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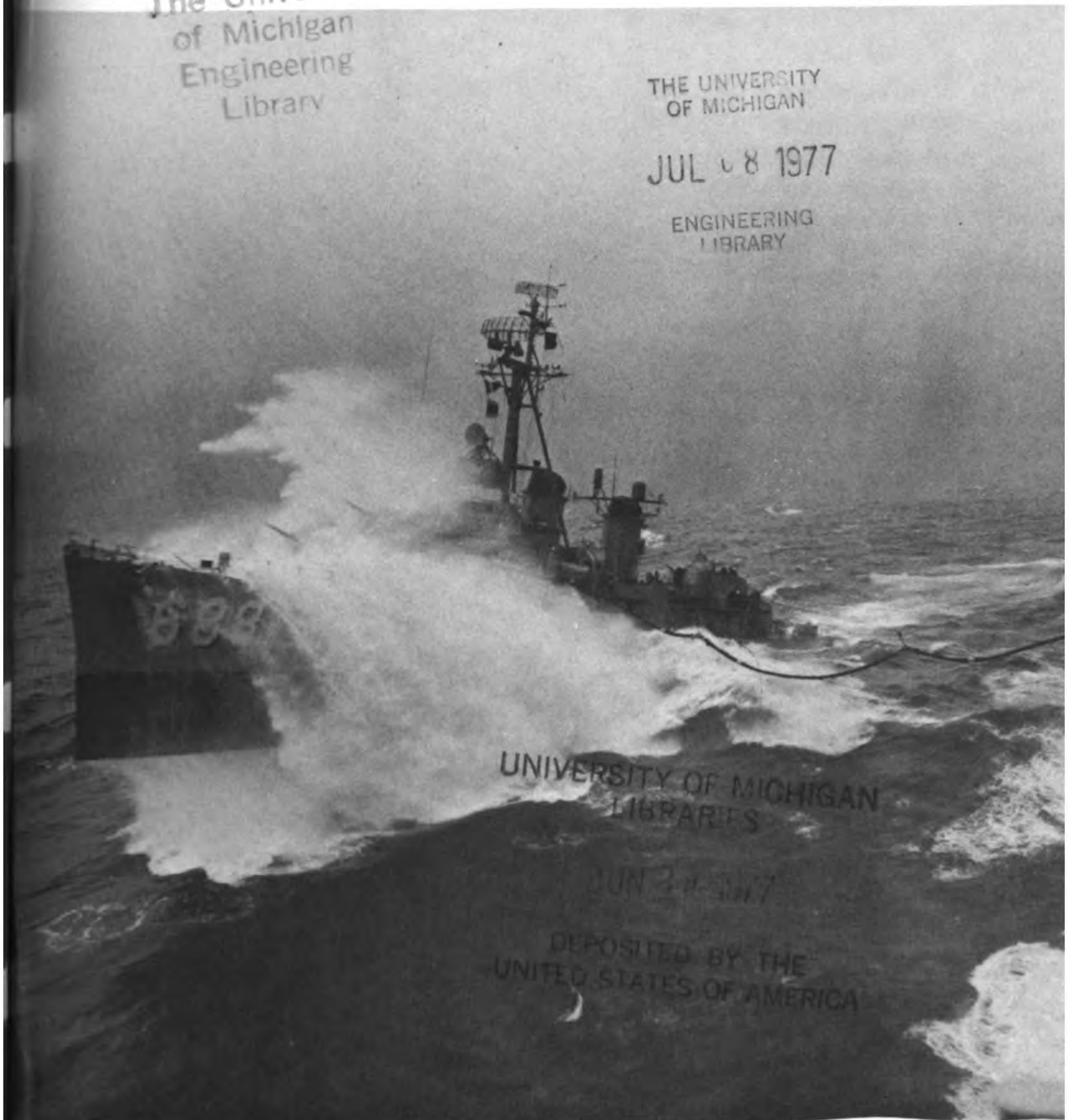

PROFILES IN SCIENCE

Dr. Norman F. Ramsey

Dr. Norman F. Ramsey, who is Higgins Professor of Physics at Harvard, has been an ONR contractor for many years. While his experimental work has ranged from molecular beams to particle physics, he has become a renowned authority in the field of precision measurements of the electric and magnetic properties of nucleons, nuclei, atoms and molecules. Dr. Ramsey and his associates discovered the deuteron electric quadrupole moment, have studied proton-proton and electron-proton scattering, and have measured many nuclear magnetic moments including those of the proton, neutron, and deuteron. The first successful theories of chemical shift in NMR and of electron coupled spin-spin interactions in molecules were proposed by Dr. Ramsey. Also he developed the theory of thermodynamics at negative absolute temperatures. He and his associates invented high precision methods of molecular beam spectroscopy including the atomic hydrogen maser and have set low limits to the electric dipole moment of the neutron as a test of time reversal symmetry.

Among his books are the following outstanding texts: *Experimental Nuclear Physics, Nuclear Moments, Molecular Beams,* and *Quick Calculus*. Currently he is Chairman of the Physics Section of the American Association for the Advancement of Science, Vice-President of the American Physical Society, and President of Universities Research Association which operates the Fermi National Accelerator Laboratory.

Programs on Small-Scale Applications of Superconductivity in the United States*

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The coldest temperatures of the North Pole are scorching heat by comparison with those that physicists and engineers routinely create in their laboratories today for the purpose of studying physical phenomena. At extremely low temperatures near absolute zero (− 273° Centigrade or 0° Kelvin), many strange phenomena occur in nature which at higher temperatures are masked by the random heat motion of atoms and electrons. One of these is the flow of electric current in wires with zero resistance, for indefinite periods of time. This phenomenon has fascinated scientists for over half a century, but it is only within the last decade that the properties of superconducting materials have found practical utility, both civilian and military. A whole host of technological applications has resulted, ranging from powerful magnets to infrared detectors and ultrasensitive sensors of minute magnetic fields.

One can divide the applications of superconductivity into two broad groupings. The first is sometimes referred to as megasuperconductivity. This includes the big machinery items that involve high power, large magnetic fields and big volumes. With this class of applications usually go big sums of money. For the most part these applications exploit the zero electrical resistance properties or the perfect diamagnetic properties of superconducting materials. Some of the large scale applications under development in the U.S. are superconducting magnets for fusion, MHD, energy production and energy storage; superconducting d.c. and a.c. cable for energy transmission; a.c. and d.c. superconducting motors and generators and superconducting magnetically levitated trains.

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The other class is small-scale applications, sometimes called microsuperconductivity or superconducting electronics. Here one is usually dealing with those applications which exploit the d.c. and a.c. Josephson tunneling phenomena. Devices in this class include ultra-sensitive magnetometers, millimeter and submillimeter wave detectors, voltmeters and ammeters, gravity meters, parametric amplifiers, and computer elements. This list is by no means complete; it continues to grow each day.*

Introduction

This survey of forty seven U.S. programs on small-scale applications of superconductivity is organized into six categories. For each program the organization, key investigator, brief description, source, and amount of funding are given in six summary tables.

As a guide in our compilation of material for this survey, we adopted an arbitrary operational definition of "small-scale application of superconductivity". If a research or development program in the U.S. attempted to exploit a unique property of superconducting materials and the resultant device or application consumed or produced no more than a few watts of power, it was defined as a "small-scale application" and included in this paper. The programs are either currently active or have been recently completed. Programs completed prior to 1976 are excluded.

Five categories are based on specific applications: (1) biomedical, (2) metrological, (3) geophysical, (4) detection and generation of electromagnetic radiation, and (5) digital processing; (6) the sixth category, called device properties, includes research programs which appear to be directly related to small-scale superconductive devices. Theoretical and experimental research which was related to superconductivity more generally was excluded. Preceding the six summary tables is a short list of abbreviations used in the tables. These are primarily abbreviations of funding agencies (see Table I).

Biomedical

The use of Superconducting Quantum Interferance Device (SQUID) magnetometers and gradiometers to measure the minute magnetic fields

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*The ability of the superconducting wave to cross small normal regions giving current flow without voltage is called the dc Josephson effect. Such a sandwich type device of two superconductors separated by a thin region of normal material, which may be a metal semiconductor, or an insulator, is called a Josephson junction. In addition to the dc Josephson effect, there is the ac Josephson effect in which an osollating current flows across the junction when a constant voltage is applied.

Table I
Abbreviations Used in Summary Tables

ERDA	Energy Research and Development Administration, Germantown, MD 20767
NASA	National Aeronautics and Space Administration, Washington, DC 20546
NIH	National Institutes of Health, Bethesda, MD 20014
NSF	National Science Foundation, Washington, DC 20550
NYHRC	New York Health Research Council, New York, NY
USGS	U.S. Geological Service, National Center, Reston, VA 22090
AFOSR	Air Force Office of Scientific Research, Bolling AFB, Washington, DC 20332
ARO	Army Research Office, Research Triangle Park, North Carolina 27709
ARPA	Advanced Research Projects Agency, Department of Defense, Arlington, VA 22209
NAVELEX	Naval Electronics Systems Command, Washington, DC 20360
ONR	Office of Naval Research, Arlington, VA 22217
DoD	Other DoD Agencies
my	man-years ($50 - 100 K/yr)
JJ	Josephson junction
G	1 gauss = 10^{-4} Tesla

Table II
Biomedical Programs

Organization	Contact	Program Description	Funding ($K) and Source
National Magnet Laboratory Mass. Inst. of Technology Cambridge, MA 02139	D. Cohen	Magnetocardiography, magnetoencephelography, magnetic measurements of lungs and total body.	200/NSF, NIH and ARPA
National Bureau of Standards Cryogenics Division Boulder, CO 80302	J. Zimmerman	Magnetic measurements of the human heart and brain.	15/internal
Stanford University Department of Physics Stanford, CA 94305	J. P. Wikswo	Vector magnetocardiography; magnetic measurements of blood flow	50/NSF
New York University Departments of Physics and Psychology New York, NY 10003	S. J. Williamson L. Kaufman D. Brenner	Measurements of visually evoked magnetic fields from the human brain.	25/ONR 25/NSF 10/NYHRC
Oakland University Department of Physics Rochester, MI 48063	N. Tepley	Magnetic measurements of blood flow.	11/Michigan Heart Assoc.
TRW Redondo Beach CA 90278	A. Rosen	Magnetocardiography; diamagnetic susceptibility measurements of carcinogenic tissue	0.5 my/ internal

produced by various organs of the human body has probably created more interest than all other small-scale superconducting device applications combined. Measurements of the magnetic signals from various parts of the human body can yield new information about the organs which generate the electric currents, not available to surface electrodes, and also about organs which contain foreign ferromagnetic particles. Signals measured from the heart are called magnetocardiograms (MCG), those from the brain are called magnetoencephalograms (MEG), and those due to eye movements are called magnetooculograms (MOG). Magnetic signals have also been detected from blood flow, injured tissues, and fetuses in utero. Measurements of magnetite dust in the lung have two potential biomedical applications: (1) as a deliberately inhaled harmless tracer for pulmonary diagnosis, and (2) for assessment of the amount of asbestos accumulated in the lungs of heavily-exposed workers, since most asbestos (which is clinically harmful) occurs with adhered magnetite.

Physicist David Cohen and his colleagues at the National Magnetic Laboratory at Massachusetts Institute of Technology have developed shielded rooms and highly sensitive magnetic field detectors able to reveal patterns of magnetic fluxes in the human body. Their equipment permits them to detect fields as weak as one billionth that of the Earth's magnetic field, as low as about 1×10^{-9} gauss. They have detected alpha waves in the brain with fields typically ten times this strength — 10^{-8} gauss. Also they have detected magnetic fields associated with the electrical activity of the human heart which are ten times greater than that of the brain — 10^{-7} gauss.

Metrology (The science of measurement)

Josephson junction technology offers the metrologist possibilities for developing dc, rf, and microwave systems for more accurate and wider range of measurements than can presently be performed. Presently the use of a superconducting primary voltage standard is probably the single most important application in this area.

Geophysical

The use of superconducting devices in geophysical studies appears to be growing slowly. In the light of various potential applications of superconductive systems in geophysics, this is surprising. The paucity of entries in Table IV may, in part, be due to our inability to locate investigators. For example, the measurement of rock magnetism using superconductive magnetometers is in progress at several institutions.

Table III
Metrology Programs

Organization	Contact	Program Description	Funding ($K) and Source
National Bureau of Standards Cryogenics Division Boulder, CO 80302	D. McDonald	Rf power and attenuation standards.	80/DoD 80/internal
National Bureau of Standards Electrical Measurements Division Gaithersburg, MD 20234	R. Dziuba T. Finnegan	Maintenance of US legal volt via ac Josephson effect measurements.	30/internal
National Bureau of Standards Electrical Measurements Division Gaithersburg, MD 20234	R. Soulen	Precision (± 0.1%) absolute noise thermometry from 11 mK to 10 K using Nb point contact JJs.	50/internal
National Bureau of Standards Electrical Measurements Division Gaithersburg, MD 20234	J. Schooley R. Soulen	Superconductive thermometric fixed points below 13.8 K.	15/internal
University of Utah Department of Physics Salt Lake City, UT 84112	G. Symko	Nuclear magnetic thermometry from 1 K to sub-milliKelvins using SQUID magnetometer.	40/NSF
National Bureau of Standards Time and Frequency Division Boulder, CO 80302	S. Stein A. Risley	Spectrally pure superconducting Nb-cavity oscillator for frequency synthesis and multiplication.	40/internal
Stanford University Department of Physics Stanford, CA 94305	J. Turneaure	Superconducting cavity stabilized oscillator achieves 6 x 10 (-16) stability for 10 to 1000 sec.	50/ONR

Table IV
Geophysical Programs

Organization	Contact	Program Description	Funding ($K) and Source
National Bureau of Standards Cryogenics Division Boulder, CO 80302	J. Zimmerman W. Campbell[a]	Ultra-low frequency geomagnetic field-test measurements with superconductive magnetometers. Comparison with conventional magnetometers.	15/internal
Stanford University Electronics Laboratories Stanford, CA 94305	A. Fraser-Smith J. Buxton[b]	Superconductive magnetometer measurements of 0.1 - 14 Hz geomagnetic background demonstrate superiority over conventional systems. Future work planned.	40/ARPA
Naval Research Laboratory Communication Sciences Div. Washington, DC 20375	J. Davis R. Dinger M. Nisenoff	Superconductive magnetometer measurements of 45-75 Hz natural and manmade signals at and below sea level. Work continuing.	200/NAVELEX
Physical Dynamics, Inc. P.O. Box 556 La Jolla, CA 92037	G. Gillespie W. Podney J. Buxton	Measurements of 5 x 10 (-4) to 20 Hz geomagnetic gradient noise. Superconductive gradiometer measurements of ocean-wave generated electromagnetic fields to be made.	400/ARPA
University of California Department of Physics Berkeley, CA 94720	J. Clarke	Superconductive magnetometer and gradiometer measurements of geomagnetic gradient activity and magnetic activity precursor to earthquakes.	20/USGS 20/ERDA
University of California Dept. of Mat. Sci. & Eng. Berkeley, CA 94720	H. Morrison W. Dolan A. Dey	Airborne superconducting coil system developed for prospecting via earth conductivity measurements.	400/AMAX. EXPLORATION INC.
Naval Coastal Systems Laboratory Panama City, FL 32401	K. Allen R. Clark J. Titus M. Wynn	Airborne superconductive magnetic sensor system for dipole tracking.	10my/DoD

a. - U.S. Geological Survey, Denver, Colorado 80225.
b. - Stanford Research Institute, Menlo Park, California 94025.

Electromagnetic Detection and Generation

The use of superconductivity in the detection and generation of electromagnetic radiation has attracted considerable interest and attention, as is evidenced by the breadth of the program described in Table V. In the detector application, Josephson junctions are expected to respond sensitively to frequencies far higher than do conventional semiconductor devices. An upper frequency limit can be calculated for Josephson detectors based on the energy gap, yielding about 1400 GHz for niobium, but there is evidence, for example, from the frequency comparison work of McDonald et al. of the National Bureau of Standards (see section on Metrology) that Josephson devices may provide a useful response to frequencies much higher than the gap limit.

To construct a competitive detector of high sensitivity, many practical engineering problems must be solved. In past years the emphasis of Josephson detector work has been on the demonstration and gross characterization of various detection mechanisms, such as video response, mixing and parametric amplification. It is a sign of the growing maturity of this field that in recent years there has been an increasing amount of work devoted to the construction of practical detectors designed for maximum coupling efficiency and sensitivity.

Total funding for work on superconductive detectors and generators is substantial, amounting to approximately $1200K. Of this total amount, about 70% is provided by the Department of Defense with the Office of Naval Research the largest contributor supplying 25% of the total. Other large sponsors are the Naval Electronic Systems Command, the Aerospace Corporation, and the Defense Advanced Research Projects Agency.

Digital Processing

Unlike the other application areas discussed, work on digital applications of superconductive devices is performed largely in industrial laboratories rather than universities or government laboratories. Also, the work of one organization, namely, the International Business Machines Corporation (IBM), is clearly dominant. The total investment by the listed organizations is very large, probably comparable to the expenditures in all other application areas combined. However, the exact magnitudes of these industrial efforts are considered proprietary. The estimates given in Table VI correspond to frequently rumored numbers, although guesses vary by at least an order of magnitude, depending in part on the definitions used for a man-year of effort.

The reason for this substantial investment is the promise of superfast computers. In order to achieve greater speeds, it is necessary

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Table V
Electromagnetic Detection and Generation Programs

Organization	Contact	Program Description	Funding ($K) and Source
Aerospace Corporation P.O. Box 92957 Los Angeles, CA 90009	A. Silver H. Kanter	Parametric amplification studies at 9 GHz (degenerate mode) and 90 GHz (preliminary measurements). Super-Schottky mixer work at 9 GHz (13 K noise temperature and 9 dB conversion loss) and higher frequencies.	110/ONR and DoD 170/internal
University of California Department of Physics Berkeley, CA 94720	R. Chiao	Series array of 80 unbiased JJs demonstrates 12 dB parametric gain at 10 GHz in doubly degenerate mode. Continuing theoretical and experimental studies.	50/NSF 50/NASA
University of California Department of Physics Berkeley, CA 94720	J. Clarke P. Richards	Superconductive bolometer built with NEP of 3×10 (-15) W/$\sqrt{\text{Hz}}$ and 50 ms response time.	30+/ERDA
University of California Department of Physics Berkeley, CA 94720	P. Richards	36 GHz JJ mixer attains 50 K noise temperature with conversion gain. Preliminary measurements at 144 GHz. Parametric amplification and coupling to JJ arrays at 36 GHz studied.	55/ONR
University of California Dept. of Elec. Eng. Berkeley, CA 94720	T. Van Duzer	Silicon-membrane JJs built for video detector and mixer evaluation. JJ array and super-Schottky diode studies planned.	25/ARO
Case Western Reserve Univ. Dept. of Elec. Eng. Cleveland, OH 44106	E. Thompson	100 GHz JJ detector and FM demodulator with internal oscillator locked to external signal to be built.	30/NSF
Louisiana State Univ. Department of Physics Baton Rouge, LA 70803	W. Hamilton	Detectivity of JJ video detector with magnetic field coupling measured from 22 GHz to 1 THz.	30/AFOSR

Table V (continued)
Electromagnetic Detection and Generation Programs

Organization	Contact	Program Description	Funding ($K) and Source
National Bureau of Standards Cryogenics Division Boulder, CO 80302	D. McDonald J. Edrich[a]	300 GHz receiver containing 57 K noise temperature JJ mixer with 12 dB conversion loss attains 850 K overall noise temperature.[a] Theoretical analysis of high frequency detection mechanisms in progress.	10/NSF 15/ONR 35/internal
Naval Research Laboratory Communication Sciences Div. Washington, DC 20375	J. Davis	ELF H-field detection system using 3-axis SQUID magnetometer and 90-day dewar under test. Scalar output processing developed.	210/NAVELEX
Naval Research Laboratory Communication Sciences Div. Washington, DC 20375	J. Davis	HF antenna array elements using SQUIDs	90/internal
State University of New York Department of Physics Stony Brook, NY 11794	J. Lukens	1-10 GHz tunable coherent source using large JJ arrays and stripline coupling under study.	150/ONR
Research Advisory Institute 218 Monarch Bay South Laguna, CA 92677	J. Mercereau	Use of deformable superconducting cavities for conversion of mechanical and electro-magnetic energy under experimental and theoretical study. Prototype construction planned.	100/ARPA
University of Rochester Dept. of Elec. Eng.	C. Stancampiano	Analytical study of detection processes for rf-driven resistively shunted JJ. Comparison with experimental data on injection-locked oscillators.	20/internal
University of Texas Department of Physics	B. Ulrich	JJ video detector used for astrophysical studies at 1 mm. Josephson parametric amplification and mixing under theoretical and experimental study.	10/NASA
Westinghouse Research Labs. Pittsburgh, PA 15235	M. Janocko	Small JJ arrays as microwave sources under study.	33/ONR

Table VI
Programs on Digital Processing

Organization	Contact	Program Description	Funding ($K) and Source
Bell Laboratories 600 Mountain Avenue Murray Hill, NJ 07974	T. Fulton	JJ logic and memory circuit investigation. Analysis of flux shuttle concept.	less than 10 my/internal
University of California Dept. of Elec. Eng. Berkeley, CA 94720	T. Van Duzer	Fabrication of tunnel junctions with barriers of semimetals, silicon membranes and stabilized oxides. Investigation of JJ logic circuits.	35/NSF 40/DoD
Hewlett-Packard Corp. Palo Alto, CA 94300	D. Rose	Investigation of JJ digital circuit applications and development of commercial JJ voltage standard.	Approx. 3 my/internal
IBM Research Center Yorktown Heights NY 10598	J. Matisoo	Evaluation of JJ logic circuits, memory cells, adders and shift registers. Fabrication yield reliability, reproducibility and stability of tunnel JJs under study.	Approx. 50 my/internal
National Bureau of Standards Cryogenics Division Boulder, CO 80302	D. McDonald	Fabrication of stable lead alloy tunnel junctions. Analysis of digital circuit application: picosecond pulsers, A/D converters, three-terminal devices, and transmission lines.	175/internal 15/ONR
Sperry Research Center Sudbury, MA 01776	K. Kroger	Memory and logic circuits using niobium and lead alloy tunnel JJs under study.	Approx. 3 my/internal

to minimize signal propagation delays, which requires that computer elements be placed very close together. However, it is no longer possible to increase the packing density of semiconductor circuits because the heat generated by the semiconductor devices is too large. It has been determined that the heat dissipated by a Josephson logic gate is at least two orders of magnitude smaller than by semiconductor competitors, permitting higher packing density and greater resultant speed.

Device Properties

Programs in this category, summarized in Table VII, are more closely concerned with the physics of Josephson-effect devices. Because the work is of a more general character, it is often related to more than one of the application areas discussed in this paper.

Research on device properties is funded by a number of agencies. Of the total funding in this category of $650K, more than 40% is provided by the Office of Naval Research. Other major sponsors are the National Science Foundation and the Energy Research and Development Administration.

Trends

Attempts to predict the future of some segment of science and technology often tend to reflect the professional interests, prejudices and limited knowledge of the self-proclaimed "prophets". Bearing in mind this admonition, we will discuss a few of the possible future directions of some of those areas of small-scale applications of superconductivity (SSAS) reviewed in this paper.

During 1975 six Federal agencies supported a total of about $3.5 – 4 million in basic and applied research and exploratory development in the area of SSAS via grants, contracts and in-house laboratory projects. This figure is up significantly from what we estimate it was in 1972, indicating that the field is experiencing a healthy growth. The largest single sponsor is the Department of Defense and, within the military, the U.S. Navy supports over 75% of the total DOD effort in SSAS. In the industrial sector IBM is by far the largest single sponsor (see Table VI). Estimating a man-year at $50,000, the annual IBM expenditure in this area is about $2.5 million. Including the other industrial activities listed in Table VI, the total investment by U.S. industry in SSAS is around $3.5 million. Thus the dollar value of the total U.S. effort in SSAS, government and private industry, in 1975 was $7 – 8 million. We believe this to be a conservative estimate. We do not have reliable data to estimate the annual rate of growth.

There are a few factors which could significantly influence the rate of future growth. Discounting such "breakthroughs" as room temperature (or even liquid-nitrogen temperature) superconducting

Table VII
Programs on Device Properties

Organization	Contact	Program Description	Funding ($K) and Source
University of California Department of Physics Berkeley, CA 94720	J. Clarke	Measurement of: (1) JJ properties under microwave irradiation; (2) properties of superconductor/normal-metal boundaries; and (3) LF SQUID noise including theory.	125/ERDA 20/USGS
University of California Department of Physics Santa Barbara, CA 93106	D. Scalapino	Superconductive nonequilibrium phenomena calculations: quasiparticle and phonon energy distributions; microwave and phonon enhancement of T_c, etc.	30/ONR
California Institute of Technology Department of Physics Pasadena, CA 91125	J. Mercereau	Experimental and theoretical study of coupling between JJ array elements in terms of element spacing, material, frequency, temperature, etc.	60/ONR
Catholic University Department of Physics Washington, DC 20017	R. Peters	Experiments on nonequilibrium effects in superconducting devices.	19/ONR
Cornell University Department of Applied Physics Ithaca, NY 14850	R. Buhrman	SQUID noise measurements and theory. Heating effects in microwave irradiated thin-film JJs.	47/ONR
Naval Research Laboratory Material Sciences Division Washington, DC 20375	M. Nisenoff	Niobium microwave excited SQUIDs evaluated. Niobium thin-film JJs fabricated.	95/internal
Stanford University Department of Applied Physics Stanford, CA 94305	M. Beasley	Investigation of weak-link and tunnel JJs fabricated from high T_c materials.	20/DoD

Table VII (continued)
Programs on Device Properties

Organization	Contact	Program Description	Funding ($K) and Source
University of Pennsylvania Department of Physics Philadelphia, PA 19174	D. Langenberg	Theoretical and experimental study of nonequilibrium effects in JJs. Excess quasiparticle production via tunnel barrier injection and laser irradiation.	30/ONR
Science Applications 1205 Prospect Street La Jolla, CA 92037	D. Rogovin	Theoretical analysis of quantum wave function phase locking in coupling between JJ array elements.	25/ONR
Stanford University Department of Physics Stanford, CA 94305	R. Giffard	SQUID noise fully characterized. Study of LF ultra-low-noise amplifiers using SQUIDs with tuned input circuits.	40/ONR
University of Wisconsin Dept. of Elec. Eng. Madison, WI 53706	J. Nordman	Niobium-based semiconductor-barrier tunnel JJs studied for switching applications.	35/NSF
Yale University Dept. of Applied Science New Haven, CT 06520	D. Prober	dc SQUIDs using alloy thin-film microbridge JJs evaluated.	15/NSF
Harvard University Department of Physics Cambridge, MA 02138	M. Tinkham	Fabrication of variable thickness microbridge JJs. Evaluation of microwave and laser response. Study of fundamental device limits.	40/NSF 50/DoD

materials, the present efforts to increase the transition temperature a few degrees above the present record of 23K would appear to have little effect on either the near or far-term future growth of SSAS. One factor which could have a significant effect on the rate of future growth is the commercial availability of an inexpensive, reliable, miniature, portable, low-maintenance cryogenic refrigerator operating at about 4-5K, with a cooling capacity of a few tenths of a watt and requiring low power input. The ability to eliminate the need for liquid helium and the periodic transfer of helium would, we estimate, act as an important stimulus to the future increased growth of SSAS, particularly in the areas of biomedical, geophysical and military applications. Within the area of military applications, surveillance, communication, digital processing and weaponry could be strong candidates for SSAS employing miniature closed cycle cryogenic refrigerator systems. Many of the potential military applications require the refrigerator to be reasonably free of mechanical and magnetic noise at the cooling head so as not to interfere with the long time routine operation of a single SQUID or array of SQUIDs. In these applicaions it is a strong requirement that the refrigerator be sufficiently simple in operation and rugged in construction so as to be operable in field conditions, away from a laboratory, by personnel with little formal training in cryogenic engineering. To our knowledge there is no commercial refrigerator presently available which meets all or even most of these constraints without extensive modification. Severe as these requirements may appear to be, they may be realizable in the next five years. Our optimism stems in part from the results of the preliminary research of J. Zimmerman of NBS/Boulder who has built a laboratory model low-power Stirling-cycle refrigerator which has maintained a temperature of about 16K for more than 2000 hours. Most recently Zimmerman has succeeded in operating the unit down to 13K. Also, he has successfully demonstrated the operation of an rf-biased niobium-tin SQUID at 16K. It will take a considerable development effort to integrate these devices into a single system which is available as an off-the-shelf item. However, we are optimistic that such systems will be available in the future provided industry becomes convinced of the commercial potential of miniature cryogenic refrigerator systems.

An alternate less desirable possible future system which would still have appeal for several civilian and military applications is the use of an integral refrigerator to reduce the evaporation rate of a liquid helium cryostat so that the interval between transfers is significantly extended. This has the advantage that the refrigerator can be turned off for those periods of time when it interferes with the operation of the SQUID. This system still retains the problems attendant with the transportation, supply and transfer of liquid helium.

In terms of the present state-of-the-art in SSAS and possible future trends in specific areas, the following comments are listed.

1. Considerable progress has been made in recent years in designing and constructing practical Josephson-effect detectors which have certain performance advantages over competitive detectors in the same region of the electromagnetic spectrum. For instance, in the microwave region the super-Schottky mixer of Silver et al. has a lower noise temperature than the best competitive mixers. At 36 GHz the Josephson mixer of Richards et al. is characterized by a noise temperature about four times lower than the best competitor and also produces conversion gain. The 300 GHz receiver of McDonald and Edrich, which utilizes a Josephson mixer and a maser IF amplifier, also constitutes a substantial improvement. The work on Josephson parametric amplifiers is at a somewhat less advanced stage, but the measurements made to date suggest that these devices may also have certain performance and possibly cost advantages over other paramps.

It is likely that this work on quantitative characterization of Josephson-effect detectors will continue for the next several years in order that the performance limits can be established in detail. These Josephson low-noise receiver components will then be available for use in a variety of systems applications. It is expected that the first use of this new technology will be in readio astronomy and other space-to-ground and space-to-space applications.

2. Work on Josephson sources is at an exploratory stage, and it is expected that research activity in this area will increase. Possible applications are injection-looked local oscillators and rapidly tunable narrowband sources where only low power levels are required. The problems of extracting radiation from Josephson junctions are poorly understood and must be investigated.

3. Arrays of Josephson junctions may be useful for both detection and generation applications. However, the coupling mechanisms in arrays are not yet fully understood. The phenomena of frequency locking and phase locking must be investigated in detail. It is expected that research interest in this subject will remain at a high level.

4. Fundamental to a proper understanding of junction arrays is a thorough understanding of the physics of an individual Josephson device. Of particular practical importance are the distinctions between weak links and tunnel junctions, specifically, in terms of coupling with an external radiation field and the potentialities for coupling in an array. The role of heating in junctions will also be investigated further, and possible improvements using variable thickness bridges will be established.

5. Work on digital processing applications is particularly demanding in terms of technology requirements, since large numbers of devices

and circuits must be made reliably, reproducibly and economically. These technology matters will continue to be dominant in the near future, but we can also expect a greater diversity of applications being explored as more groups become interested in this extremely promising field. As one example, ultrafast analog-to-digital converters using Josephson logic circuits appear to be promising possibility. As the capabilities of this new digital technology become known more widely, it is likely that systems requirements will provide direction for further research and development.

6. SQUID magnetometers are by far the most sensitive magnetic sensors available today and for the foreseeable future. In the laboratory, flux sensitivities of 10^{-19} W or less can be achieved. For example, Wikswo (see Table II) routinely makes measurements down to 50 pT, which is some six orders of magnitude smaller than the earth's magnetic field and about three orders smaller than the magnetic noise in an average laboratory. The extreme sensitivity and broad band frequency response of SQUIDs assures their continued and growing future use. There are two U.S. companies producing superconductive magnetometer systems for both laboratory and field use. What presently appears to limit the growth in some application areas is the need to use liquid helium. Once this hurdle can be overcome, the biomedical, geophysical and military applications of superconducting magnetometry should experience marked growth.

7. In electrical metrology, the extraordinary sensitivity of SQUIDs from dc through the microwave range assures their future in precise measurements and standards. Thus for the maintenance of the legal volt, precise measurements of direct current, voltage, rf power and attenuation, the future of SSAS is good. For example, routine voltage measurements down to 10^{-15} volts are readily attainable with a SQUID voltmeter. One property of SQUIDs that makes them highly desirable for rf measurements is their linearity. This property will become increasingly important with the trend towards techniques for precise rf measurements which can overcome the present-day dependence on carefully made and maintained artifact standards.

Recent improvements in noise thermometry have significantly reduced the integration time required for a given measurement precision. The fact that 0.1 percent precision noise thermometry measurements can now be routinely made over the range from 10 mK to 10K gives some indication of the bright future of this area of SSAS.

New applications of superconductivity involving the precise measurements of selected electrical and thermometric quantities as well as the development of precision devices and components appears promising. What appears particularly interesting for the future is the blending of cryoelectric techniques with superconducting devices.

Thus an entire system can be at cryogenic temperatures. This offers the possibility of solving metrology problems which are not readily souble by any other means. While the development of practical superconducting metrological systems is on the increase and will continue to grow, the number o potential future users appears to be relatively small and thus the commercial market for these applications may remain limited.

8. The biomedical applications are among the most interesting and also among the most difficult to assess in terms of future trends. As a research tool in physiology, biology and medicine, there seems little doubt that SSAS will continue to grow. The research activities of Williamson, Cohen, and Wikswo are excellent examples of the present-day endeavors in this field. As their research results become more widely known and as the commercial availability of rugged, reliable, simply-operated SQUID magnetometer systems increases, more workers will certainly enter the field. Also an encouraging note is the growth of the number of Federal agencies supporting research in MCG and MEG.

What is perhaps most intriguing is the potential of exploting superconductivity during the next decade in ways which will revolutionize our present defense technology while at the same time providing significant spin-offs to medicine, controlled thermonuclear power, electric power transmission and many other sectors of our society. The development of this field of superconductivity is an interesting and illuminating example of how the support of basic research by the Office of Naval Research and other DOD agencies, from the mid 1940's to the present, is now resulting in the transformation of intriguing laboratory techniques into the realm of military and industrial practicality. This transformation will have profound implications in a number of areas, ranging from anti-submarine warfare, to communication, to navigation, to propulsion and to the entire field of electronic systems.

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The Surface of the Sea

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Since that distant time when man first ventured to entrust himself to some primitive craft, he has been conscious of the ever-changing face of the sea. He learned to make use of the wind to propel himself effortlessly, and at the same time to cope with the waves that are born from that same wind. The Phoenicians, the Romans, the Arabs and the lonely voyagers of the Pacific gradually developed sturdy craft of beautiful proportions adapted to the business of man carrying, fighting, and sometimes playing. Sometimes then and even now the ever present waves would overwhelm an incautious or unlucky sailor; more often they would make difficult or impossible the tasks that he had to perform at sea.

Extreme conditions can still of course impede or prevent operations at sea. It is frequently worthwhile to route commercial shipping around regions of heavy sea. Even if the track is longer, the savings in time by being able to maintain speed and the avoidance of possible damage more than compensate for the additional distance. For the Navy there is not always the choice; a submarine may escape to quieter water below, but the surface ship must still not only survive but remain operational. But no matter whether the sea is rough or calm, the surface is what the navigator sees; he has always used his eyes to warn him of danger or of the onset of wind. Sometimes the signs are obvious – the breaking of waves in shoaling water, the choppiness when waves encounter an ebbing tide, the cats-paws disturbing the glassy sea in a calm that heralds the arrival of a breeze, the sudden darkening of a patch of the surface when a school of menhaden flee from a predator. Sometimes they are much more subtle and still not properly understood; but if they can be interpreted correctly, they will give indications of what lies beneath. We have new 'eyes' with which to see the sea surface. Radar pulses are scattered both forward and back by waves, and infra-red sensing devices can detect small changes in the temperature of the thin sheet of water just at and below the surface. Interpreting these signals is, however, not always easy. The sea surface is the site of a remarkable range of interacting physical processes in balances that may be constantly changing. Often it is only small disturbances of these balances, coherent over a certain area, that can provide a visual or other signal which can be interpreted.

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Waves are generated by the wind; the causality is obvious. But far from obvious are the flow patterns in the air blowing over the waves, the forces that this air flow induces on the water surface, the rate at which energy is fed into the waves from the wind, lost from them by breaking and re-distributed by wave-wave interactions. It is far from obvious why certain wavelengths are excited and others not, how much of the energy transferred from the wind to the sea in fact appears as waves, and how much is transmitted downwards as turbulence stirring the water and as wind-generated currents. Superficial answers are always incomplete and sometimes misleading. To say that the wind pushes on the back of a wave to make it grow is to a certain extent true but gives no hint about how rapidly the waves will grow in the face of other competing processes.

Even this simplest question has proven tough to answer. Lord Kelvin and Helmholtz addressed it in the nineteenth century, but their work has more to do with the generation of spindrift – bursts of spray sweeping across the ocean surface in a high wind – than of waves. Fifty years ago, Harold Jeffreys postulated that the air flow separated from the water surface at a wave crest producing a closed eddy in the lee. This also proved not to be correct unless the wave happened to be breaking at the crest. Careful experiments and observations have indicated that in general the air stream of the wind hugs the water surface except at very small scale roughness – steps of the kind shown in the cover picture associated with small-scale breaking. Important contributions have been made by John Miles and by this group at Johns Hopkins, much of it under ONR sponsorship; but the goal of calculating reliably the rate of energy transfer from wind to waves remains elusive. At present one can certainly make good order-of-magnitude estimates but not a great deal more. The central problem remains that the water surface itself is random, containing many wave components and that the undulating air stream above is turbulent and also random. The full solution involves not only all the intricacies of turbulent flow but the back-reaction of the turbulent flow upon the mean air stream itself.

The heights that waves attain depend not only on the rate at which energy is supplied to them from the wind, but also the rate at which it is lost from the waves by breaking, the dominant dissipative process. When larger scale waves break, the water at the wave crest tumbling forward entrains air bubbles; and the breaking zone is clearly visible as a whitecap with its trailing veil of foam. In an actively wind-generated sea, whitecaps occur sporadically over the surface and signal the fact that the wind is continuing to supply energy to the larger scale waves at a rate faster than it can be transferred to other wave components by wave-wave interactions. In essence the process of wave breaking involves some elements of the fluid near the wave crest moving ahead

Figure 1 — Microstructure on the ocean surface. This photograph, taken by Mr. M. Peep shows small scale breaking waves, the irregular steps on the surface with a characteristic spacing of about 10 cm, superimposed on a longer wave whose crest is in the upper left-hand corner. The wind is blowing, and the longer wave moving from this direction.

faster than the wave profile, and tumbling down the forward face. Air entrainment occurs only at the larger scales and is not a necessary accompaniment to breaking. Breaking occurs also on a much smaller scale without the formation of foam - the water near the crest of wavelets of perhaps 10 cm in length slides forward and rolls under. This micro-scale breaking appears to be much more widespread than is the formation of whitecaps and influences strongly the properties of the surface in a number of different ways (Figure 1).

One important set of consequences derives from the influence of micro-scale breaking on the sea surface temperature. The sea surface is generally cooled by evaporation, and the heat flux necessary to provide the latent heat of evaporation must be brought through the last millimeter or two by molecular conductivity. Usually then there is a substantial temperature gradient at the surface because the water temperature one or two centimeters below the surface is as much as one or two degrees greater than the temperature of the surface itself. If micro-scale breaking occurs, the sea surface is turned over along the breaking line and fresh, warmer water is brought to the surface behind. This leaves a trailing warmer scar which gradually heals as the thermal conductivity regime is re-established. Widespread micro-scale breaking, even without whitecaps, will substantially modify the average sea surface temperature as measured radiometrically. It is also likely to be extremely important in the exchange of heat and water vapor between the atmosphere and the ocean, which exchanges are responsible for modifying climate on a very large scale. Older methods of expressing the measured heat transfer and rate of evaporation are based essentially on ideas of turbulent flow over a flat, rigid surface and give results that scatter widely. It seems probable that the neglect of this additional effect, unique to the sea surface, is responsible for at least a substantial fraction of this uncertainty.

The presence or absence of micro-scale breaking also has a strong influence on 'sea clutter', the back-scattering of short radar pulses at glancing incidence to the sea surface. The intensity of the back-scattered signal is dependent on the characteristics of sea surface structures whose wavelength is half that of the incident radiation. For 10 and 20 cm radar, the scales of interest of those characteristic of the micro-scale breaking wavelets in a moderate wind and the statistics of the amplitudes, spatial and directional distribution of these wavelets are of immediate concern. A complicating factor is, of course, that these wavelets do not exist alone; they are riding over much longer and higher wave components which both modify the structures themselves and also vary the effective angle of incidence of a radar pulse on a group of wavelets. Classical scattering theory is concerned with small perturbations of a surface that is essentially smooth and a direct application to the ocean surface where the small wavelets doing the scattering are superimposed on a random distribution of much larger, longer waves, involves more faith than deductive logic.

The sea surface is usually covered with a thin layer of surface active material, generally disperse but sometimes dense enough to cause a visible slick. These occur not only as a result of oil spills but naturally, the smooth appearance of the water surface making them readily visible. A sufficiently dense accumulation of material at the water surface, often of organic origin, forms a skin that is resistant to stretching; it increases the dissipation rate from small wavelets, but its strongest influence appears to be the suppression of small-scale breaking. In essence, the surface skin prevents the water at the surface from surging forward near the crest of a wavelet so that breaking is inhibited, and the generally smooth appearance of the surface in a slick results from the absence of such breaking with the accompanying small-scale roughness.

The appearance of the water surface frequently reflects dynamical processes that are taking place below. In temperate latitudes, the upper

50 meters or so of the ocean is generally well mixed as a result of small-scale turbulence produced both by wave breaking and by the instability of wind-induced shear. Below this mixed layer, the water is generally colder and more dense and the contrast between warm, lighter surface water and this denser underlying water can support internal gravity waves that are structurally similar to surface waves. The wavelengths of internal waves are generally longer than most surface waves, perhaps 100 or 300 meters, and they travel much more slowly than do surface waves, of order 20 or 50 centimeters per second. An example of low mode internal waves on a shallow thermocline is shown in Figure 2. The upper trace from an acoustic echo-sounder pointing vertically downwards shows oscillations in shallow scattering layers at depths around 30 m, and in the lower diagram the temperature oscillations at a fixed depth are produced by the vertical displacements of the water column in which the temperature decreases with depth. A wave crest corresponds to a temperature minimum. One characteristic of oceanic internal waves on the thermocline seems to be that they occur in groups, the energetic intervals being interspersed with more quiescent ones.

These internal waves induce a pattern of surface currents that can, under appropriate circumstances, influence quite strongly the distribution

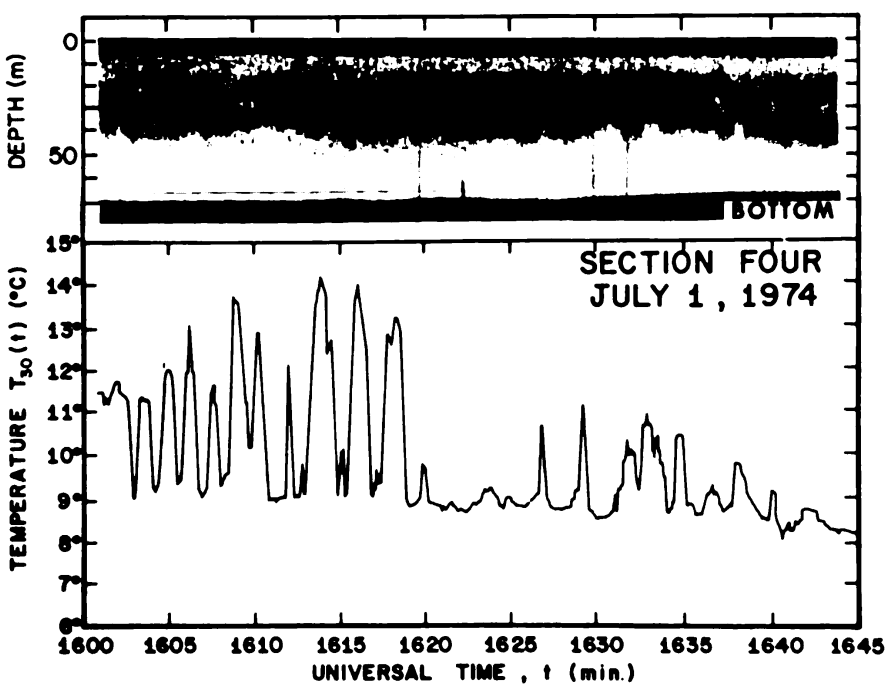

Figure 2 — Internal wave packets in shallow water off New Jersey. The upper part of the figures shows an acoustic echo-sounder track and the lower part is a temperature record from a towed thermistor at 30 m depth. This figure was kindly supplied by Dr. John R. Apel of the NOAA Pacific Marine Environmental Laboratory.

of surface, wind-generated waves. One remarkable example was observed by Perry and Schimke from the U.S. Coast and Geodedic Survey ship *Pioneer* in 1964 near the Nicobar Islands to the northwest of Sumatra. In a paper published in the Journal of Geophysical Research in 1965, they write, "On the morning of June 12, 1964, distinct zones of whitecaps ranging from 200 to 800 m in width and stretching from horizon to horizon (approximately 30 km) in a north-south direction were observed in the Andama Sea north of Sumatra. At least five of these zones with a spacing of about 3200 m between each zone were observed. The observed zones or bands of choppy water had short, steep, randomly oriented waves with heights of about 0.3 to 0.6 m. Each band stood out distinctly in an otherwise undisturbed sea. A 4-m/sec NW wind and a surface water temperature of 29°C were observed but neither changed significantly as the ship crossed the bands of choppy water.... Later in the day several other bands of similar dimensions but having smaller waves were observed."(1) Bathythermograph measurements indicated the simultaneous occurrence of large amplitude internal waves with phases that were related consistently to the occurrence of these bands of choppy water. The conditions encountered by Perry and Schimke are certainly extreme, but by no means unique. Similar visual observations have been made among the islands along the west coast of British Columbia where a relatively thin layer of fresh water lies over denser ocean water.

Variations in the density of surface material under certain circumstances can also provide visual indications of internal gravity waves beneath the surface, an association noted by LaFond as long ago as 1959.(2) The effect is strongest when the wind is blowing in the same direction as the internal waves are moving, causing a surface drift about the same speed as that of the internal waves. A given patch of surface material therefore remains in phase with the internal wave below, and surface material tends to collect at the moving regions of maximum convergence in the pattern. A series of slicks will tend to gather at such points, suppressing small-scale breaking and giving the surface a banded appearance with alternating smooth and ruffled zones. This kind of structure is not uncommon in coastal waters particularly off southern California.

Variations in surface brightness that are almost certainly associated with internal waves are visible on occasion from satellite observations. Figure 3, is a Landsat-1 image taken on 23 July 1976 south of Long Island, New York. What at first sight appeared to be wispy clouds, evident over much of the area, are believed to be surface roughness variations associated with light winds; but towards the right-hand side and particularly at the bottom, there are clear groups of semi-periodic striations with intersecting curved fronts. The scales and other characteristics of the striations are consistent with their having been generated by internal waves. But precisely how are they produced? Presumably, they represent changes in surface roughness that result from small modifications to the short wave structure of the sea that is somehow locked in phase with the internal wave. But precisely how are the modifications produced? The answer is not known with certainty. The variations in surface current to which wind-generated waves respond are relatively small compared with the motions associated with the wind-waves themselves. The signal, whatever it is, is frequently buried in a great deal of noise, and one would like to be confident about the range of sea conditions and the internal wave properties over which detection is possible. The search is complicated in a number of ways. First, there are a variety of interacting processes which occur simultaneously. For example, the internal waves may modify the middle scale surface waves as they move from crest to trough of the underlying internal wave pattern, and changes in these may in turn influence the structure of the short waves which are rapidly regenerated by the wind. The changes in short wave structure may be small but observable if they are coherent over many hundreds of meters. Alternatively, the striations may reflect a direct internal wave-short wave interaction. The difficulty with this is that short waves adjust rapidly to the ambient wind conditions but only slightly to the surface currents that are produced by internal waves; nevertheless, a small change might possibly be enough. Alternatively, one might speculate that systematic variations in surface film properties produced by the internal wave may influence the short wave surface roughness more strongly than a direct coupling between the two types of motion. If this is so, the internal waves would not be visible if the surface film were either too compacted or too diffuse. This last possibility would appear to be tenable only if the wispiness of Figure 3 represented variations in surface film density upon which is superimposed the influence of internal waves.

Images of this kind pose more questions at this stage than they provide answers. In some regions there are no indications of internal wave striations. Is this because these are quiescent regions (probably so, in this image)? But perhaps there are regions of internal wave activity that are not detectable because the conditions necessary for their visualization are not present. What is the threshold of detectability of internal waves in this way? Until we know precisely how the striations are formed, the general question remains unanswered.

Internal wave structures can also be detected on occasion by the variations in intensity of a radar back-scattered signal at glancing incidence. The radar pictures of Figure 4 show a group of traveling internal waves near Gibraltar, marked by the differential intensity of the return in different phases of the internal wave. In this case, one can be reasonably certain that the striations are caused by variations in surface

Figure 3 — A Landsat-1 image of 23 July 1976, showing an area south of Long Island, New York. Internal wave activity is visible particularly in the lower left. Courtesy Dr. John R. Apel, Pacific Marine Environmental Laboratory.

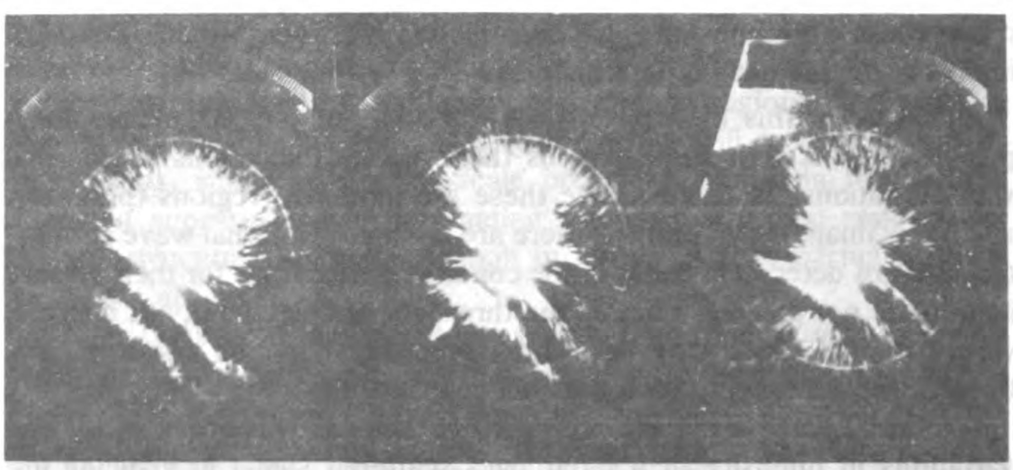

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Figure 4 — Three successive radar images, at intervals of 5 minutes, showing variations in back-scattered return associated with internal waves off Gibraltar. Courtesy Dr. J. Ziegenbein, SACLANT ASW Research Center.

roughness whose scale is about one-half the scale of the radar wavelength, but again the precise way in which these variations are produced by the internal wave and the range of conditions over which they are observable remain elusive.

Infra-red images of the sea surface provide considerable information (though not always unambiguous) on the sea surface temperature. The sea is quite opaque to infra-red wavelength so that the radiated energy in this part of the spectrum is derived from (and is an index of the temperature of) the top millimeter or so of the ocean. The difference between the surface temperature and the temperature at even 1 m depth is influenced strongly by wind and short wave breaking and by the evaporation rate; thus quantitative inferences are difficult. Nevertheless temperature contrasts between underlying water masses are detectable as temperature contrasts between the surface temperatures as can be seen in Figure 5. The intensity of the image indicates temperature, lighter areas being colder. Cape Hatteras is near the center of the picture and the Chesapeake Bay and Potomac River are towards the top, just west of a cloudy area. Further to the west, near the top left corner is

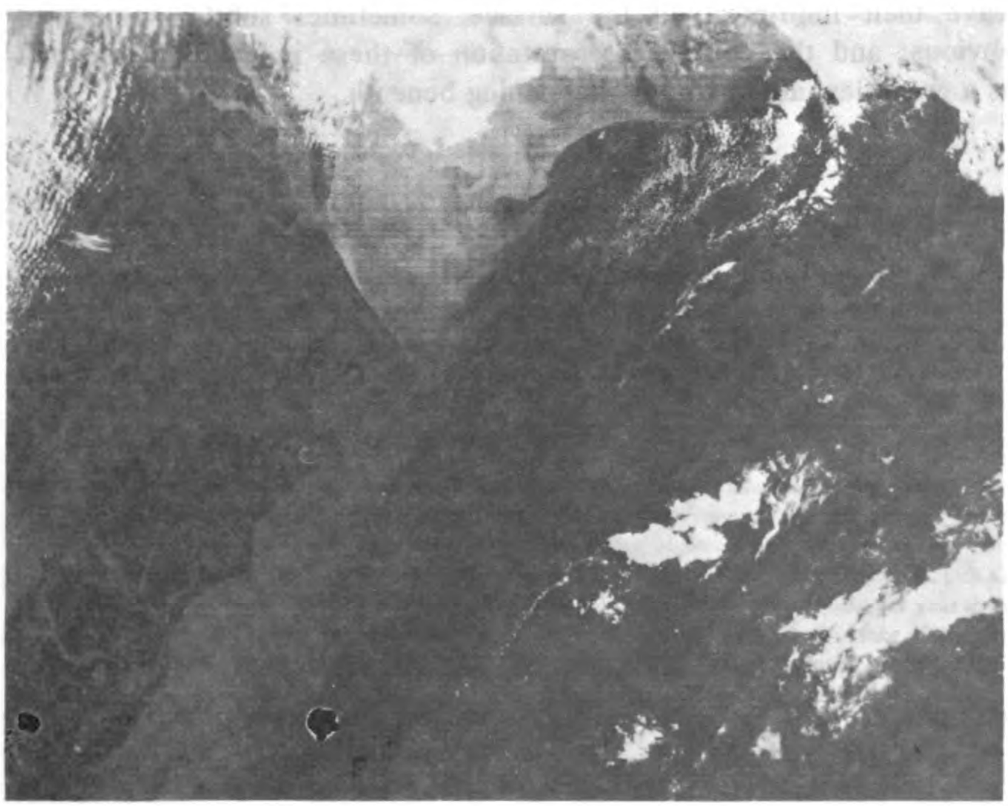

Figure 5 — An infra-red image of the sea surface off Cape Hatteras. The depth of the image represents temperature, lighter areas being colder. Courtesy Dr. Fred M. Vukovich, Research Triangle Institute.

a train of lee waves, atmospheric internal waves marked by cloud lines are generated by the air flow over the Appalachians, just outside the area shown. In the ocean, the Gulf Stream is marked as the boundary between warmer (darker) oceanic water and the cool water inshore. Some eddies and detachments can be seen south of Cape Hatteras as the Gulf Stream flows north; at this point it leaves the coastal shelf and proceeds northeast. Water to the west of the Gulf Stream is colder (lighter) here, having drifted southwards from the New England coast. As the stream progresses north, the amplitude of its meandering appears to increase. Near the top there is evidence of a particularly large convolution which may ultimately detach to form a separated cold eddy with a lifetime as an observable entity of several months. Satellite observations enable information to be collected quickly from a large region of the ocean surface, but the difficulty and the challenge is that the direct information provided is generally restricted to the top few millimeters of the whole ocean column.

Oceanographers have in the past sometimes regarded the ocean surface as the uninteresting boundary with the atmosphere. For many true oceanography begins perhaps 10 or 15 meters below the surface. It is becoming increasingly apparent, however, that deeper motions leave their imprint upon the surface, sometimes subtle, sometimes obvious; and the correct interpretation of these indications may tell us a great deal about what is happening beneath.

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Radiation Effects in Fiber Optic Glassy Materials

Work supported a little over a year ago by the Metallurgy Program on radiation effects in fiber optic glassy materials at Naval Research Laboratory (NRL)(Dr. G. Sigel) is finding use in dealing with crucial problems limiting development of DF laser solid windows. It seems that the optical absorption coefficients for fiber optic glasses and laser windows can be measured by the same simple (and sensitive) laser calorimetric technique developed under this previous work. These measurements are being made under an Office of Naval Research (ONR) supported effort with Dr. M. Hass at NRL. In addition, it happens that the optical absorption coefficient of water in the blue-green region is of the same magnitude as for fiber optic glasses. This absorption coefficient has never been measured but would be useful for application to underwater communication systems. Dr. Hass has been measuring this parameter via the above-mentioned calorimetric technique.

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Cover Caption

The USS Remey (DD-688) withstands rough seas while refueling from the USS Lake Champlain (VS-39). *See page 19.*

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