATIVITY THEORY

Bell Laboratories (Grant)

Michael H. Brill

If only by analogy, the study of perception can clarify issues in physics. Sometimes we can use perceptual considerations to find common-experience analogs of "counter-intuitive" physical propositions. For example, consider the following proposition in Special Relativity: If A and B are co-moving observers, and each holds a ruler in the direction of their relative velocity, then each sees the other's ruler as shorter than his own. This proposition has a more mundane perceptual analog: A and B stand twenty feet apart and each holds a ruler vertically at arm's length. Then A's ruler subtends a larger visual angle to A than B's ruler, and B's ruler subtends a larger visual angle to B than A's ruler. This example shows how observed relationships between objects

can become symmetric when observer labels change together with object labels.

Not all the lessons of perception render established physical theories intuitively plausible. One lesson in particular, that different states of the world – such as metameric colors – can be indistinguishable to an observer, might cause one to look again at some seemingly incontrovertible connections between theory and experiment. Consider the famous Michelson-Morley experiment, which showed that the round-trip travel time of light is isotropic (the same in all directions). Does this imply that the speed of light is isotropic? It is easily shown that the following eikonal (direction dependence of the speed of light) gives the same round-trip travel times for all directions, even though it prescribes a nonisotropic speed of light:

$$u(\theta, \phi) = \frac{c}{1 + \epsilon \cos(\theta - \theta_o)},$$

where u is the speed of light, θ and ϕ are angular coordinates, and c, ϵ, and θ_o are constants.

This is an ellipsoid with two equal axes and the observer at one focus. It is only one – the simplest – eikonal that does the trick. It is implicit in an alternative to special-relativistic kinematics based on clock synchronization other than by electromagnetic waves.[1-3]

The above example does not challenge Special Relativity (which has many more empirical confirmations than the Michelson-Morley experiment), but illustrates the caution that must be taken in connecting measurement – and the observer – with physical theory. The numbers that emerge from a theory reflect implicit assumptions about the observer.

Let us examine this point as it relates to General Relativity, which promises deference to the observer via the Principle of Equivalence and the Principle of General Covariance. Most liberally interpreted, the Principle of Equivalence states that the local effects of a gravity field near an observer are indistinguishable from the effects of accelerating the observer,[4] and the Principle of General Covariance states that the observations of the universe by different observers can be connected by a coordinate transformation.[5]

Although both these principles guided Einstein's formulation of the gravitational field equations, no prescription has been derived from the field equations for determining the change in the observed universe when the observer undergoes acceleration. By itself, this is not a problem: The coordinate-independent formulation of the field equations cannot be expected to carry the observer dependence if this dependence resides in choice of coordinates (as dictated by the Principle of General Covariance). Solving the field equations, however, involves selecting a coordinate condition (boundary condition) on the equations. If observer frames of reference can be connected by a coordinate transformation, it is in the coordinate condition that we would expect to find the

prescription of observer dependence. Such a prescription has not been incorporated in solutions of the field equations in which there are gravitational sources (i. e., in which the space is not flat). Eddington's idea of "proper coordinates"[6] is an acknowledgment of the problem, but without a detailed formulation. The field equations with gravitational sources have been solved for only a few special cases, none of which parametrically incorporates the state of motion of the observer.

These considerations bear significantly on the empirical interpretation of nonflat solutions to Einstein's field equations. The fundamental tests of General Relativity – light-bending, red shift, and the perihelion advance of mercury – all invoke the static, spherically symmetric Schwarzschild solution, which has a coordinate condition at spatial infinity. It might be argued that this coordinate condition is a statement about the universe seen by an observer on earth, but then how would this vary when the observer is not on the earth? If General Relativity is to be able to distinguish between observers on and off the earth in its description of such effects as the red shift of light from the sun (which is certainly influenced by observer velocity, for example), it must include in its explanation of present earth-bound observations the fact that the earth is neither at spatial infinity nor static with respect to the sun. To do this, the theory must be augmented to incorporate the observer's state of motion and position in the gravity field.

One possible approach is to extend the approach of Anderson[7] to nonflat spaces. By a coordinate transformation, Anderson extended Special Relativity to a uniformly accelerated observer in a gravitational-source-free space: Given the universe seen by inertial observer A, accelerating observer B's world line in that description, and the acceleration sensed by B, B's description of the universe can be inferred. Ultimately, the acceleration sensed by B should prove to be unnecessary information if the Principle of Relativity is to be suitably generalized – i. e., if any observer's picture of the universe is to be complete. If an observer's picture of the universe is incomplete (as it is, for example, in visual perception when one viewed object eclipses another in depth), an additional "observer-free" description is required to make a theory predictive. Such an "objective" description of the universe is foreign to the ideas of Relativity.

H. Yilmaz[8] has developed an alternative to Einstein's theory with static solutions in which the observer's position in the gravity field figures explicitly. We are now exploring more general observer dependences in the theory, within which a change of observer is not simply a coordinate transformation. We hope to be able to predict such things as the appearance of the perihelion advance of Mercury to an observer in space co-moving with respect to the earth. Any claims that the effects of such observer changes are small must be supported by approximations within the gravity theory being tested (not from Special Relativity or Newtonian physics) in order that they should carry weight.

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5. COMPUTER SIMULATIONS OF MYELINATED-FIBER REFRACTORY PERIODS

Bell Laboratories (Grant)

Michael H. Brill, Stephen G. Waxman

We have used computer simulations to study relative refractory periods (RRP's) in myelinated fibers, for fibers with uniform and nonuniform nodal and internodal properties. The study examined the relationship between latency variations during the relative refractory period, and conduction path length. The methods used were adapted from those we used previously,[1, 2] and involve integration of differential equations[3, 4] which yield voltage vs time curves at nodes of Ranvier. Stimuli consisted of two 250-μsec current pulses at twice the control threshold. Conduction latencies and average velocities were calculated from the first 50-mV crossings of action potentials at designated points along our simulated 60-node fiber.

The first part of our study concerned RRP's in fibers with identical nodes and internodal regions (uniform fibers). RRP is conventionally defined as the time of recovery of threshold after the absolute refractory period (ARP). Following the suggestion of Raymond and Lettvin[5] that conduction velocity after the ARP has the same time course as threshold recovery, we adopted the convention of defining the RRP as the time during which the conduction velocity of the second spike is less (by a criterion amount) than that of the first spike.

We found that the amplitude of the spike occasioned by the second stimulus is at first significantly less than that occasioned by the first stimulus, but recovers substantially (not completely) by the time the second spike has passed the tenth node of Ranvier.

Also, the latency of the second impulse conducting during the RRP depends on both the interstimulus interval and the propagation distance, being maximal at interstimulus intervals corresponding to the beginning of the RRP, and returning monotonically toward control latency with increasing interstimulus intervals. For any given interstimulus interval, the latency variations are greater for longer conduction distances. The conduction velocity is most slowed at the beginning of the fiber, but increases with increasing conduction distance toward control conduction velocity (that of the first spike, which is 19.7 m/sec). This statement does not imply that the interspike interval also aproaches an asymptotic value with increasing distance. We were unable to determine whether the latter asymptote, in fact, exists. Whereas we used a modified Hodgkin-Huxley model of active nerve fiber, models incorporating a period of enhanced conduction speed (a supernormal period) following the RRP cannot have a velocity asymptote without a concomitant latency asymptote. This points up a possible significance of the supernormal period for spike entrainment in long fibers.

In addition to the above study for myelinated fibers with identical nodes and identical internodes, we also performed a refractory-period simulation on inhomogeneous fibers. In these fibers, the first ten nodes were the same as those of the above (fiducial) fiber. The remainder of the fiber (nodes 11-20) was examined for three alternative cases:

a. The nodes had 10 times the area of the fiducial-fiber nodes.

b. The internodes were 75 percent demyelinated compared to those of the fiducial fiber (i.e., myelin thickness was reduced 75 percent, holding constant the axonal diameter).

c. The internode lengths were 2.5 times as long as those of the fiducial fiber.

Uniform fibers with these properties all displayed an increased ARP compared with that of the uniform fiducial fiber. In all three types of nonuniform fiber, we noticed the following effect:

If the second impulse is started near the beginning of what would be the RRP of the fiducial fiber (that is, about 2.1 msec after the first stimulus), the second impulse propagates from one end of the fiber to the other. However, if the second stimulus occurs somewhat later (or is twice the magnitude of the first stimulus), the impulse is blocked when it reaches the inhomogeneity.

This effect, an apparent paradox, can be explained as follows: When the second stimulus is near the beginning of the RRP, there is a utilization time of approximately 1 msec during which the spike develops at the strongly refractory first node before it propagates farther. At subsequent nodes, there is further latency increase relative to control. This latency is large enough for the second part of the fiber to complete its ARP in the wake of the first spike; however, when the interstimulus interval is somewhat longer (or the second stimulus magnitude is larger), the utilization time is shorter,

leading to arrival of the second spike at the inhomogeneity before the second part of the fiber is ready to fire. Thus our simulations provide an example of a situation in which axons may function as high-pass filters. We are now planning to examine the possibility of this effect arising from a cold block in the fiber, in order to assess its further implications.

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6. FUNCTIONS IN R^m THAT INVERT THEMSELVES AFTER n APPLICATIONS

Bell Laboratories (Grant)

Michael H. Brill

Following the suggestion of D. DeVitt (Perception Technology Corporation; personal communication) that such efforts might be useful in encryption, we examined properties of self-inverting functions – vector-valued functions from R^m to R^m that, when composed n times, give the identity. Some examples for m = 1, n = 2 (functions in one dimension, each its own inverse) are $\pm x^{\pm 1}$, $x/(x-1)$, $\ln(a-e^x)$ ($x < \ln(a)$ in the last case). Examples for higher m and n are n-fold rotations in m-space.

Many of the properties of the case m = 1 generalize to higher m, so we look at the case m = 1 first.

If an invertible function f is its own inverse (n=2), then $y = f(x)$ can be written $G(x,y) = 0$, where G is symmetric in x and y. [Proof: An expression for the inverse of $y = f(x)$ is $x = f(y)$, in which the variables x and y are reversed. If f is its own inverse, then both of these equations must be true at once, whence $f(x) + f(y) - x - y \equiv G(x,y) = 0$. Here, G is manifestly symmetric in x and y.] An easy way to generate a function f is to find a symmetric differentiable G such that $\partial G/\partial y \neq 0$ and then try

to solve for y.

Now, we show that, if an invertible rational function f is its own inverse (n=2) – except at zeros of its denominator – then f is bilinear. [Proof: Consider a rational function

$$f(x) = \frac{ax^2 + bx + c}{dx^2 + ex + h} = y.$$

This expression cannot be symmetric in x and y unless a = d = 0 (f is bilinear). The result also applies when higher order terms (in x^k) are added to the numerator and denominator. Thus, from the above paragraph, all rational self-inverting functions with m = 1, n = 2 are bilinear.]

What bilinear functions are self-inverting? In one dimension, the general bilinear function is

$$f(x) = \frac{ax + b}{cx + d}.$$

If we define $\begin{bmatrix} a & b \\ c & d \end{bmatrix}$ as the characteristic matrix of the transformation (unique up to a scaling factor p), we can *show that composing bilinear functions corresponds to multiplying* their characteristic matrices. Clearly, then, a bilinear function is self-inverting after n applications if we can choose p such that the eigenvalues of its characteristic matrix are distinct n^{th} roots of unity. (When the matrix is nondiagonal, the eigenvalues must be distinct. This can be seen from the counterexample y = x + c, which is not self-inverting even though its characteristic matrix has two eigenvalues +1.)

What other functions are self-inverting? Let f be a bilinear function that inverts itself after n = 2 applications. Let g be an invertible function whose domain and range span the real line. Then $g^{-1} \circ f \circ g$ will be self-inverting. If we are careful to restrict the domain x (which must anyway be restricted so the denominator of f is nonzero), we can enlarge the class of g by removing the restriction on the range. Thus, in the above example $\ln(a - e^x)$, x must be less than ln (a). For n > 2, the domains of f and g must, of course, be further restricted so $(g^{-1} \circ f \circ g)^k$ is invertible for $k \leq n$. We conjecture (but have not proved) that the above constructive method will generate all self-inverting functions for m = 1.

The findings of the last two paragraphs can be generalized to all m > 0. The bilinear transformation becomes a projective transformation (each of whose components has the same denominator), and the characteristic matrix (a_{ij}) has dimension (m+1) × (m+1). The bilinear function f has m components

$$f_i(\underline{x}) = \frac{a_{i1}x_1 + \cdots + a_{im}x_m + a_{i,m+1}}{a_{m+1,1}x_1 + \cdots + a_{m+1,m}x_m + a_{m+1,m+1}} \qquad (i = 1, \ldots, m).$$

The eigenvalue condition carries over from the case m = 1; however, the eigenvalues need not be distinct so long as the matrix (a_{ij}) is diagonalizable (i.e., it is in block-diagonal form such that the eigenvalues in each block are distinct).

A straightforward generalization of g defines vector-valued $\underline{g}$.

An example for m = 2 is $(x^a y^b, x^c y^d)$, where the characteristic matrix is chosen as $\begin{pmatrix} a & b & 0 \\ c & d & 0 \\ 0 & 0 & 1 \end{pmatrix}$, $\underline{g}$ is the logarithm (in any base) applied to the two coordinates, and one must insure $x, y > 0$. When n = 2, the eigenvalue conditions correspond to $a + d = 0$, $a^2 + bc = 1$. Two of the eigenvalues are the same here, but not in the same matrix block.

Since any projective transformation $\underline{f}$ is expressible as $\underline{F}^{-1} \circ \underline{L} \circ \underline{F}$ (where $\underline{F}$ is a projective transformation and $\underline{L}$ is an affine transformation), the above theory can be recast about the affine transformation. $\underline{L}(\underline{x})$ has components of the form $L_i(\underline{x}) = a_{i1}x_1 + \cdots + a_{im}x_m + a_{i,m+1}$. The characteristic matrix is defined as before, but the bottom row is $(0, \ldots, 0, 1)$, and there are no singularities in $\underline{L}$.

A note about projective transformations as they might apply to vision:

Cornsweet[1] has noted that, as a function of light intensity x, the visual response (at the receptor level) is $\frac{ax}{b + x}$. Since this is a one-dimensional projective transformation, it supports the 4-point invariant

$$\left| \frac{(x_1 - x_2)(x_3 - x_4)}{(x_1 - x_3)(x_2 - x_4)} \right|.$$

This may be useful in understanding how the visual system can deduce brightness relationships independently of the constants (adaptation state) of the transduction function.

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7. NEW TEST PATTERNS FOR CAMERA LENS EVALUATION

National Institutes of Health (Training Grant 5 TO1 EY00090)

Bradford Howland

The method preferred today for testing camera lenses is the direct measurement of the modulation transfer function (mtf) using specialized electronic instruments.[1] Photographic methods for making similar measurements are less accurate, and usually require the use of a microdensitometer. An attempt to circumvent this limitation is

that of Putora, who photographs circular test patterns of varying fineness with high-contrast film; the lens resolution is determined directly by inspection of the negative.[1] We describe here additional test patterns which provide direct indication of lens performance when photographed with high-contrast film.

Figure XXV-1 shows two of the new charts, as follows: (a) the vernier resolution chart, and (b) the triangular-wave pattern. The vernier chart utilizes pairs of black lines, displaced by successively increasing increments, on a 20% grey background. White borders to the black lines are placed as indicated. The action of the chart depends on the small differential motions of the images of the black lines due to the spreading of the white into the black, and the black into the grey when an unsharp image is rendered. The degree of unsharpness of the image is indicated by the altered vernier correspondence of the displaced line images.

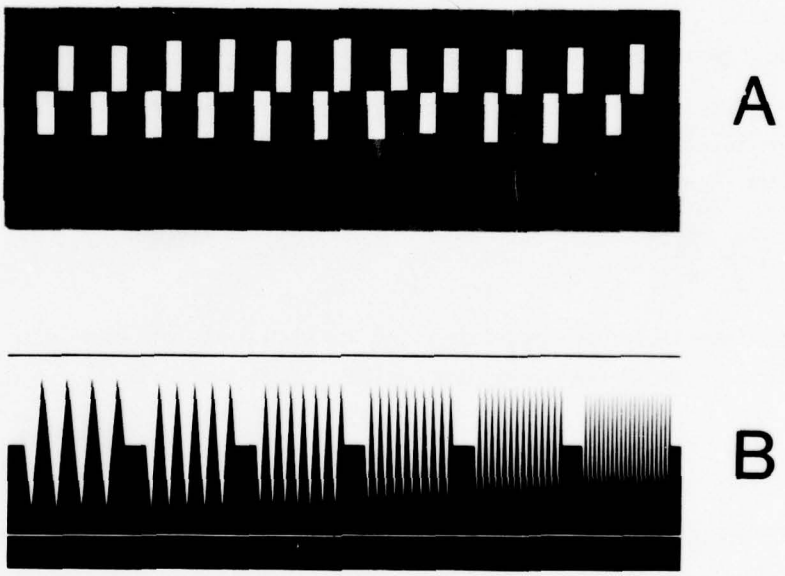

Fig. XXV-1. Two new charts for the measurement of lens resolution: (A) the vernier resolution chart, (B) the triangular-wave pattern.

This behavior is illustrated in Fig. XXV-2, which shows photographs of the chart with successive stages of defocus – note that the vernier correspondence, which occurs at number 0 in the original (A), occurs at line pairs numbered 3, 8, and 10 in the progressively defocused images B, C, and D. Here we are using a defocused image as a simulation of the lens defects of astigmatism, or curvature of field. Tests indicate that defocus, lens aberrations, and diffraction blur all affect the vernier sharpness index.

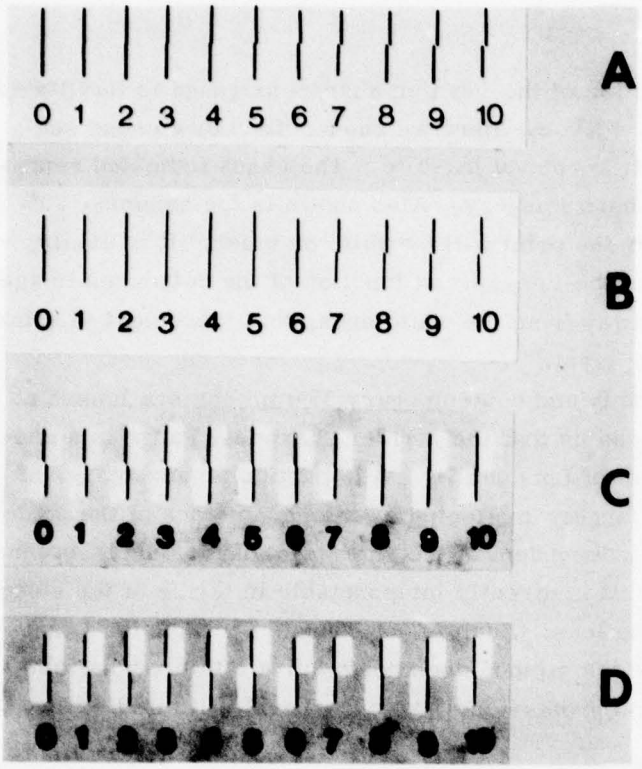

Fig. XXV-2.

High-contrast photographs showing (A) sharp imagery, and (B, C, and D) successive stages of defocus of the vernier resolution chart. Note that vernier correspondence occurs at line pairs marked 0 in frame A, 3 in frame B, 7 in frame C, and 10 in frame D.

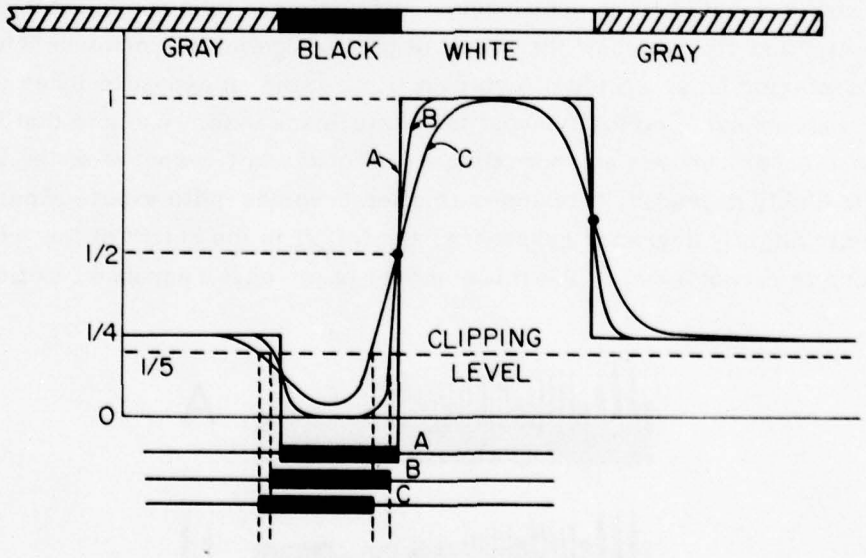

Fig. XXV-3. Reflectance cross sections of (A) sharp, and (B, C) unsharp images of lines forming the vernier resolution chart.

A qualitative explanation for the action of the vernier sharpness gauge is facilitated by consideration of the diagram of Fig. XXV-3. Here we show reflectance cross sections of images of the lines of the chart, bordered in white. The cases indicated represent perfect, slightly unsharp, and unsharp imagery. Also shown is the assumed 20% clipping level which determines whether the print will be white or black. It is easily seen that the result of the finite slope of the line-spread function of the defocused images is to move the image of the black line away from the white area; this increment is somewhat dependent on the choice of clipping level.

Extensive tests with a variety of early and contemporary 35-mm camera lenses at differing aperture settings have convinced us that the vernier sharpness gauge is a useful and sensitive test for the assessment of lens quality. The particular advantages of this method are: (a) the test result is largely unaffected by the parameters of the photographic process, (b) the test result is independent of the sharpness of the enlarging lens used to make the print, (c) the test result is directly interpretable in terms of the steepness of the edge response function of the lens, which is, of course, the Fourier transform of the mtf response, and (e) since the method does not require a microdensitometer, it can be used both by amateur and professional photographers of limited budget or little scientific training.

A second test method is the use of the triangular-wave pattern shown in Fig. XXV-1(b). For this purpose, a set of patterns of geometrically increasing spatial frequency was generated on an oscilloscope and combined as a photo-montage. In Fig. XXV-4(a) and 4(b) we show the result of photographing this montage with an excellent and an inferior lens, with high-contrast film, using an exposure index chosen to render the pattern symmetrically about the white-black axis. We note that the envelope of the shaded areas renders an approximate plot of the mtf response of the lens; if the response is highly degraded, this approximation becomes quite exact. Analysis shows that, for only slightly degraded responses, the falloff in the height of the triangular-wave pattern is proportional to the linear extent of the edge response function, evaluated

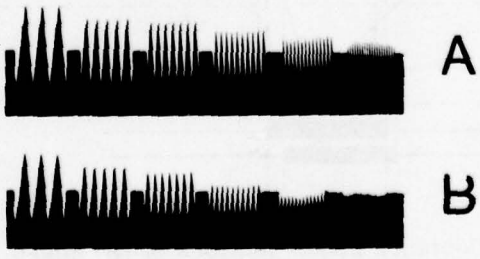

Fig. XXV-4. High-contrast renditions of the triangular-wave patterns photographed at a distance using (A) a high-quality lens, and (B) an inferior lens.

at the 25% and 75% points.

These results suggested the possible existence of a pattern which, when photographed with contrast ratio approaching infinity, would indicate the exact mtf

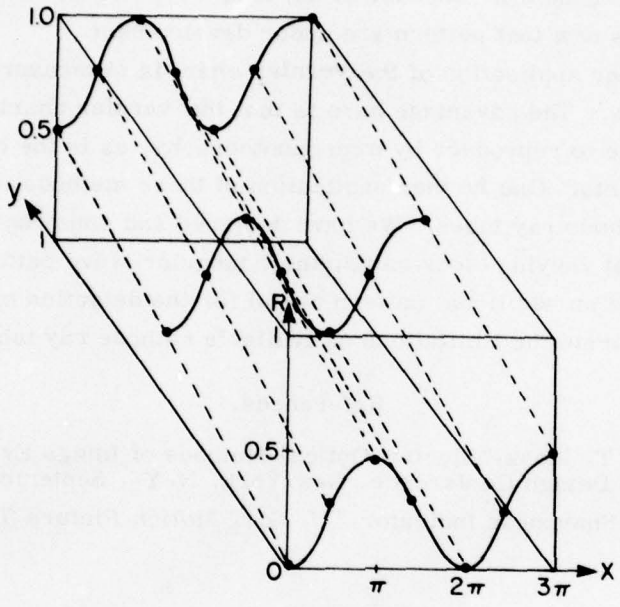

Fig. XXV-5. Two-dimensional pattern of reflectance for a new form of mtf measurement chart. High-contrast photographs of an ensemble of such patterns of increasing spatial frequency render an exact plot of the mtf function.

response of the lens. In Fig. XXV-5 we show the realization of such a pattern, which requires continuous tone reflectance variation according to the equation:

$$R = \frac{1}{4} \sin \omega x + \frac{1}{2} y + \frac{1}{4} \qquad 0 \leq R \leq 1, \quad 0 \leq y \leq 1.$$

In this figure, the scale of the x-coordinate has been enlarged for clarity. The reflectance exhibits a sinusoidal variation with x, together with a linear shading with y. The operation of this chart is explained by analogy with the sphygmomanometer, used to measure blood pressure. The reflectance at the top of the chart varies from 50% to 100%, at the middle from 25% to 75%, and at the bottom from 0% to 50%. Thus, if the film clips at 50% reflectance, all levels of the chart will contain both black and white areas, and the sinusoid will be reproduced in silhouette. Now, however, if the sinusoidal component of reflectance is reduced during the imagery by a factor, $a < 1$, then the regions

below the line $y = \alpha/2$ will be solid white, and above the line $y = 1 - \alpha/2$ will be black. The extent of the intermediate, shaded region will therefore be reduced by the same factor α. A composite chart, reminiscent of Fergus Campbell's variable-contrast mtf chart, featuring progressively increasing spatial frequencies will, when so photographed, render an exact plot of the mtf response of the lens. Electronic circuits to facilitate the generation of this new test pattern are under development.

A possible further application of the vernier chart is to measure the performance of microscope lenses. The advantage here is that the vernier chart does not require line elements too fine to reproduce by microphotography, as is the case with conventional resolution charts. One further application of these methods is measurement of the resolution of cathode ray tubes. We have designed and constructed TTL-logic circuitry to generate, at varying clock rates, the triangular-wave patterns, the vernier resolution chart, and an additional pattern useful for the detection of coma. These patterns easily demonstrate the limitations of available cathode ray tubes.

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P. Kiparsky, Panini as a Variationist (p. 28)

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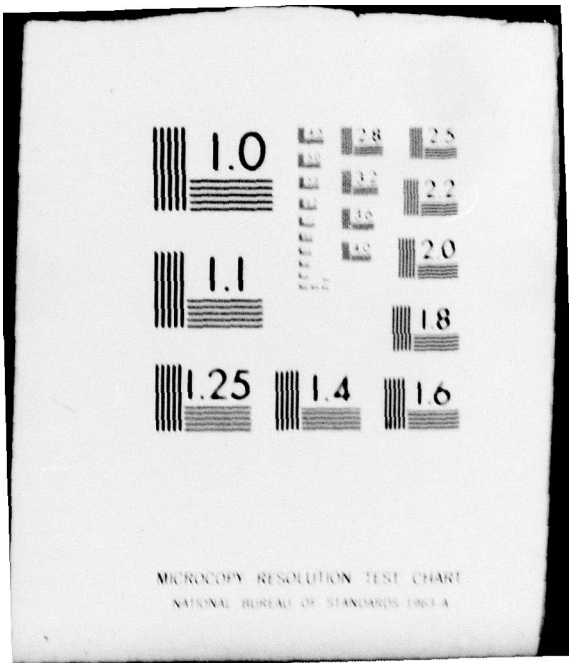
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