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Technical Activities 1986

Center for Basic Standards

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U.S. DEPARTMENT OF COMMERCE
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U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Measurement Laboratory
Center for Basic Standards
Gaithersburg, MD 20899

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary
National Bureau of Standards, Ernest Ambler, Director

ABSTRACT

This report summarizes the research and technical activities of the Center for Basic Standards during the Fiscal Year 1986. These activities include work in the areas of electricity, temperature and pressure, mass and length, time and frequency, quantum metrology, and quantum physics.

Keywords: Astrophysics; atomic and molecular physics; chemical physics; electrical standards; fundamental constants; gravity measurements; laser physics; length standards; mass standards; pressure and vacuum standards; temperature standards; time and frequency standards; X-ray and gamma-ray wavelength standards.

INTRODUCTION

This report is a summary of the technical activities of the NBS Center for Basic Standards (CBS) for the period October 1, 1985 to September 30, 1986. The Center is one of the four centers and operating units in the National Measurement Laboratory.

The summary of activities is organized in six sections, one for the technical activities of the Quantum Metrology Group, and one each for the five divisions of the Center. Each division or group tells its own story in its own way. In general, there is an overview followed by a series of short reports on current projects. Then the publications, invited, talks, committee participation and professional interactions during the year are listed.

More information about particular work may be desired. To obtain this, the reader should address the individual scientists or their division, c/o Center for Basic Standards, B160 Physics Building, National Bureau of Standards, Gaithersburg, Maryland 20899.

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OVERVIEW

During the past year, this group has become noticeably smaller and somewhat more focussed. Two persistent themes remain: of more obvious relevance to CBS we have several fundamental measurement exercises, each of which has required serious improvement in metrological technique and all of which bear strongly on issues of basic scientific moment. The second, less metrologically demanding exercise, concerns the physics of inner-shell processes where need for clarification of fundamental mechanisms has led us to extensive involvement with synchrotron radiation facilities and the National Synchrotron Light Source (NSLS) at Brookhaven, in particular. Although practiced in the organizational locale of CBS, rationalization of this work needs to look toward molecular and condensed matter science and applications include even surface studies.

For convenience and variety, this year's review is organized geographically, focussing in order on Gaithersburg, Grenoble and Brookhaven. (Although the West-German connection for high Z, few electron systems remains important, it was, aside from planning and analysis, dormant.) As described below, there have been notable successes at these three sites but none appears ripe for closing at this time.

TECHNICAL ACTIVITIES

Gaithersburg Activities:

As mentioned in last year's panel book, our most serious and urgent problem has been the large discrepancy between our (1974-76) measurements of a Si lattice parameter and the subsequent (1979-82) results from PTB. Over the past three years, we established two major efforts to deal with this important question. Firstly, the entire x-ray/optical interferometer (XROI) experiment was re-constructed with major improvements including: use of a frequency-agile, offset-locked slave laser to drive the system through each x-ray interference profile studied; provisions of a unique and sensitive 4-beam path curvature interferometer for on-line trajectory characterization; full computer controlled automation; and, an advanced non-contacting, servoed vibration isolation system. Secondly, an entirely new lattice spacing comparator (the delta-d machine) was built so the question of sample-to-sample variability could be addressed with a precision well in excess of the targeted accuracy range.

The re-constituted XROI experiment was working at the time of the last panel meeting but had not achieved definitive results or suggested a resolution of the NBS-PTB discrepancy. The Δ-d machine had been assembled but was not yet operational. It is gratifying to report major successes in both areas. In the case of the XROI experiment, through the on-line path monitoring capability, a serious systematic error was uncovered which arose from a combination of pitch error larger than indicated by x-ray fringe contrast and an Abbe′ offset differing slightly from zero owing largely to x-ray beam non-uniformity. Our efforts to follow this trail began last winter and required installation of a considerably up-graded table suspension before reliable control could be obtained. Subsequent data runs in March, June and September showed good concordance (better than 0.1 ppm) and give numerical values which substantially remove the NBS-PTB discrepancy. Actually small differences remain but these are well within the range of generally expected sample-to-sample variability.

It is just for this state of affairs that the Δ-d machine was designed. Following initial testing, the spectrometer was moved to a passive vibration isolated surface plate in the basement. The instrument was surrounded with a curtain-type enclosure and the crystals were thermally shielded. An electrical umbilical cord was installed from the spectrometer to the electronics rack. Two x-ray tubes are used to permit simultaneous recording of left and right nondispersive curves. Operation of both tubes with a single x-ray power supply and two constant potential units was achieved. Computer software to automatically control the spectrometer and permit round-the-clock comparisons of four crystal samples was developed.

The spectrometer uses a long transfer crystal (≈10 cm long x 1 cm high) on a rotating axis whose angular position is measured with a polarization sensitive Michelson interferometer. The crystals whose lattice spacings are being compared reside on a motorized slide and are automatically moved in and out of the x-ray beam. These crystals are approximately 1 cm x 1 cm and are equipped with piezo electric tippers which permit establishing parallelism of the planes of the transfer and test crystals. The long transfer crystal and four test crystals were oriented, cut, and etched from several silicon samples. Non-dispersive double crystal reflections from thin samples (≈0.5 mm) of nearly equal thickness (<10 μ) show narrow fine structure on the normal x-ray profile. This fine structure which is about 0.02 of the FWHM makes the comparison of profile positions much more accurate. Great care was exercised during the crystal preparation to insure that crystal thicknesses were within the required tolerances.

First profiles were recorded in the spring and after some modifications to improve both performance and convenience profiles containing symmetric distinct fine structure were obtained. As of September (when this report is being written) it appears to live up to all of our expectations regarding sensitivity and stability. With the clear delineation of expected hyperfine detail one easily sees lattice constant differences (Δd´s) near 0.05 ppm with the expectation of accuracies at or below 0.01 ppm after more careful analysis.

There are evidently two approaches to analyzing data, one depending on fitting model profiles, the other simply uses a shifting algorithm to compute the correlation integral, the location of whose maximum yields Δd in a simple, model-independent way. Theoretical profiles have been obtained from calculations using dynamical diffraction theory.

At the present time (September) we have in hand samples of monocrystalline silicon from the PTB and from NRLM in Japan. Near the close of the month´s running currently underway (assuming no unforseen problems), we plan to open XROI and extract the NBS primary sample. With a few weeks of sample preparation and alignment we should begin an intercomparison exercise that will mark the terminus of this long-standing problem. Of course, there is much writing to do and a need to normalize as well the crystals we use in Grenoble, those used in the Avogadro constant work and those used to establish markers for exotic atom spectroscopy.

Thereafter it should be possible to use this same apparatus and measurement procedures to address some other questions of both fundamental and practical significance. Among these are: Just how perfect are these samples? Are the symmetry-equivalent spacings equal? Are the angles 90°? What happens to the spacing when oxidization is forced? What about ageing? Annealing? .... We look forward to perhaps 1-2 years of fairly productive exploration and would welcome, as well, outside users with specific problems.

Grenoble Activities:

In December 1985, the upgraded NBS double flat crystal γ-ray spectrometer (GAMS-4) was shipped to the Institut-Laue Langevin in Grenoble (thus completing its third transatlantic voyage). During the month of January, the approximately 8 tons of equipment was unpacked and the instrument reassembled within a new concrete shielding house inside the reactor containment vessel. The new installation benefits from a variety of significant improvements which include:

1) New Source Holder

During the long shutdown of 1985, a new in-pile source changer was installed. This will allow a several-fold increase in the sample mass which can be placed in the high neutron flux region near the reactor core. This new source changer is now fully operational.

2) Positional Servo

A new type of non-contacting electro-pneumatic servo, which fixes the position of the spectrometer within a few microns has been incorporated into the passive vibrational isolation system of the instrument. This new system allows much greater precision in the orientation of the instrument with respect to the in-pile source. This system is fully operational. (Note: A patent for this servo is currently pending.)

3) Fully Automatic Calibration

Significant mechanical changes to the instrument have been made which allow the calibration of the angle interferometer to be carried out completely under computer and CAMAC control. This provides a significant simplification from what was formerly a very labor-intensive operation. By eliminating the thermal and mechanical perturbations inherent in the previous method we expect a several-fold improvement in the accuracy of our calibrations. This system is fully operational, though detailed tests of reproductability remain to be done.

4) Improved Collimation

New adjustable slit collimators which are four times longer than the previous fixed width collimators will allow a wider acceptance at higher energies. These have been installed and aligned to ≈ 100 μm of the beam axis.

5) Controlled Atmosphere Chamber

The optical interferometers have been enclosed in a hermetic chamber which will allow the precise control of temperature pressure and gas composition. With the use of a gas density servo (pycnostat) we expect to reduce to insignificance any possible errors due to gas index of refraction. This system is in the process of final installation.

Our first opportunity to observe the behavior of the upgraded GAMS-4 came in April during our first beam allocation of 1986. Using a test source of ^{48}Ti we had successful operation in the 1-2 MeV region. In the course of this work we observed for the first time a Recoil Doppler broadening in neutron capture gamma-ray lines. This was only possible due to the extremely high resolution of the GAMS-4 Instrument. This broadening, which provides a new technique for the measurement of excited state nuclear lifetimes has generated considerable enthusiasm in the nuclear physics community. Already two proposals to employ this method have been submitted by outside users. We expect continued developments in this area.

The ultimate target accuracy of this instrument is ≈0.1 ppm at 5 MeV. Since the efficiency of this instrument is inherently very low ($\approx 5 \times 10^{-13}$ at 5 MeV) great care must be taken to maximize count rate. To this end we have carried out a detailed study of the reflectivity of perfect crystals in this extremely high energy range. In the course of this study we have identified a unique feature of the dynamical theory of diffraction which can yield an approximate factor of ≈3.5 improvement in integrated intensity. This technique, which involves a careful "tuning" of crystal thickness (for a given energy) takes advantage of the so called thickness pendellösung intensity oscillations in a perfect crystal. New "tuned" crystals have been prepared and will be tested during our next allocation of beam time in November 1986.

Brookhaven Activities:

In support of long-standing interests in inner-shell spectroscopy and x-ray physics in general, the Quantum Metrology Group has been active for some years in the NBS/NRL Participating Research Team (PRT) at the National Synchrotron Light Source. The PRT has brought four beamlines into operation, X23-A3, X23-B, X24-A and X24-C, and plans to bring a fifth line, X23-A2, into operation before December 1986. The Quantum Metrology Group (QMG) of the National Bureau of Standards has assumed primary responsibility for the design, construction, commissioning and operation of beamline X24-A.

Beamline x24-A is designed to deliver tunable monochromatic x-rays in the energy range from ≈500 eV to 5000 eV. This tuning range is complemented by other PRT beamlines such as X24-C (10 eV to 2000 eV) and X23-B (3 keV to 12 keV). The energy range of X24-A includes inner shell ionization thresholds (either K, L or M) for all elements with $z \geqq 9$ (Fluorine). This energy range also represents the long wavelength limit for x-ray diffraction by crystals. As such it is an ideal testing ground both for new spectroscopic techniques, such as high energy resolution x-ray fluorescence spectroscopy, and for studies of the physical optics of x-rays, including x-ray interference and boundary effects.

Beamline X24-A became fully operational just before the beginning of fiscal 1986. It currently produces the highest flux, the highest intensity and the narrowest band width of any synchrotron radiation beamline in its energy range. This unexcelled performance is attributable to a number of novel design concepts. Beamline X24-A focusses 8 mrad of horizontal divergence from the bending magnet, more than any other x-ray beamline. It was also the first x-ray beamline to incorporate two x-ray mirrors. Novel mirror coatings were used for optimal performance in this energy range. X24-A also included the first linkage-based, constant-offset, UHV-compatible crystal monochromator, a design which has been adopted for the Facility's own monochromatic beamlines as well as other NBS/NRL beamlines.

Despite the exemplary performance of the beamline itself, operations have not been trouble-free. From the beginning, Beamlines X24-A and C have received only a fraction of the expected flux due to misalignment of apertures within the ring itself. Resolution of this problem has been dependent upon the Facility's staff. Operations are also dependent upon the Facility's schedule. The x-ray ring did not operate from mid-December 1985 through January 1986, or in June 1986 due to scheduled downtime. In addition, operations time in October 1985 was lost in the aftermath of hurricane Gloria, and no effective operations were possible in February, March or April 1986 due to beam instabilities following the January shut-down.

During the available beamtime the Quantum Metrology Group has concentrated on x-ray spectroscopy. Activities in this area included the following: optimization and characterization of a novel high-energy resolution secondary x-ray spectrometer, studies of threshold excitation of multi-vacancy states in atomic Argon using x-ray absorption, fluorescence and photoelectron spectroscopy, studies of resonant x-ray scattering (elastic and inelastic) from atomic Argon, and studies of molecular orbitals of chloro-fluoromethanes via x-ray absorption and fluorescence spectroscopy. Additional experiments on x-ray absorption and fluorescence spectroscopy of crystalline potassium-chloride are expected to be completed before the end of the fiscal year.

Progress also continued in studies of the physical optics of x-rays. Although no experiments have been performed at NSLS to date, analysis of experiments performed at the Stanford Synchrotron Radiation Laboratory and the Hamburger Synchrotronstrahlungslabor during 1984-1985 has yielded fresh results. In addition, theoretical work by P.L. Cowan now enables one to predict a number of effects involving simultaneous x-ray reflection and diffraction from crystals with epitaxial or amorphous overlayers, surface reconstructions, rough surfaces and adsorbed monolayers.

At the beginning of fiscal 1986 the Quantum Metrology Group supported full-time involvement in synchrotron radiation research by two staff scientists (P.L. Cowan and S. Brennan) and one NSLS technician (B. Karlin). In addition half-time participation by T. Jach was funded by QMG with additional collaboration by R.E. LaVilla, R.D. Deslattes and A. Henins supporting this effort. The departure of S. Brennan in March 1986 depleted the available manpower significantly for most of the year. A replacement, D. Lindle, is expected to arrive just before the end of the fiscal year.

Collaboration with scientists from other institutions has also been important in the past year. Prof. S. Banna from Vanderbilt University and several of his students collaborated in measurements of multivacancy satellites in photoelectron spectra from Argon. A collaborative research project is already underway with the Center for X-ray Optics at LBL to produce a wide bandpass synthetic multilayer optical element to replace X24-A's first mirror to reduce the heat load upon the crystals in the monochromator when operating at low photon energies. We plan performance tests of the first of these elements prior to the extended x-ray ring shutdown in 1987. Also, several research groups have expressed interest in performing theoretical calculations of molecular orbital effects in x-ray spectra to complement our measurements.

Neutron Physics:

Since the last review there has been considerable activity in the area of Fundamental Neutron Physics. A highly successful workshop on "The Investigation of Fundamental Interactions with Neutrons" was held at NBS which brought together approximately 70 participants from laboratories and universities in the U.S., Canada and Europe. Sponsored jointly by the Department of Energy (DOE) and NBS, this workshop not only reviewed recent work in this area but also focussed on several promising future activities. An examination of potential efforts at the proposed NBS National Cold Neutron Facility was made and several "proto" collaborations were initiated.

Work is continuing on a joint NBS/Los Alamos experiment to determine the neutron half life. This work will be carried out at the existing NBS research reactor. Development of a new class of absolute neutron flux detectors, a central feature of this collaboration, is proceding.

A proposal is pending at DOE for support of another neutron lifetime measurement which will be a joint effort between NBS and the University of Sussex (U.K.). The second generation experiment promises an order of magnitude improvement in our knowledge of this fundamental quantity. We note that partial support (≈$100 K) has already been granted by the Science and Engineering Research Council (U.K.).

In addition to this work, members of the Q.M.G. have continued their participation in various planning groups for future neutron facilities. This includes participation in the National Steering Committee for Advanced Steady State Reactor and the National Academy of Sciences Panel on University Research Reactors.

INVITED TALKS

Quantum Metrology Group (520.06)

Sean M. Brennan, "Applications of Grazing Incidence Scattering," Photon Factory of Japan, Tokyo, Japan, October 1985.

Sean M. Brennan, "Grazing Incidence Scattering: A Tool for Surface Crystallography," Tokyo Institute of Technology, Tokyo, Japan, October, 1985.

Paul L. Cowan, "High Energy Resolution X-Ray Spectroscopy," Lawrence Berkeley Laboratory Workshop on Advanced Soft X-Ray and Ultraviolet Synchrotron Source, Berkeley, California, November 13, 1985.

Paul L. Cowan, "Diffraction of Evanescent X-Rays," Argonne National Laboratory Workshop on the Scientific Case for a GeV Synchrotron Source, Argonne, Illinois, December 9-11, 1985.

Paul L. Cowan, "X-Ray Emission from Argon Stimulated by Resonant Absorption," at the Annual American Physical Society Meeting, Washington, D.C., April 28-30, 1986

Paul L. Cowan, "Multilayer-Coated Mirror for NBS Beamline (X-24A) at NSLS," Brookhaven National Laboratory Workshop on X-Ray Optics: Problems in Materials, Manufacture and Performance, Upton, New York, June 3, 1986.

Paul L. Cowan, "Monochromatic X-ray Excitation of Argon K-Fluorescence," at the National Synchrotron Light Source Annual Users Meeting at Brookhaven National Laboratory, Upton, New York, June 5, 1986.

Paul L. Cowan, "Surface Studies by the Diffraction of Evanescent X-Rays," at the Annual Meeting of the American Crystallographic Association, McMaster University, Hamilton, Ontario, Canada, June 22-27, 1986.

Richard D. Deslattes, "Atomic Physics with Cooled Stored Heavy Ions," at the Oak Ridge National Laboratory, Oak Ridge, TN, January 13-15, 1986.

Richard D. Deslattes, "Multivacancy Effects in Atomic and Molecular Spectra," at the University of Tasmania Workshop on Excited Ionized States of Atoms and Molecules, Tasmania, Australia, Feb. 3, 1986.

Richard D. Deslattes, "New Links Between X-Rays and Visible Light," at the Massachusetts Institute of Technology, Cambridge, Massachusetts, March 4, 1986.

Richard D. Deslattes, "Z-Dependicies in the Spectra of One-, Two- and Z-1 Electron Ions," at the Harvard-Smithsonian Astrophysical Observatory, Boston, Massachusetts, March 5, 1986.

Richard D. Deslattes, "Spectroscopy of Heavy Ions," at the symposium "10 Years of Uranium Beam," at the Gesellschaft fur Schwerionenforschung, Darmstadt, West Germany, April 2-4, 1986.

Geoffrey L. Greene, "The Silicon Lattice Spacing, the Neutron Mass, and the Fine Structure Constant," at the Notre Dame University, South Bend Indiana, November, 21, 1985.

Albert Henins, "Bending of Crystals for X-Ray Spectroscopy," at the Physikalisches Institut der Justus-Liebig-Universität Giessen, West Germany, July 10, 1986.

Ernest G. Kessler, Jr., "GAMS 4 - Past, Present, and Future," at the Institut Laue Langevin Nuclear Physics College, February 5, 1986.

Ernest G. Kessler, Jr., "One-Electron and Inner-Shell Energy Levels in High Z Atoms," at the symposium on Relativistic Many-Body Problems, at the International Centre for Theoretical Physics, Trieste, Italy, June 30, 1986.

Robert E. LaVilla, "X-Ray Spectra of Molecular Gases," at the Department of Chemistry, Indiana University, Bloomington, Indiana, March 31, 1986.

Robert E. LaVilla, "Threshold Studies of the Multivacancy Processes in the $K\alpha$ Region of Argon," at the Annual American Physical Society Meeting, Washington, D.C., April 28-30, 1986.

Gabriel G. Luther, "Equivalence of Active and Passive Gravitational Mass," at the Los Alamos National Laboratory, Los Alamos, New Mexico, December 3, 1986.

Gabriel G. Luther, "Eötvös, Fischbach, Stacy and the Equivalence Principle," at Northrup Electronics, Los Angeles, California, April 17, 1986.

PUBLICATIONS - 1986

Quantum Metrology Group (520.06)

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P.L. Cowan, S. Brennan, T. Jach, M. Bedzyk and G. Materlik, "Observation of the Diffraction of Evanescent X-Ray at a Crystal Surface," submitted to Phys. Rev. Lett. (1986).

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TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Metrology Group (520.06)

R. D. Deslattes, Chairperson, The American Physical Society, Division of Atomic, Molecular, and Optical Physics

R. D. Deslattes, Member, Organizing Committee, International Conference on X-Ray Spectroscopy, X-87, Paris.

R. D. Deslattes, Member, NAS/NRC Panel on Scientific Opportunities for the Use of Cooled Heavy Ion Storage Rings

P. L. Cowan, Executive Committee, National Synchrotron Light Source Association of Users

P. L. Cowan, Organizing Committee, Workshop on an Advanced Soft X-Ray and Ultraviolet Synchrotron Source: Applications to Science and Technology, Lawrence Berkeley Laboratory, November 13-15, 1985

G. L. Greene, National Academy of Sciences Panel on University Research Reactors

G. L. Greene, National Steering Committee for the Advanced Steady State Reactor

TECHNICAL ACTIVITIES
ELECTRICITY DIVISION
FISCAL YEAR 1986

Overview

The Electricity Division (ED) concerns itself with the fundamental electrical quantities such as current, voltage, and impedance at dc and low frequencies (to roughly 100 kHz) over many orders of magnitude and at the highest possible levels of accuracy. Its primary mission is to provide the central basis for a reliable and consistent system of electrical measurement throughout the U.S., including the Nation's scientific and defense communities as well as industry and commerce; and to ensure that the U.S. system is consistent with those of other countries and the internationally accepted system (i.e., the International System of Units or SI).

The justification for all of the ED's work comes directly from the Bureau's Organic Act, as amended, and is in its prime mission areas, that is, the areas of responsibility for which the Bureau was originally founded in 1901. The major technical areas which benefit from the ED's work include fundamental physical theory; high technology-based R&D; electrical power revenue metering, transmission, and distribution; industrial process control; quality control in the manufacture of electronic components and products; testing and maintenance of electronic systems, which includes civilian contract suppliers of defense and aerospace programs; and national defense requirements directly under the Department of Defense. End user groups include scientists in universities; electric power utilities, both public and private; electric equipment manufacturers; process engineers who design, build and use industrial process control system; manufacturers of electronic components and consumer products; high technology civilian companies and government agencies involved with communications, computers, aerospace, transportation, health, and defense; and finally the armed services.

It is probably not an overstatement to say that the Nation's electric power system, the cost-effective manufacture of reliable consumer goods, the economic production of industrial materials, a viable national defense, and R&D at the cutting edge of science and technology, would not be possible without adequate electrical measurements; and that the basis for all such measurements within the U.S. is the fundamental electrical units the ED maintains and disseminates through its various services; the measurement methods and instrumentation it develops; and the tests and calibrations of standards and instruments it performs. For example, each year well over one thousand calibrations are carried out on primary electrical standards of voltage, resistance, capacitance, inductance, and ac-dc difference (i.e., thermal ac/dc voltage and current converters) that belong to some of the Nation's most important corporations, utilities, universities and government organizations, including Hewlett-Packard, General Motors, IBM, General Electric, Pacific Gas and Electric, Rockwell, McDonnell-Douglas, Boeing, TRW, the TVA, the FAA, and the DoD. These standards are used in turn to calibrate and otherwise support a wide range of work-horse electrical measuring instruments and systems numbering literally in the hundreds of thousands, such as digital voltmeters (DVMs), programmable voltage and current sources, analog-to-digital and digital-to-analog converters, resistance/inductance/capacitance (RLC) meters, impedance bridges, electrometers, oscilloscopes, data recorders, component and printed circuit board testers, automatic test equipment (ATE), including ATE for weapons system, etc. Without reliable measurement results from such equipment, a technologically sophisticated society like that of the U.S. could not even exist, let alone advance.

To fulfill its main responsibility of providing the central basis for the U.S. electrical measurement system, the ED carries out work in eight distinct but related areas with the following objectives:

1. Realize the SI definitions of basic electrical measurement units such as the ampere, volt, ohm, and farad, thereby ensuring that the U.S. legal electrical units are consistent with the internationally accepted system.

2. Develop and maintain U.S. Legal or National Reference Standards for the basic electrical units and related quantities, thus providing a central basis for the U.S. system of electrical measurement.

3. Disseminate the basic electrical measurements units to users within the U.S. via a variety of measurement and calibration services, and develop new means for doing so, thereby ensuring the traceability of electrical measurements made throughout the country to National Reference Standards.

4. Develop new methodologies and the required instrumentation and standards which will lead to advances in the state-of-the-art of electrical measurement, thus ensuring the availability to the technical community of adequate measurement techniques.

5. Determine fundamental physical constants closely related to the electrical units in order to provide the scientific community the means to test basic physical theory.

6. Initiate and participate in international comparisons of the basic electrical units, thus ensuring that the U.S. system of electrical measurement is consistent with those of other countries.

7. Participate in voluntary national and international standardizing activities related to the electrical units, and the fundamental physical constants, in order to foster international compatibility of electrical measurements, eliminate and prevent non-tariff barriers to trade, and contribute to internationally acceptable data compilations.

8. Provide training for personnel active in the field of electrical measurements and standards, including the presentation of seminars and

workshops, and the generation of tutorial written material, thereby elevating the overall level of competence in the field.

The objectives, current activities, FY 86 accomplishments, and future plans of the various projects underway within the ED which contribute to these principal areas are described in detail in the following Project Reports. Highlights, categorized according to these eight principal areas of work, include:

1. Realize SI Units. Good progress was made during the year to redetermine the NBS farad and ohm in terms of their respective SI units by means of the NBS calculable cross capacitor. With the assistance of Guest Scientist G. W. Small from NML (Australia) and H. P. Layer of the CBS Length and Mass Division, the calculable capacitor was taken apart, cleaned, "fine tuned," and reassembled after the completion of extensive ancillary measurements. The end result of this considerable effort will be significantly increased confidence in the experiment. A sub-tenth ppm value for both the NBS farad and ohm should be available during CY 1987. The extensive rebuilding of the NBS moving coil ampere balance being used to determine the ratio of the NBS as-maintained ampere to the SI ampere (or equivalently, the value of the Josephson frequency-voltage ratio 2e/h in SI units) to an eventual accuracy of 0.1 ppm was nearly completed. The new moving coil, which will give a factor of ten increase in force, and the new balance wheel, which should eliminate the observed large variations in the velocity measurements, were necessitated by excessive noise in the weighing portion of the experiment and excessive scatter in the velocity portion. Numerous additional improvements were also incorporated in the experiment during the course of the year.

2. Develop and Maintain U.S. Reference Standards. Measurements to monitor the U.S. Legal Unit of resistance based on the quantized Hall resistance (QHR) continued during the year and confirmed the approximate 0.05 ppm/year decrease of the unit measured last year. Excellent progress was made on the construction of the new QHR lab which will be used both to maintain the U.S. Legal Ohm and to carry out fundamental research on the quantum Hall effect. The collaboration with the Cryoelectronics Group NBS/Boulder, on the development of a Josephson array voltage standard to maintain the U.S. legal unit of voltage was vigorously pursued; many measurements were made in the Division with prototype array standard and optimum procedures were developed to use an array to calibrate Zener references.

3. Dissemination. Although the workload this year was relatively heavy and Calibration Services Manager absent for an extended period due to illness, electrical calibration services including MAPs were generally provided in a timely way without serious problems. Nearly 1400 calibrations of basic standards were performed along with 16 MAP transfers. The required documentation of the Division's calibration services was essentially completed during the year after considerable effort by the senior calibration services support staff. Good progress was made on the construction of a number of automatic capacitance bridges

and a new inductance bridge for eventually use in the impedance calibration service. Both will replace badly worn, aged instruments. An additional automated ac-dc difference calibration system was completed and put into service. This should, in due course, significantly reduce the waiting time for this service. A second automatic 10 V standard calibration system was completed and put into service, thereby freeing the original system for research applications. Significant improvements were made in the scaling system which enables client 10 kilo-ohm standards to be calibrated in terms of the U.S. Legal Ohm maintained at the 1-V level.

4. New Methods, Instruments, and Standards. The development of new methods, instruments, and standards is, of course, prevalent throughout all of the Division's projects. Especially noteworthy this year was the design and construction of a new, automatic, highly flexible instrument for comparing quantum Hall reference resistors to quantum Hall effect devices with an accuracy of 0.01 ppm. A new, easy to use bridge which enables two inductors which differ by up to a factor of ten to be compared with an accuracy in the range 0.02 - 0.2 ppm was constructed and tested. It should be especially useful in calibrating inductive voltage dividers. Good progress was made on the construction of a semi-automatic capacitance discharge system for calibrating high valued resistors (e.g., > 1 teraohm) and an automated resistance bridge for comparing resistors in the 10 kilohm range with an accuracy of 0.01 ppm.

5. Fundamental Constants. Since the quantum Hall Effect can also be used to determine the fine-structure constant α, the work described above under 1. and 2. relating to the realization of the SI ohm and determining the quantized Hall resistance directly impacts the determination of α via the Hall effect. Also as noted above, determining the ratio of the NBS ampere to the SI ampere is equivalent to measuring 2e/h in SI units. There was excellent progress during the year on the determination of the proton gyromagnetic ratio by the low-field method. The system for determining the dimensions of the precision solenoid was made completely operational and used to obtain several complete sets of data of excellent quality. However, an unexpected and still unexplained systematic effect in the NMR portion of the experiment has delayed obtaining a final result. The 1986 least-squares adjustment of the fundamental constants was completed and the CODATA report giving the results was prepared in draft form. Two new NBS Precision Measurement Grants were awarded, one to F. R. Raab, University of Washington to test gravity and the equivalence principle using atomic physics; the other to D. R. Stinebring, Princeton University, for high precision timing of millisecond pulsars.

6. International Comparisons. Two comparisons of the NBS and NML (Australia) units of resistance using transportable resistors were carried out during the year and one of the NBS and NRC (Canada) units of resistance. A Division staff member went to NML with an NBS quantized Hall resistance sample, carried out measurements while there, and found that the difference between the NBS and NML resistance units as measured by the quantum Hall effect agreed with that obtained from the

transportable resistors to within 0.02 ppm. This was a very satisfying result. The scaling apparatus of NML for measuring 6453.2 ohm quantized Hall resistances in terms of one-ohm standards was brought to NBS and directly compared with that of NBS; the two were found to agree within 0.01 ppm, another very satisfying result. (All of the work was in preparation for the CCE meeting discussed under Standardization, below.) A comparison of the NBS and NML units of capacitance using transportable capacitors was also completed as were comparisons of thermal converters with the PTB (Federal Republic of Germany) and NML.

7. Standardization. On September 16-18, 1986, the Consultative Committee on Electricity (CCE) meets to consider questions relating to the international adoption of (1) a new value of 2e/h consistent with the SI for volt maintenance purposes via the Josephson effect, and (2) a value of the quantized Hall resistance R_H consistent with the SI for ohm maintenance purposes via the quantum Hall effect. In preparation for the CCE meeting a panel discussion session to address the impact of the changes in the electrical units which would occur if such values were adopted was organized as part of the 1986 Conference on Precision Electromagnetic Measurements (CPEM 86) held at NBS June 23 - 27, 1986, as well as an informal meeting immediately after the close of the conference of active research workers to discuss the technical aspects of measurements of 2e/h and R_H. Considerable effort was also devoted to preparing the agenda for the CCE meeting and discussion materials.

8. Training. In collaboration with the National Conference of Standards Laboratories, a very well attended and received one week course entitled "Workshop on Electrical Measurement Assurance Programs" was given in Oakmont IL, 27 October - 1 November 1985. W. D. Phillips served as the American organizer of the highly successful Helsinki Summer School on Laser Cooling and Trapping held during the first two weeks of July, 1986. He and his NBS collaborators delivered a number of lectures at the summer school. During the year, some eight foreign Guest Scientists were trained in various aspects of electrical metrology, as were some eight students including two from the metrology program at Butler Community College outside Pittsburgh, PA. There were many shorter visits (i.e., one day to two weeks) by metrologists from U.S. and foreign government and industrial standards laboratories. The Division staff published over a dozen papers during the year, prepared extensive, detailed documentation concerning the Division's calibration services, and gave numerous presentations. Finally, Division staff members played active roles in organizing CPEM 86, e.g., N. B. Belecki served as Chairman of the Technical Program Committee and R. F. Dziuba as Editors of the Program Digest.

In summary, the Electricity Division has once again met its principal electrical unit maintenance and dissemination responsibilities and at the same time made good progress on a number of important research projects. This should continue in FY 87.

DISSEMINATION SERVICES:

SUPPORT AND OPERATION

(N. B. Belecki, P. A. Boynton, C. B. Childers, R. F. Dziuba, B. F. Field, G. M. Free, R. C. Fronk, J. R. Hastings, F. L. Hermach, G. R. Jones, T. E. Kiess, J. R. Kinard, L. H. Lee, C. R. Levy, T. E. Lipe, R. E. Long, T. P. Moore, E. S. Nowicki, D. D. Prather, J. E. Sims, R. L. Steiner, S. B. Tillett, A. R. Wise)

Objectives:

The overall objective of this project is to enable all measurements of electrical quantities performed in the United States to be made in terms of the U.S. legal electrical units at the required levels of accuracy. The legal units are provided to the user community via reimbursable calibration and MAP services listed in NBS Special Publication 250 and its appendices. The timeliness and adequacy of these services must be ensured by research and development work on new measurement techniques, standards, and apparatus, since the quality of both MAP and calibration services ultimately depends on the basic metrology competence of the NBS.

The outputs of this project are used directly by the metrology community - the major standards laboratories of industry, government, and the academic community - and indirectly through them by industry for the quality control and maintenance of electronic products, for the control of manufacturing processes in basic industry, for the support of research and development aimed at the improvement of instrumentation and in response to Federal and state regulatory requirements, such as those for traceability of voltage measurements used for the establishment of local power and energy standards and watt-hour meter testing by power companies. In large measure, the pre-eminence of the U. S. in high-technology areas, such as electronics, avionics, communications, aircraft, and space vehicles, has been made possible by our country's sophisticated measurement capability, reflected in automatic test equipment (ATE) systems and high-quality electronic instrumentation. Likewise, advances and progress in these areas have been rapid because they have not been limited by measurement constraints, such as the nonavailability of electrical instruments of adequate accuracy. This condition can only occur if NBS maintains a strong R&D program to ensure the availability of adequate electrical standards for the instrumentation industry.

Current Activities

The measurement services offered by NBS in the electrical area include the calibration of primary standards of alternating current and voltage, impedance at audio frequencies, direct voltage, and resistance at direct current, as well as MAP services for dc voltage and dc resistance. Some measurements are also done on ac ratio standards of the highest accuracy. In FY86, 17 MAP transfers and approximately 1588 calibrations were performed on 1145 basic standards, as detailed at the end of this project description, for a total income of about $656 K for the year.

Turnaround time in the various calibration areas remains roughly the same on the average as last year. The times in the ac-dc area have been reduced significantly (from 144 days average to 75 days) and the queue is being shortened. There was a large increase in the average time in the shunt area, and a serious problem with tracking the workload came about with the absence o Avis Wise, the administrator of the service, for eight months due first to medical problems and finally to her near-fatal involvement in an automobile crash. The turnaround times were also affected by the loss of three technicians, two of whom retired and the other resigned to take a position in the private sector. These losses had heaviest impact on the resistance area.

The majority of NBS calibration clientele is represented by the National Conference of Standards Laboratories (NCSL), which is a major source of information for planning future calibration activities, as well as a mechanism (through its technical committees) for disseminating NBS electrical metrology information. This past year saw heavy interaction between the Division management and the NCSL through its Measurement Requirements Committee and interactions at regional meetings. The military and its defense systems contractors and the instrumentation community are the heaviest users of electrical calibration services and it is from them that the most stringent measurement requirements arise. We continue to maintain close ties with the DoD via the Calibration Coordination Group technical subcommittees and projects funded by them.

Measurement services support activities fall into three broad categories: the documentation of measurement services, the development of improved measurement methods and standards, and the automation of the measurement systems used to perform both calibrations and MAP activities.

A Division-wide effort to document all of the calibration services according to guidelines propagated by the NBS Calibration Advisory Group has been a major activity this FY. The guidelines require there be a description of the services offered, an exposition of the theory and rationale behind the measurement systems used, a complete analysis of the measurement uncertainties, and detailed, written operating procedures. We have produced a series of documents primarily for internal Division use which would permit a reasonable knowledgeable and competent physicist or electrical engineer to step in (in the event of an emergency) and maintain operations in any of the services in a reasonable length of time. Revised versions of these documents more suited to use by our customers will be published over the next two years. These will concentrate less on the technical and procedural details of performing the calibrations, in most cases, and more on the uncertainties of calibrations and their application. Complete and new reevaluations of the published uncertainties have been done in the capacitance and resistance areas and major revisions in the reports of calibration will result.

Work in the second category, is directed toward improvement of the processes by which the electrical units are maintained, scaled, and disseminated. In the ac-dc difference area, supporting ac current and voltage measurements, the thrust of the work is to enhance the accuracy available by investigating and adding improved standards to the set used as working standards, especially in the upper end of the frequency range. In the impedance area, aged bridges are being replaced with new bridges that take advantage of modern electronics. One of these, a capacitance bridge to replace the 1957-vintage Type 2 bridge, has been finished and is being tested. The thrust in the resistance area has been to improve scaling from the national standards at one ohm to a thousand ohms and 6453.2 ohms for the absolute ohm and quantized Hall effect experiments respectively. Both cryogenic current-comparators and Hamon devices are being employed in this effort. In the voltage area, emphasis is being placed on improved dissemination, mainly through the use of solid-state standards based on Zener diodes.

In the automation category, several of the hardware systems have been completed; future activities are being aimed at the construction of complex software systems to collect and analyze calibration data. This activity is particularly heavy in the ac-dc difference and voltage areas. The resistance automation activity has been reduced in priority this year to increase the scaling work in preparation for the change in the ohm mentioned above and to complete the documentation.

Details of these and other accomplishments and activities are to be found in the following reports from each of the areas.

Estimated Calibration Workload -- FY86

SP-250 51100's Resistance Measurements

494 Standard Resistors and Shunts
4 MAP Transfers

54100's Precision Apparatus

25 Inductive Voltage Dividers

52100's Impedance Measurements

180 Standard Inductors
185 Standard Capacitors
2 Eddy-current Conductivity Standards

53100's DC Voltage Measurements

94 Standard Cell Enclosures (274 cells)
12 MAP Transfers
15 Unsaturated Cells
31 Zener-diode Based Standards

53300's Electrical Instruments (AC-DC)

44 Standard Thermal Converter Instruments (1017 points)

Estimated FY86 Billing $656,000

Direct (DC) Voltage

(B. F. Field, J. E. Sims)

Objectives

The objective of this project is to disseminate the U.S. legal Volt to industrial and other Government laboratories via calibration of customer voltage references and MAPs (measurement assurance programs). The project must also support the needs of standards laboratories using state-of-the-art calibration apparatus and voltage references with research and development of improved measurement methodologies and measurement apparatus.

Current Activities

This project consists of four major technical activities: (1) calibration of customer standard cells sent to NBS, (2) operation of the Volt Transfer Program (a MAP for maintaining a laboratory volt via standard cells), (3) calibration of customer solid-state references (Zener references) at voltages other than 1.018 volts, and (4) research and development of improved solid-state 10 V transportable standards and evaluation of existing solid-state transportable standards to support new customer calibration apparatus. Items (1) - (3) require accurate (0.01 ppm) comparison of customer or transport standard cells to NBS reference cells and the maintenance of a stable/predictable volt using standard cells. Activities to support these items therefore include development of improved measurement hardware for comparison of standard cells and measurement of solid-state references, and improved data base software for efficient production of calibration reports.

Accomplishments

Two fully automated measuring systems for intercomparing standard cells were constructed, installed, and tested. One of the systems is used to compare NBS reference cells to cells in VTP transport standards, and the second is used to compare NBS reference cells to customer cells sent to NBS for calibration. The first system has been running for about a year; the second was started in December 1985. Over the year minor adjustments have been made to the procedures, and the data base file structure has been modified slightly to make the systems easier to use. Currently all standard cell calibrations for dissemination purposes are performed using these systems.

Support for an Interdata minicomputer currently being used to maintain an historical cell data base and produce calibration reports has been discontinued. We have converted nearly all usable software written for the Interdata minicomputer for operation on the new VAX minicomputer and will stop using the Interdata as soon as possible.

Despite the promise of being able to use a Josephson array on a weekly (or even daily) basis in the future we see a continued need for stable standard cells to be used as working standards. We are currently limited, with only two high-quality enclosures, and have started construction of two more enclosures similar to the high stability 20 K Cutkosky/Field enclosures currently used for our reference cells. The mechanical design is identical to the original, but the electronics have been redesigned because many of the original electronic parts are obsolete or not available. Twenty-nine cells have been mounted in an oil bath and are currently being monitored. Cells will be selected from this group for installation in the enclosures.

A computer-operated controller has been constructed to connect the modular Braudaway low-thermal switching system to one of the automated systems. This increases the number of circuits available for reference cells (which will be needed when the above enclosures become operational) and permits us more flexibility in intercomparing these cells. All NBS reference cells can be intercompared using the modular switches, or any reference cell can be compared with any VTP transport cell. When the unsaturated cells currently used for Josephson 2e/h measurements are replaced with a reference of 1.018 volts, the automated systems will be used to compare that 2e/h-calibrated reference with any or all of the NBS reference cells instead of the manual comparisons currently being made.

The number of solid-state calibrations has increased so that the existing automated 10 V measurement system is used almost exclusively for workload calibration, thereby interfering with research and development of an improved 10 V transportable standard. We are constructing a second system to be used for routine calibration and the original system will continue to be used for development of the 10 V standard. The new system is a revised version of the original with the Fluke 731B transfer reference replaced by the improved Fluke 732AD reference and has the capability of calibrating up to 75 references simultaneously. (The original system will be modified to use a 732AD reference after the new system is complete.) The new system has been constructed, and all software has been re-written to operate on a Hewlett-Packard (H/P) 9816 computer rather than the H/P 9845A computer of the original system. The software has been improved to make it compatible with the automated standard cell systems, to make it easier to use, and to provide more quality control checks on the system. Preliminary testing has begun and we expect the system to be fully operational by the end of CY 86.

Four additional systems similar to the new NBS system are under construction for the DoD laboratories. These systems will use a commercially available DataProof 320A Scanner capable of calibrating 15 references simultaneously instead of the crossbar scanner used in the NBS system. With the exception of the Fluke 732AG references (which have not been delivered), all four systems have been assembled and partially tested. Software provided with the system will be a modified version of the NBS system software with an additional "shell" program to make it easier to use. These systems should be delivered by December 31, 1986.

Two documents have been written describing the dc volt calibration services for standard cells and Zener diodes. These documents cover the new hardware and measurement procedures used with the automated systems fully.

An experiment was conducted to determine the uncertainty with which the volt could be transferred to different laboratories at the ten-volt level. Three Fluke 732A references were shipped in a round robin experiment to NBS (twice) and four DoD laboratories. The references were calibrated in terms of each laboratory's local volt and the data are plotted in the figure. Using each of the three references, three values for the $V_{Lab} - V_{NBS}$ difference can be calculated for each laboratory as shown in the table. The agreement between the differences at each laboratory was found to be excellent with a pooled standard deviation of the mean of 0.045 ppm. When all uncertainties in the transfer are included, we conclude that the local laboratory volt can be determined to an uncertainty of 0.11 ppm (95% confidence interval) with respect to the NBS Volt. These results will be reported in a paper to appear in the IEEE Trans. Instrum. Meas.

Testing of diodes for inclusion in a 10 V transportable standard has continued. We have investigated the effects of temperature, shock, and power cycling on a variety of devices in an effort to develop a standard that does not need continuous battery power during shipment. Most devices show a permanent 1 - 20 ppm voltage shift when subjected to a momentary (8 hour) temperature shift of 20 °C. Discussions with diode manufacturers have led us to investigate the lead bonding arrangement as a possible source of this voltage shift. We are currently testing diodes with soft-soldered, metallurgically brazed, and thermal compression bonds.

In an effort to partially circumvent this lengthy diode testing procedure, we intend to purchase stable, fully-tested devices from a number of manufacturers and continue with the construction of a prototype standard. We have also begun testing two types of 10 V to 1.018 V dividers, a traditional wire-wound divider in an oil-filled can, and multiple (5) bulk-metal-film dividers in parallel. Early data is not promising for either, although the bulk-metal-film type may be used at the 0.1 - 0.2 ppm accuracy level. We will continue to improve the mounting of this divider (perhaps use more dividers in parallel) in an effort to improve the ratio stability.

A sixth seminar on MAP's for electrical quantities was held in Chicago, Illinois during the week of October 27, 1985. The 35 attendees in the workshop participated in five days of lectures and workshops covering statistics, voltage metrology, quality-control techniques, and NBS MAP procedures. Two hands-on workshops using computer-aided instruction were held permitting the attendees to make actual measurements on groups of standard cells and reduce the data, and to analyze data and develop procedures for generating control charts. The instructors for the seminar were N. B. Belecki (CBS), M. C. Croarkin (CAM), B. F. Field (CBS), D. Vecchia (CAM), and A. O. McCoubrey (CBS), who also was responsible for logistics and administrative support.

One staff member (T. E. Kiess) who was working on the 10 V transportable standard resigned this year to continue his education. We are attempting to hire a replacement but progress in this area may be slowed if one can not be found quickly.

Future Plans

Software currently used on the Interdata will be converted to run on either the VAX minicomputer or the H/P desktop computers. This is an interim solution, eventually we wish to rewrite major portions of the software to make it much easier to use, and to provide more information about the performance of the standard cells.

With the new standard cell measurement systems in use, a re-examination of the measurement uncertainties of the Volt Transfer Program and the regular standard cell calibration is necessary and will be conducted next year.

The construction of the two standard cell enclosures started this year will by completed next year.

The new solid-state measuring system will be evaluated and the remaining software completed. It then will be used for routine calibrations of solid-state standards.

We will continue with our development of a Zener-based 10 V transportable standard and will construct and begin testing a prototype with 10 V and 1.018 V outputs.

DC RESISTANCE

R. F. Dziuba, P. A. Boynton, T. P. Moore, E. S. Nowicki

Objectives

The primary objective is to provide our customers with state-of-the-art, accurate, and reliable resistance measurement services that are delivered in a timely and professional manner. To achieve this goal it is necessary to develop new and improved resistance standards and measurement techniques.

Current Activities

The NBS provides calibration services for primary standard resistors with nominal decade values in the range between 10^{-4} Ω and 10^{12} Ω and resistance Measurement Assurance Program(MAP) transfers. Special resistance measurements are undertaken if they require the unique capabilities of NBS.

The present NBS resistance scaling process used to relate the 1-Ω reference group to other resistance levels is being reassessed and improved by (a) construction of improved Hamon transfer standards, (b) the development of a cryogenic current comparator resistance bridge for resistance scaling, (c) monitoring the NBS Ohm in SI units via the cross capacitor, (d) monitoring the stability of the NBS Ohm via the quantized Hall effect, and (e) international comparisons of the Ohm.

The 10-kΩ measurement system and the capacitive-discharge system for multimegohm reistors are being automated in order to improve the accuracy of these measurements as well as providing improvements in the delivery of these services to our customers.

Accomplishments

The major accomplishments for FY86 in the area of dc resistance in addition to our main service of calibrating customer standard resistors include the following:

* The internal version of the documentation that describes the NBS calibration service for dc resistance standards has been completed. This document contains the theory, description, operational procedures, and uncertainty assessment of the eight NBS measurement systems used to calibrate customer resistance standards over the range 100 μΩ to 1 TΩ.

* Three Hamon boxes were constructed and placed into operation in order to improve the accuracy of the NBS scaling process from: (a) 100 Ω to 10 kΩ and, (b) 10 kΩ to 1 MΩ. One Hamon box is permanently housed in the oil bath used for the calibration of customer 10-kΩ resistors. It is calibrated in situ at the 100-Ω level. This will enable the scaling to the 10-kΩ level to be done more frequently and should significantly reduce the uncertainty assigned to these calibrations.

* Three international comparisons of the Ohm took place during FY86. Two international comparisons were with NML of Australia, and one was with NRC of Canada. The results of these comparisons based upon the 1-Ω measurements are given in chronological order below:

10/30/85	$\Omega_{NBS} - \Omega_{NML} = -1.34\ \mu\Omega$
2/26/86	$\Omega_{NBS} - \Omega_{NRC} = -1.90\ \mu\Omega$
6/26/86	$\Omega_{NBS} - \Omega_{NML} = -1.36\ \mu\Omega$

The dates given are the mean dates the transfer resistors were at NBS. Comparisons were also done at the 10-kΩ level with NML and NRC. The results of these measurements agreed with the 1-Ω results given above to within 0.05 ppm for both NML and NRC.

* Three special in-house transfers were completed. These transfers involved the scaling down in resistance from the 6453.2-Ω transport standard used in the quantized Hall experiment to the 1-Ω reference bank of Thomas-type resistors. Specially-built Hamon boxes were used for the measurements. The results indicate that the NBS Ohm is decreasing about 0.05 ± 0.02 ppm/year (see section on Quantized Hall Resistance).

* A comparison between the NBS and NML methods that are used to establish the ratio between 1 Ω and 6453.2 Ω was completed during July and August at NBS. The NML ratio instrument consisted of a Hamon-type Build-Up

Resistor (BUR) containing 83 resistance elements. The NBS method of achieving this ratio is done in two stages using two Hamon-type boxes. First a 1 Ω to 100 Ω Hamon network of ten 10 Ω resistors is used and, then followed by a 100 Ω to 6453.2 Ω series/parallel Hamon network consisting of eight 800 Ω resistors plus a series connected 53.2 Ω resistor. Agreement between the NBS method and the NML BUR was typically 0.01 ppm.

Future Plans

The future work in dc resistance will primarily be concentrated in three areas: (a) documentation, (b) resistance scaling, and (c) automation.

Although the first draft of the calibration documentation is completed, it still needs revision in order to make it worthy of publication. It is expected that sometime in FY87 this document will be available as a NBS technical note to our customers. In addition the re-assessment of the calibration uncertainties will mean a revision of the calibration reports issued to our customers. These reports will contain more detailed information on the assignment of the uncertainty to a measurement and may contain, if available, an analysis of the past history of a customer's standard. Special software will have to be written in order to provide this extra service to our customers.

The development and characterization of Hamon boxes will continue in order to improve the accuracy of the NBS resistance scaling process. More Hamon boxes will be constructed and special tests made to check their scaling accuracy. Improvements in the cryogenic current comparator bridge, especially reducing the noise level in its current sources and detector system, will be made so that it can be used to verify the accuracy of the NBS scaling process as determined by Hamon boxes.

The automation of two resistance measurement systems is planned for FY87. The 10-kΩ measurements will be automated using a special feedback system to balance a guarded resistance-ratio bridge. A novel stepper-motor/air-cylinder assembly under computer control will be used to connect or disconnect BPO connectors for the switching of resistors. A protoype automated version of the capacitance-discharge system for measuring multimegohm resistors in the range from 100 GΩ to 100 TΩ is planned for FY87. The detection, counting and timing, feedback, and motor controller circuits are in various phases of construction and evaluation.

IMPEDANCE MEASUREMENT

(G. M. Free, G. R. Jones, Jr., C. R. Levy, S. B. Tillett, R. C. Fronk)

Objectives

To construct,test and calibrate nine automatic capacitance bridges.

Accomplishments

One bridge has been completely assembled and is lacking only in the calculation of the gain correction table. Three other bridges are in various states of construction with mechanical completion by the end of the calendar year. Most of the circuit boards for an additional five bridges have been completed along with some of the transformers used in the bridge.The programs for the initial calibration of the bridges have been written and will soon be used to generate the gain correction tables as each bridge is completed.

Current Activities

At present four bridges are being constructed by New Systems Technology Corp. through an outside contract. The programs, which calculate a lookup gain correction table at various frequencies and then burn this information into a PROM located within the capacitance bridge, are being rewritten to run on an IBM AT and a Hewlett-Packard Series 300 computer. Once this is done, the complete bridges will be calibrated. The internal 10 pF fused-silica dielectric capacitors are being assembled and tested by L. Lee who was instrumental in the development, construction and testing of the original prototype bridge.

Future Goals

All nine bridges will be completed by September 1987 along with the lookup gain correction tables. A method to calculate the absolute ratios of the transformers should be in use at this time so as to complete the calibration of the capacitance bridges. A documentation package including instructions on how to use the bridge in a stand-alone situation and through an external computer, and the schematics of the circuit boards should also be available by this time.

Objective

To upgrade the measurement capabilities of the impedance laboratory.

Accomplishments

Funds were received during the past year to upgrade the capabilities of the impedance laboratory. This was the first of a five year plan of special funding for improvement. To achieve this improvement a plan has been developed having three parts.

First improvement in the design and use of space. The laboratory will be made modular in the sense that different areas of the laboratory will have different functions. In order to carry this out storage cabinets and laboratory benches have been/or will be purchased for the storage of electrical standards and the variety of components and tools used in the laboratory. Parts of the laboratory are being rewired so that the dedicated area concept can be completed and the amount of exposed cables in the laboratory reduced. Some of the storage cabinets and laboratory work stations have been received and are now functional.

Second. The improvement of present calibration systems. State of the art frequency synthesizers and detectors have been purchased. Synthesizers have been incorporated in the Type 12 and Type 2 capacitance bridges used for two and three-terminal measurements, respectively. A new detector has been placed in the Type 12 system.

Temperature measurement will be improved through the purchase of an automatic resistance bridge. An 8 port switch is being used with this bridge so that up to 8 platinum resistance thermometers may be measured consecutively.

Third. Diagnostic equipment for the maintenance and development work done in the laboratory. An impedance analyzer and spectrum analyzer have been purchased and tested. These have proved useful in bridge error analysis and development work on the new inductance bridge.
A major change with respect to capacitance calibration is the change in the capacitance standard used as the primary standard. For a number of years due to the poor temperature stability of the laboratory oil baths the primary standard has been a 10 pF fused silica capacitor enclosed in an temperature controlled air bath. Scheduling the use of this standard and some uncertainty about the standards true value in the laboratory often caused problems. One of these oil baths was modified with a new temperature control unit. In tests so far it would appear that this modification is successful with the bath controlling at +0.001 C over a 24 hour period. Fused silica capacitors have been placed in the bath and are now being measured. The primary standard in the laboratory will become this oil bath capacitor at the conclusion of testing. The transfer unit will be necessary only for checking this standard on a periodic basis.

A second oil bath has been ordered and should arrive during the next fiscal year. This bath will be used to test customers capacitors and for development work.

Present activities

The new resistance bridge is being tested for accuracy. The oil bath primary standard is being monitored and compared with the transfer standard to determine the accuracy of calibration and variations due to temperature variation in the oil bath.

Future plans

More equipment will be purchased in the coming years to continue the upgrade of the laboratory. Where appropriate, equipment purchased will have the capability of computer control. Programs will then be written so that monitoring of equipment will be done automatically.

Objective: To document all NBS measurement systems in order to standardize methodology where possible, clarify accuracy and uncertainty of measurement systems, and make possible the replacement of personnel with the least amount of lost time.

Accomplishments

At present documentation is proceeding on three measurement systems, inductance, capacitance and, inductive voltage dividers. It was found upon reading the vast amounts of documentation done in the past that there were some major areas in which little existed e.g., uncertainty statements. A large amount of time has been spent in organizing the relevant material from the past and in some cases writing completely new material for the different systems. The capacitance and inductive divider documentation final drafts will be complete by the end of the fiscal year.

Present activity

Reviews of the three documents by a panel of experts. The final copy of these documents (with corrections by review panels) should be done by December 86.

Future plans

Documentation of the eddy current system, the automatic capacitance bridge and the new inductance bridge.

Objective

To make available to interested users some form of capacitance Measurement Assurance Program(MAP).

Accomplishment

During the past three years the ac laboratory personnel have studied the MAPs' problem to the extent that time was available to do the project. Changes of capacitance value due to temperature cycling in 8 GenRad 1404 (1000pF) capacitors were studied during the period 3/83 to 9/85. During this time two of the capacitors were used as controls while the other 6 were cycled at temperatures of −20 C(−4 F) and 66 C (150 F). A single temperature cycle would last for a period of 24 hours. The capacitor at the end of the 24 hours would be removed from the temperature chamber and allowed to stabilize at room temperature.

Measurements would than be done on the capacitor using the methods normally used for calibrations of standards with an uncertainty of + 5 ppm.

In general the following can be said about changes in capacitance due to a temperature cycle. After a heating cycle the capacitor normally will decrease in value while after a cooling cycle the capacitor will normally increase in value. Unfortunately this is not always true. The average change for a capacitor for a temperature cycle in one direction (it could be either up or down) was 7.5 ppm. The maximum change seen was 24 ppm while the minimum change was 0.0 ppm. The spread of changes would appear to be Gaussian in nature. The total number of temperature cycles for all capacitors was 71. For the two control capacitors over the same time span the variation in value was + 2 ppm.

It is difficult to assess the importance of this data with respect to to customers who ship their capacitors to NBS for calibration. The experiment was designed to test the absolutely worst case that a MAPs 'package would encounter in shipping. Tests done in the early 1970's in which the temperature extremes were much lower ,i.e., 32 °F and 90 °F showed changes which were much smaller. A customer's capacitor might encounter the temperature changes of the present test, but it would be rare to have it cycle at one of the above temperature extremes for a period of 24 hours. The data could explain some of the changes seen in the present capacitance MAP package.

A study was made of the historical data taken at NBS for ten 1000 pF capacitors calibrated repeatedly between 1968 and last year. These data, summarized in the table below, indicate that the same problems that plague the NBS capacitance MAP standard also affect a large percentage of customers' standards brought in for calibration and the futility of using NBS calibration uncertainties as indicators of long-term performance. Only two of the ten capacitors behave at the 5ppm level over extended timeframes. Straight lines were fit to the data from each standard; the standard deviation given is the residual standard deviation of the fit.

Serial No.	No. of Cal's	Standard Dev. ppm	Slope ppm/yr.
187	8	2.81	- 0.32
636	8	10.98	- 1.19
564	9	1.11	0.00
1489	5	6.98	1.72
1266	5	1.39	0.24
1230	8	10.51	0.00
754	5	18.67	3.44
2145	5	6.32	2.50
1718	6	3.51	- 0.71
2571	7	2.62	- 0.62

Note that several of these standards cannot be relied on at the 30-ppm level of performance in the long term.

During the period 6/85-11/85 the feasibility of using a MAPs package consisting of a GenRad 1408 temperature controlled enclosure and a Princeton Applied Research (PAR) phase sensitive detector as the MAPs' package was studied. The 1408 contained two capacitors, a 10 pF and 100 pF. The methodology of this MAPs' would be to calibrate the 10:1 ratio of the customers' bridge using the 10-100 pF capacitors and than calibrate the customers 1000 pF capacitors in terms of the 100 pF capacitor.

The tests showed that the best sensitivity available on the 10:1 ratio would enable a calibration of the ratio at an uncertainty of ± 0.2 ppm. The uncertainty of the ratio calibration is a function of the condition of the bridge, i.e., dirty switch contacts quickly degrade the accuracy to the + 1-2 ppm range or even larger. This calibration is also a function of the skill of the operator. Considering the various other errors of the experiment it was felt that the best uncertainty would be in the 5 ppm range for such a MAP.

There are several problems with this type of MAP. First shipping of the detector would be difficult,i.e., to protect the detector a bulky package would have to be shipped. How the detector would survive repeated shipments is open to question. Secondly at the present time the 1408 standards owned by NBS are used as calibration standards and to risk damage to these when they are not replaceable is of questionable wisdom. Finally the customer laboratory must have the capability of measuring the temperature of the 1408 enclosure at the ± 0.001 C level. This last problem could be avoided by building a new temperature monitoring system for the enclosure but it would be a development project involving 3-6 months of work.

Tests were done on the best available ceramic capacitors (best that we were aware of) and it was found that these capacitors at present could not be considered as good transfer standards at the level of uncertainty (+ 1.0 ppm) we hope to achieve with a transfer standard.

Conclusions

There is not a obvious solution to the capacitance MAPs' problem. But there are several possibilities, each with its own limitations.

I) A new MAP package could be constructed which is similar to the first. It would be possible to make the package slightly smaller and easier to handle. The limitations to this option are 1) the package would be good for 2-3 years before it would be necessary to replace the capacitors. 2) Replacement capacitors would have to be selected from a large number of capacitors to obtain the necessary electrical and mechanical stress properties. This option would be both labor intensive and require a large investment in equipment and replacement of capacitors might have to be done before the two year interval is up.

II) A package consisting of a GenRad 1408 and a detector is not a good option for the reasons detailed above.

III) Have customers switch to a 100 pF standard as their primary standard. In terms of NBS this would be the best option. It would than be possible to use present technology and have a package which would be stable and easily shipped. The problem of calibration of the 10:1 ratio of the capacitance bridge would still exist and would have to be solved by the customer. Not an easy task.

IV) Have customers ship their capacitors to NBS and do a reverse map. For this option a tech note could be written explaining the methodology, calculations, derivation of uncertainty etc. that are necessary in order to insure that the reverse map gives good results. Where necessary it might be possible for NBS to do the data analysis if the customer desired. A limitation to this option is that the customer would be working with an initial +5 ppm uncertainty for the NBS calibration.

V) Explore use of new technology (ceramic capacitors, for example) to solve this problem. This would take time.

Present activity

New ceramic capacitors are being tested for feasibility as they become available.

Future activity

Future activity will be in the most reasonable of the above areas (to be decided).

Objective

To establish the values of the NBS bank of inductance standards with respect to each other and check the accuracy of the Maxwell-Wien calibrations.

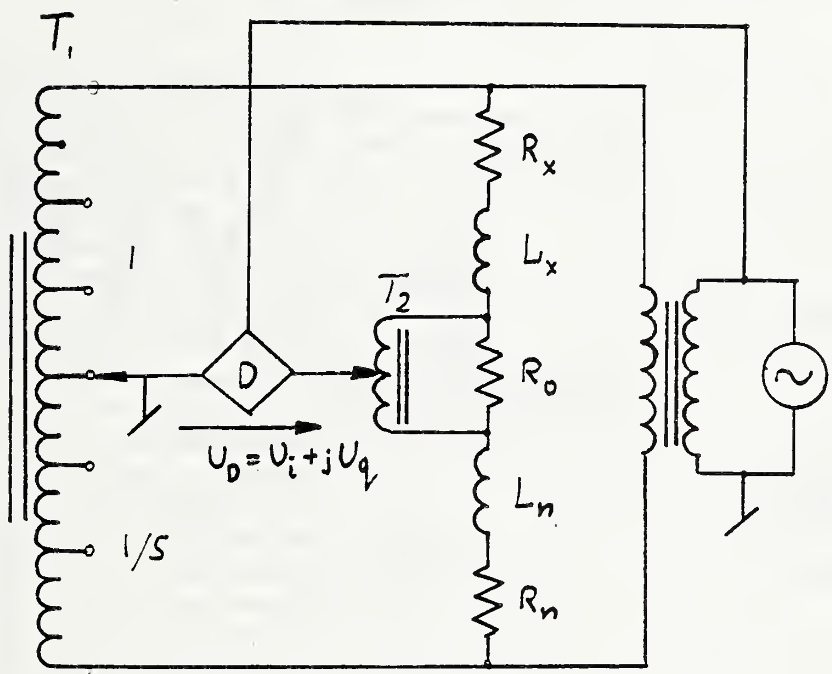
Accomplishments

During the past year a bridge has been constructed and tested which compares two impedances by measuring the in-phase and quadrature voltage offsets and with calculations based on the offsets determines the value of one impedance in terms of the other.

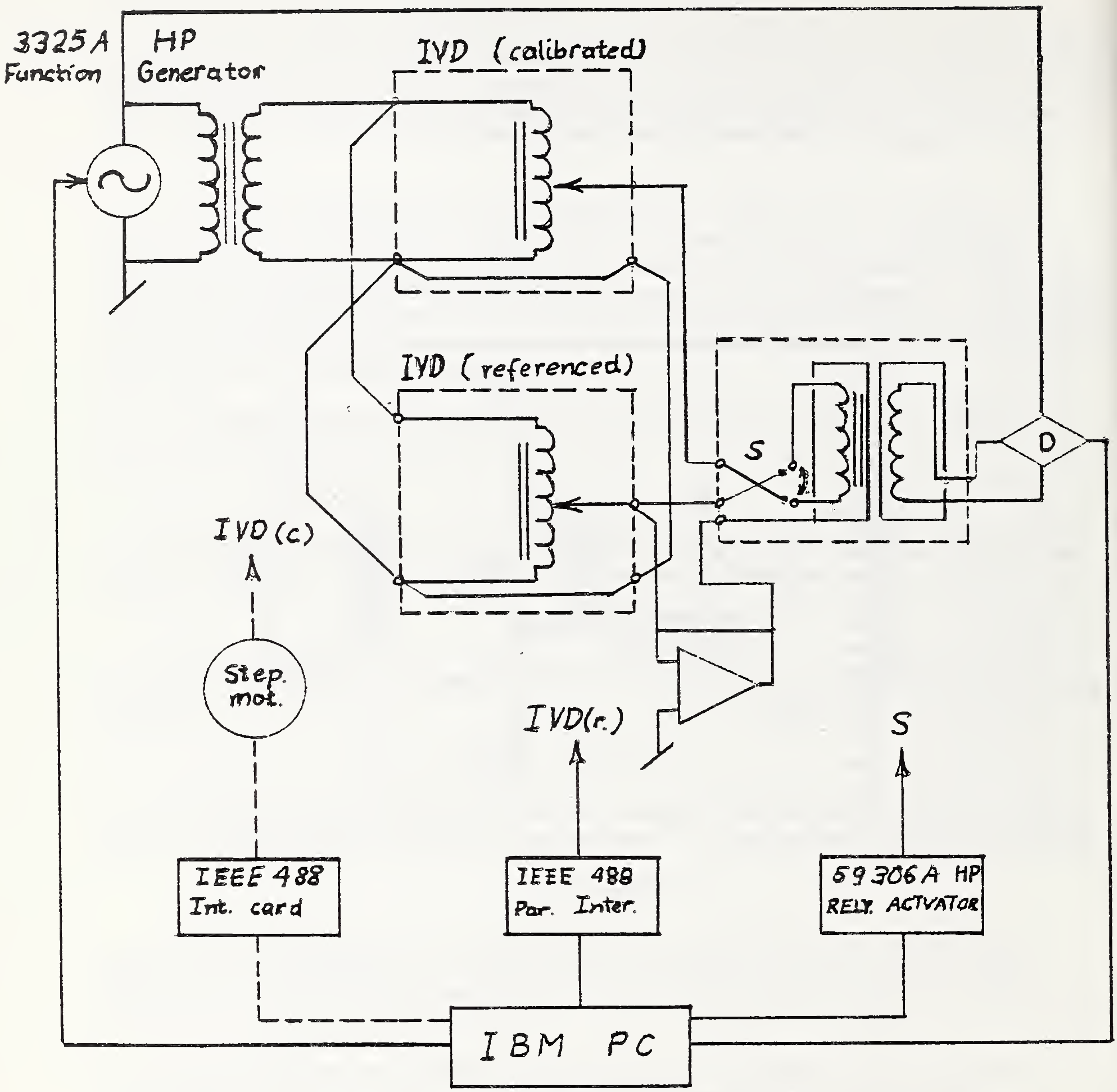
This bridge may be used to compare any two impedances whose nominal values have a ratio of 10:1 or less when the two standards have low dissipation factors.

The bridge is shown in Diagrams 1 and 2 and the equations of balance when the bridge is used as an inductance comparator are as follows.

Dia. 1 THE INDUCTANCE COMPARATOR



Фиг. 2. AUTOMATIC SYSTEM FOR IVD CALIBRATION



$$\frac{L_x}{L_n} = s\,\frac{1-(1-s)U_i-(1+s)U_q/Q_n-s(U_i^2+U_q^2)}{(1+sU_i)^2+(sU_q)^2},$$

$$\frac{R_x}{R_n} = s\,\frac{1-(1-s)U_i+(1+s)Q_nU_q-s(U_i^2+U_q^2)}{(1+sU_i)^2+(sU_q)^2},$$

where $U_i=U_I/U_O$, $U_q=U_Q/U_O$, $Q_n=wL_n/R_n$ and s is the voltage ratio.

During the past year this system has been tested in two types of calibration, the calibration of inductive voltage divider (IVD) ratios and the intercomparison of standard inductors. The results of the comparison of inductive voltage dividers are quite good. Using this system at a frequency of 100, 400 or 1000 Hz. the measurements are in agreement to 4.0×10^{-8} for in-phase corrections and $+2.0\times10^{-7}$ for quadrature corrections. The total uncertainty of this measurement using the NBS IVD calibration system is $+0.5\times10^{-6}$ and $+5.0\times10^{-6}$ respectively. Thus the error determined in the prototype system could in fact be a systematic error of the NBS calibration system. A computer controlled binary divider was used in the test system to determine its accuracy and feasibility. It was found that this divider does not degrade the accuracy, although the system noise does increase to some extent. The intercomparison of inductors has also been done on this system. Initial results are in agreement with calibrations done on the inductors using the Maxwell-Wien bridge. There are some errors in this calculation which are still being resolved and the evaluation of the total bank of inductors is now in process.

In all cases it should be noted that this is an easy way of calibrating unknowns automatically. The system depends on the operator only to turn on the system and disconnect and reconnect the standards, or change the dial as the case may be.

Present activities

The measurement method is being refined so that standards in which a large different in dissipation factor occur can still be measured. Data from measurements on all NBS inductance standards is being evaluated for determination of the relative values of the standards.

Future activities

A paper will be written describing the bridge construction, error analysis and results of the experiment.

Objective

To design, construct, test and calibrate two inductance bridges.

Accomplishments

A prototype, active (supplies current as well as being the reference ground) ground circuit which supplies up to 200 mA of current and has the capability of phase adjustment necessary for calibration of resistors, and standard inductors has been completed and is being tested for harmonic content, distortion and noise throughout the frequency range of 100Hz -100 kHz. Current pumps have been designed and tested which will be used with all standards (resistors and capacitors) that must be connected to the inductive voltage dividers. It was found that even large impedances connected to the dividers would cause error in the output voltage ratios of the dividers at high frequencies thus necessitating the current pumps. A method has also been devised for adjusting the current pumps so that the error contributed by the pump is minimal.

Coaxial chokes have been placed in the system at critical points to prevent ground loops. It was found that without coaxial chokes at the input and output of the dividers and error of approximately 20 ppm in the voltage ratio of the divider occurred at some frequencies. A computer controlled 0-5 volt power supply with 52 lines of I/O has been purchased and tested. This power supply will be used to drive switches and DACs in the ground circuit of the bridge in the automated version.

All components of the prototype bridge have been constructed and depending on the availability of time should be put together and tested by the end of FY86.

Current Activities

Measurements are being taken with the bridge to determine its accuracy and precision. Documentation of the bridge has been started and will be completed this FY. The bridge will be used as the primary inductance calibration system by the end of the FY87.

Future plans

The bridge will be made semiautomatic by using the 0-5 volt power supply mentioned above, and by replacing the decade dividers by binary dividers. This will necessitate development work on the dividers to insure accurate voltage ratios at the higher frequency. Also this project will include the writing of a large amount of software for the bridge.

ACCOMPLISHMENTS
AC CURRENT AND VOLTAGE
(J. R. Kinard, C. B. Childers, J. R. Hastings, T. E. Lipe)

Both automated ac-dc difference systems have been completed and new more elaborate software has been written. The two systems are being used for calibrations of customers thermal converters and for the study of two newly acquired coaxial, single range, thermal voltage converter sets. The new calibration systems and the new thermal converter sets are making possible the reduction of the calibration queue.

Bilateral, international intercomparisons of thermal converters have been conducted with the Physikalisch Technische Bundesanstalt (PTB) of West Germany and with the National Measurement Laboratory (NML) of Australia. Remarkably good agreement exists between the PTB values for ac-dc difference as determined from their new multijunction thermal converters (MJTC's) and the NBS values determined from the NBS primary standards, a collection of MJTC's.

A considerable body of work on the NBS primary standards of ac-dc difference has been reported to the Conference on Precision Electromagnetic Measurements (CPEM) held in Gaithersburg during June, 86. Summaries of some of the results of measurements on the NBS primary MJTC's are given in Figs. 1 and 2. For Fig 1, the numbers inside the elipses, near the voltage converter identification, represents the best estimate for the ac-dc difference of that MJTC based on the assumption that the average of the primary group is zero. Figure 2 shows the current build-down, using special single junction thermoelements (SJTE's), beginning with a MJTC at 50 mA. Additional confirmation is obtained from the MJTC intercomparison at 5 mA. These results will be published in the IEEE Transactions on Instrumentation and Measurement.

A study has been made of specially-constructed thermoelements of NBS design intended to minimize thermoelectric errors. Some of these thermoelements have very small ac-dc differences, as hoped. Unfortunately others of the same design and manufacturer's run have unusually large ac-dc differences. An investigation into possible mechanisms is underway.

Objectives

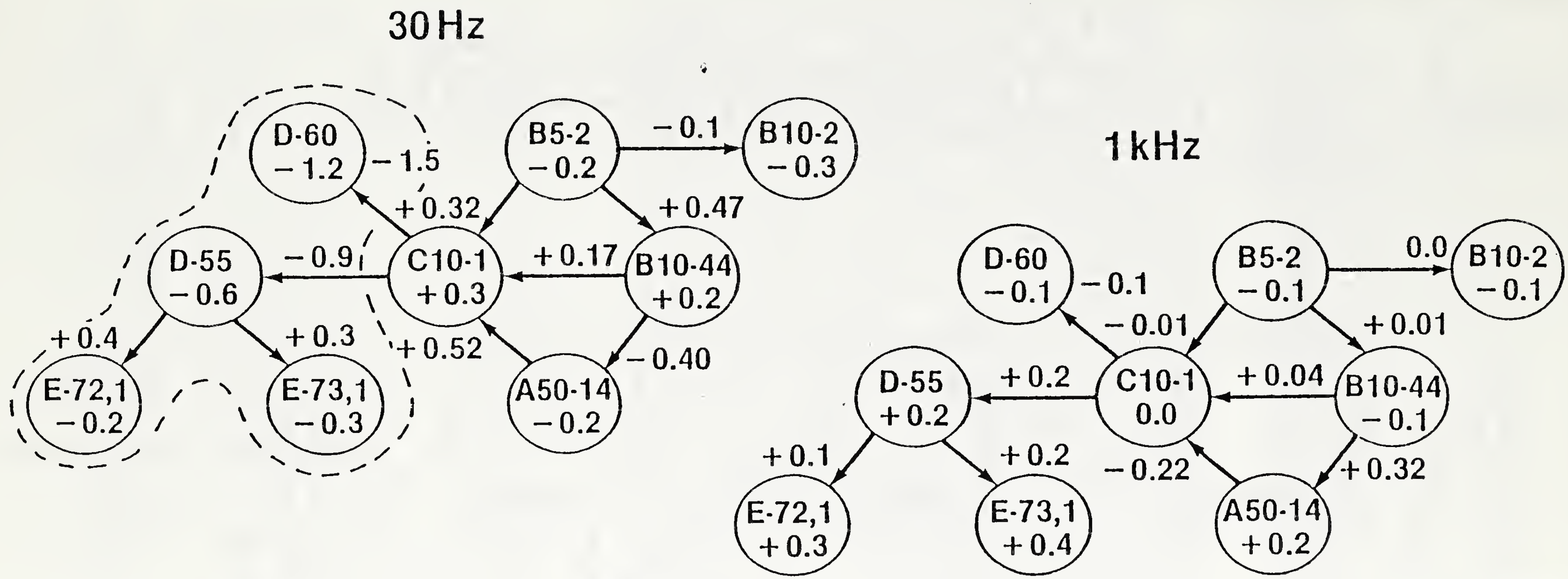
The objective of this project is to provide calibrations of the ac-dc difference for customer thermal voltage and current converters in terms of the NBS primary standards of ac-dc difference. The project maintains the NBS primary standards of ac-dc difference and the related comparator systems. The project must also support the needs of standards labortatories using state-of-the-art ac meters and calibrators with research and development into improved methods and apparatus.

A new project intended to lead to a reduction of NBS calbration uncertainties from 100 kHz to 1 MHz has been started. Candidate thermoelements and resistors have been studied and entirely new high-frequency, coaxial thermal voltage converters have been fabricated. A complete recharacterization of the NBS TVC's at 1 MHz, including studies up to 30 MHz, is planned. A chinese Guest Scientist is expected to arrive shortly to assist with this project.

A fully operational automated ac-dc difference calibration system has been constructed and delivered to the Air Force at Newark Air Force Station Metrology Center. Some further development and improvement of the system software and documentation are continuing. This system is essentially a replica of the NBS automated system.

Future Plans

Continue efforts to reduce the queue for ac-dc thermal converter calibration customers. Study the calibration of thermal current converters using transconductance amplifiers and the automated ac-dc difference calibration system with the aim of eventually extending the current range covered. Recharacterize NBS standard thermal voltage converters from 100 kHz to 1 MHz with the view of reducing calibration uncertainties for NBS calibration customers. Continue to study solid-state thermal converter systems. Study various forms of instrumentation as possible candidates for use as transport standards for ac voltage and current MAP-type calibrations.



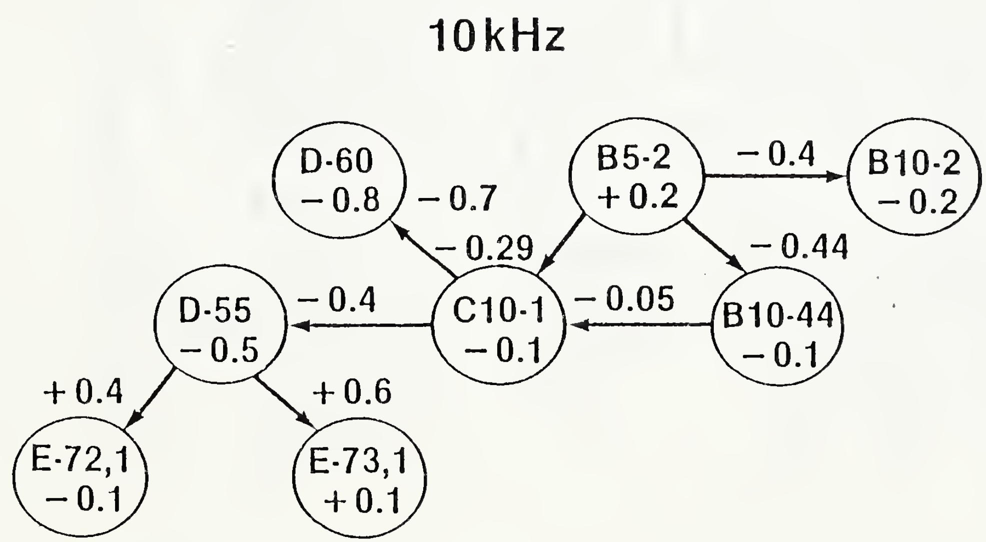


Fig. 1. Results of the intercomparisons of MJTCs as voltage converters at 30 Hz, 1 kHz, and 10 kHz. At 30 Hz the MJTCs outside the dashed line are compensated; those inside the dashed line are uncompensated.

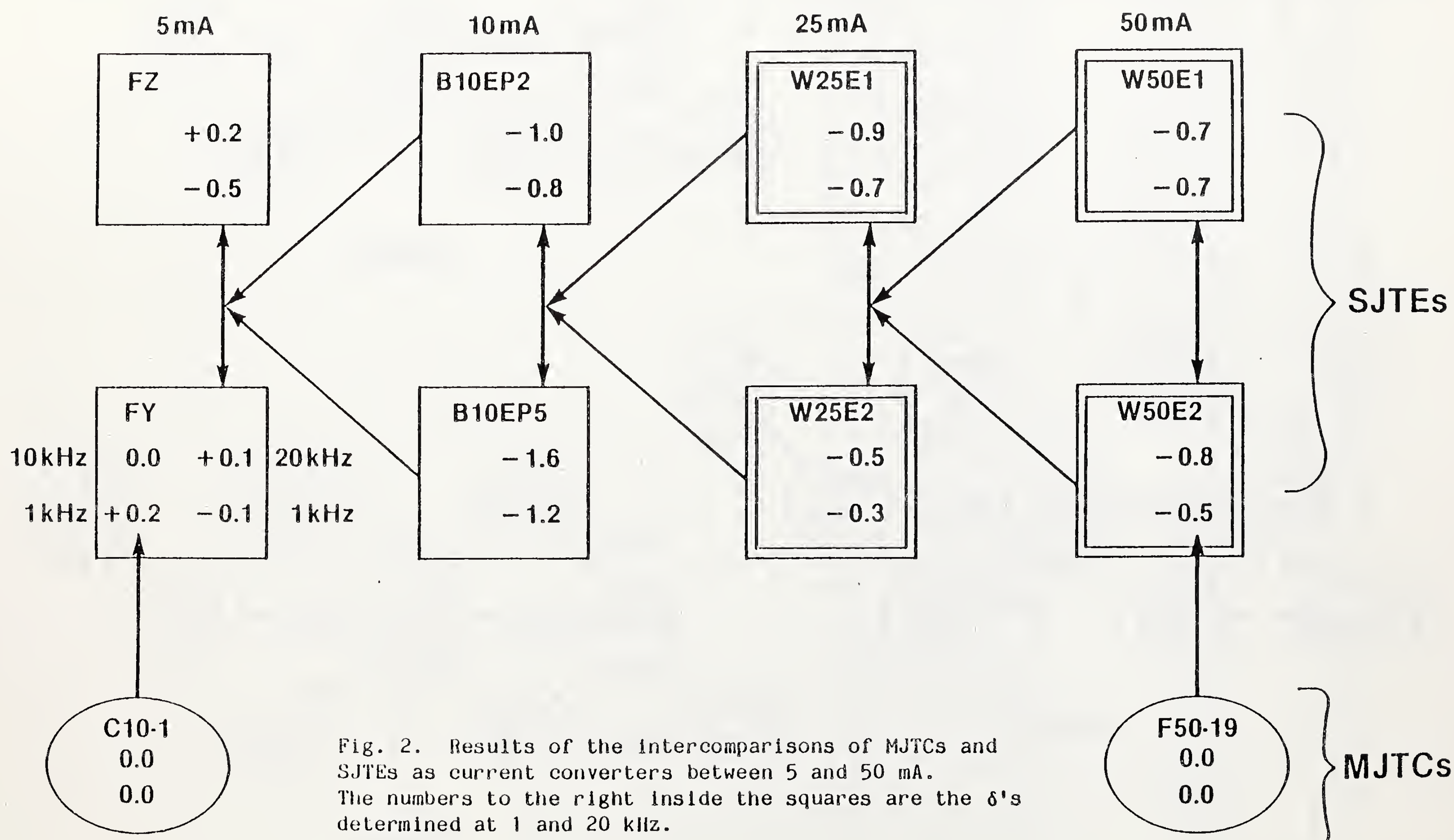


Fig. 2. Results of the intercomparisons of MJTCs and SJTEs as current converters between 5 and 50 mA. The numbers to the right inside the squares are the δ's determined at 1 and 20 kHz.

JOSEPHSON VOLTAGE STANDARDS

(R. L. Steiner, B. F. Field, J. Toots)

Objectives

The objectives of this project are to maintain the NBS or U.S. Legal Volt via the ac Josephson effect in superconductors to an accuracy of a few parts per 100 million, and to improve the maintenance and dissemination of the unit of dc voltage for the U.S. through the development of voltage standards based on this effect.

More specifically, the objectives are to (i) periodically determine the U.S. Legal Volt using the assigned value 2e/h = 483593.420 GHz/V_{NBS} for the Josephson frequency-voltage ratio and the traditional two-junction, 10 mV, 100:1 Hamon divider 2e/h system. (ii) Construct, evaluate, and calibrate a new volt maintenance system based on the zero-crossing step Josephson-junction array. Such arrays operates at a millimeter wave frequency of 70 - 95 GHz, and incorporate up to 2000 junctions in series to generate quantized voltage steps exceeding 1 volt, allowing a one-to-one ratio calibration of standard cells at an accuracy expected to be better than 1 part in 10^8. (iii) Collaborate with the Electromagnetic Technology Division's Cryoelectronics Group, NEL-Boulder, Co. on the design, fabrication, and characterization of these voltage standard arrays. This also includes cooperation with the Physikalisch-Technische Bundesanstalt (PTB) in West Germany on the design and characterization of similar arrays. (iv) Upgrade the capabilities of the Electricity Division's thin film facilities to enable local fabrication of arrays and other high quality Josephson junctions for the existing Josephson voltage standards. (v) Use the improved thin film facilities to investigate arrays made with NbN films and artificial oxide barriers. (vi) Finish supplying Josephson junctions and system hardware for the commercial 1 ppm voltage standard developed for the Calibration Coordination Group (CCG) of the DoD and the Korean Standards Research Institute (KSRI).

Current Activities

Objective (i) has the highest priority. The primary standard cells currently need one calibration measurement per month to accurately predict their behavior. Maintenance and repair of the cryogenic and electronic components continues, along with new Josephson-junction fabrication and testing, as necessary.

Objectives (ii) and (iii) are aimed at replacing the old and complex 100:1 voltage ratio system at 8.5 GHz with more accurate and operationally simpler system based on the Josephson series array. Several arrays, along with various components in a complete microwave and electronic measurement system, have been undergoing tests since February 1986. Collaboration with the Boulder Cryoelectronics Group and PTB is continuing, especially concerning the procedures required for an accurate voltage measurement.

Major improvements in the Division's thin-film fabrication facility for objective (iv) and (v) have been delayed for the year to concentrate efforts on the array system and await further developments in NbN done by a PTB representative in Japan. Two systems for $Nb/Nb_2O_5/Pb$ and Pb/PbO/Pb deposition are kept in constant use. Also, a new microscope and wire bonder have been ordered in conjunction with the Quantum Hall Effect group to upgrade photolithographic and device fabrication capabilities.

Work on the commercial voltage standard [objective (vi)] is continuing with work on an electrical contact problem, calibration and use of the Western Standards Laboratory (WSL) system, and fabrication of a reserve supply of arrays.

Accomplishments

The primary accomplishment for FY 86 has been the preliminary use of an array measurement system. Various electronic instruments, arrays, and operational procedures were tested and a completely functional system was designed. The system (Fig. 1) employs a frequency locked Gunn oscillator at 94 GHz to drive the array, the 1.018-volt output of a Zener reference standard as the transfer component, and a 7 1/2 digit voltmeter to record the voltage difference. This system now produces consistent results with a precision of one part in 10^8 or better.

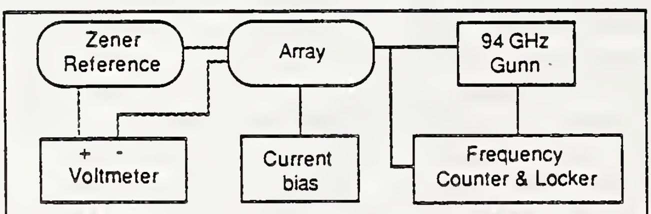


Figure 1. Array system block diagram

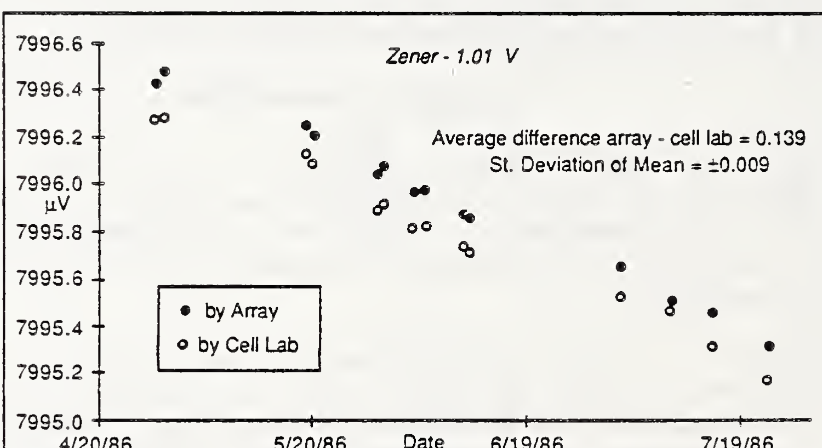


Figure 2. Calibrated Values of a Zener Reference

During the year there were twelve comparisons of the present Josephson voltage standard against the NBS reference groups of Weston cells. By contrast, the ease of use of the array system were manifested by the calibrations performed by it on thirty five days during the second half of the year alone. A consistent difference between the two systems was observed, shown by the latest data in Fig. 2, where the array gives an average value which is (0.139 ± 0.009) μV [(0.136 ± 0.009 ppm] higher than the primary reference cell values calibrated with the traditional system. Efforts to trace this difference included a comparison of the results obtained using a Gunn oscillator to those obtained using a phase-locked klystron. No significant difference was observed. In two calibration tests of the 100:1 resistive voltage divider network against the array, two similar offsets resulted, averaging 0.154 ± 0.029 μV. The first tested the ratio between the Zener (as calibrated by the array) at one 1.018 V and the two-junction Josephson device generating 10.18 mV and the second tested the Zener (as calibrated by the array) at 1.018 array) at 1.018 against the array itself generating 10.18 mV.

While developing the array system several possible problems were identified, including one in which a faulty array can give an error due to point-contact shorts within the device. Discussions concerning these problems and recent work on NbN and artificial oxide (i.e., aluminum oxide) arrays took place during a one month visit by J. Niemeyer from PTB (Federal Republic of Germany) in July 1986.

Progress toward completing objective (vi) was made with the identification of inadequate electrical contacts to the Josephson device as a significant problem. A method employing superconducting pressure Pb contacts, borrowed from Boulder array technology, is being used as a solution. Junction fabrication and testing is proceeding rapidly with the arrival of a Guest Scientist from KSRI in August 1986 for a stay of six months.

Future Plans

Maintenance of the U.S. Legal Volt will, of course, continue. A 100:1 voltage divider based on a resistor cascade interchange self calibration technique will be repaired and used to crosscheck the accuracy of the array system and 100:1 resistive Hamon divider independently. With the array system now operating dependably with greater precision (one part in 10^8), conversion to its use as the basis for the U.S. Legal Volt will occur as soon as its accuracy can be verified. Thus, understanding the source of the 0.14 ppm discrepancy and its elimination is viewed as the highest priority task for FY 87 (after maintaining the unit).

Collaboration with Boulder and PTB will continue. Several improvements in the array design, to decrease microwave power requirements and increase step stability, along with some custom built electronic instrumentation, will be tested. A new phase-locked 94 GHz Gunn source will be procured and tested. Some computer automation of the current bias control for step selection and data recording of the array system will also be initiated.

Plans for upgrading the thin film and photolithography facilities will be developed this next year. A new turbomolecular pump, ion pump and cryogenic pump repair, and reconstruction of the substrate holders are necessary before fabrication of Nb or NbN junctions can begin.

Concerning the commercial reference standards, the electrical contact problem will be attacked and a supply of replacement junctions fabricated with the help of the KSRI Guest Scientist. Only the Navy Western Standards Laboratory system remains to be calibrated and delivered

REALIZATION OF THE SI AMPERE
(P. T. Olsen, W. D. Phillips, E. R. Williams)

Objectives

The objective of this research is to measure directly the NBS as-maintained ampere in terms of the SI units of mass, length, and time (i.e., in terms of the SI definition of the ampere) to an accuracy of at least one or two parts in ten million. A realization of the SI ampere with a given uncertainty is equivalent to determining the Josephson frequency-voltage ratio 2e/h in SI units to essentially the same uncertainty.

This experiment is particularly important because measurements of other fundamental constants indicate serious inconsistencies between past direct realizations of the ampere and indirect determinations based on other constants. A new measurement will help resolve these discrepancies, provide solid contact between SI and as-maintained electrical units, and could even lead to artifact-independent definitions of the kilogram and mole. Moreover, it will help provide the Consultative Committee on Electricity the means to select a new, international value for 2e/h for volt maintenance purposes.

Current Activities

Traditional absolute ampere experiments have measured the force between current-carrying coils whose dimensions were carefully determined. Dimensional uncertainties have been the major limitation in accuracy. The new approach avoids dimensional measurement by comparing the mechanical and electrical work done as one coil is moved in the field produced by another coil. The experiment is performed in two parts. First, we measure the voltage induced in one coil while it moves in the magnetic field of the other, current-carrying, coil. Second, we measure the force exerted on the movable coil by the other when both carry current and the movable coil traverses the same path as in the first part of the experiment. From the measured voltage and force, along with the current, times, and displacements involved, quantities equivalent to electrical and mechanical work are calculated and their comparison results in an absolute ampere determination. The difficult dimensional measurement is thus replaced with a straightforward displacement measurement.

The plan for determining the NBS ampere in terms of the SI ampere has three phases. The first phase, completed in early FY 82, involved assembling and making measurements with a relatively small scale working model to evaluate the general method described above. It was surprisingly successful considering the primitive nature of the apparatus, yielding a statistical measurement uncertainty of about 2 ppm. The systematic uncertainties were not seriously evaluated, however, because of the unfavorable Pellat balance (rotational) geometry used.

Phase II involves more sophisticated apparatus in a highly favorable linear geometry. Construction of this apparatus and its assembly and partial testing was completed in FY 83; evaluation of the complete system began in early FY 84. Figure 1 schematically represents the essential components.

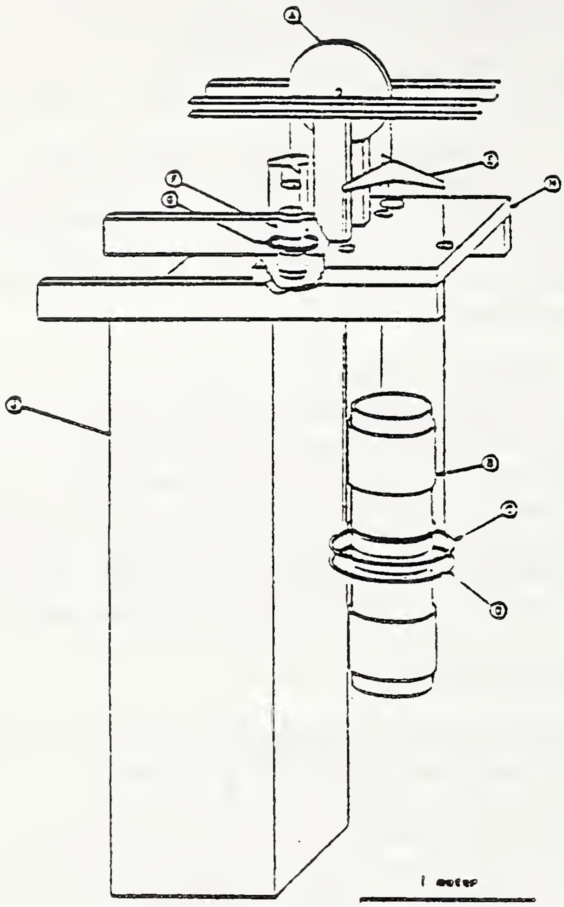


Fig. 1. A: Balance wheel; B: main magnetic field generating coil; C: movable coil; D: reference coil; E: balance support spider; F: servo magnetic field generating coil; G: servo movable coil; H: marble slab; J: stone pier.

The heart of the apparatus is the system comprising coils B and C, the fixed and moving coils respectively. Coils B, placed symetrically above and below C, provide the radial magnetic field in which C moves. The voltage induced in C and the force exerted on it are measured in the two parts of the experiment. The balance wheel A allows C to move vertically with negligible horizontal motion. This wheel, which pivots on a knife edge at its center, allows force determinations with a sensitivity equivalent to about 30 μg.

The reference coil D allows us to correct for changes in the field at C due to ambient field shifts or motion of the coils B. Coils F and G provide the force needed to move the balance and translate C during the voltage measurement phase of the experiment.

The displacement of coil C is measured interferometrically using a HeNe laser. Forces are measured in terms of calibrated masses and the measured local acceleration of gravity, while voltages and currents are measured in terms of the NBS standards of voltage and resistance.

Two versions of coil system B are available. During Phase II, we are using a room-temperature version which provides a force of 20 g on C and induces a voltage of 20 mV. In phase III, we will use superconducting coils which will provide a force equivalent to 1 kg and an induced voltage of 1 V.

Accomplishments

Having eliminated many of the sources of noise and error late in FY 85, we performed a number of ampere measurements early in 1986, establishing the capability of the system to produce sub-ppm statistics in repeated measurements over the course of many hours. This good statistical performance of the balance led us to discover a number of new sources of noise and error, which in turn allowed us to further refine the balance. One rather important error which was discovered stems from small (microvolt) offsets related to a high and variable level of ambient rf fields. This produced not only noise, but errors because the effect can change on reversal of currents and velocities. Proper rf shielding and isolation has reduced these effects to an acceptable level. We also improved the isolation from various pick-up effects through the use of separate isolation transformers on all of the sensitive instruments, elimination of ground and shielding loops, and isolation of the shield enclosing the balance and instrumentation from power-line ground. Communication between measurement instruments and data acquisition is accomplished by optical isolators.

We also found a seasonally correlated noise in weighing which became particularly severe during the cold winter weather. While the source of this noise is not firmly established, we spent considerable effort to further isolate the balance enclosure from outdoor weather by adding additional insulation all around the enclosure and in the floor which separates the upper and lower parts of the balance. In addition, we have provided a low power, large area heating element in the upper part of the balance case to establish the needed thermal stratification to minimize convection. The balance enclosure and its immediate environment has been instrumented with thirty sensors to allow continuous monitoring of the thermal conditions.

Improvements have been made to the electronic instrumentation, including reduction of drift in the reference current supply (our short-term voltage standard), construction of a 24-bit DAC to provide better feedback control than was possible with two overlapping DAC's, and construction of a 15-bit ADC to provide higher resolution, wider dynamic range measurements of generated voltage. The last two devices are nearly ready for installation.

During FY 86 we made the first direct measurements of the force profile of the balance, the variation with position of the force on the suspended coil, which is needed to calculate the mechanical work. This measurement was accomplished with a precision of about a ppm in the ampere. Its rather time consuming nature pointed to the need for automation in the weighing phase equivalent to that already available for velocity measurements. The instrumentation for this automation has been designed and is under construction. Comparison of the force profile with the profile of the voltage/velocity ratio (which must have the same form) gave agreement within the measurement uncertainty.

We also have indications of a systematic error at the few ppm level due to a weighing asymmetry. This is believed to occur because of the different behavior of the balance when the test mass is removed compared to when it is replaced. This error will be eliminated through the use of a new weighing procedure to eliminate the assymmetry and tighter servo control of the balance position during weight changes. ·

Our measurements during this year have firmly established the weighing as the major source of error and noise at this stage of the experiment. Fortunately, these effects will diminish directly with increased force. In the long run, this will be achieved with the superconducting system, but for the short run we have constructed new suspended coils which will permit an increase of about a factor of ten in the force. We will lose a bit in the voltage generated during the voltage/velocity phase of the experiment, but the smaller coil impedance will improve the frequency response of the voltage measurement, which should be an advantage. In any case, the voltage measurement does not appear to be a limiting factor at this stage of the experiment.

While the measurement of the voltage-time integral during the voltage/velocity phase of the experiment is not a limiting factor at this time, the non-uniformity of balance motion makes extraction of force profile information difficult. The problem stems in part from the roughness of the balance wheel surface. To deal with this, we have constructed a new wheel with polished glass inserts which should improve the uniformity of motion. This, along with the improved time response of the new coils, should improve this part of the measurement.

Future plans

Reassembly of the balance after installation of the new coils is nearly complete and implementation of automated weighing and improved servo and measurement instrumentation is well under way. Once these are done, we will return to measurement of the ampere, and we expect variability substantially below a ppm, allowing good evaluation of systematic errors at the ppm and sub ppm level. We expect to achieve an ampere measurement which is accurate at about the ppm level, or possibly better with this apparatus, and to implement complete automation of the measurement before changing to the superconducting version. The latter should allow a 0.1 ppm determination of the ampere and an opportunity to study the ampere balance as a way of monitoring the kilogram.

REALIZATION OF THE SI VOLT

(F. K. Harris, J. R. Kinard)

Objectives

The objective of this project is to realize the SI volt directly by force measurements in terms of the base SI mechanical units of length, mass, and time interval, and the assigned SI magnetic constant.

The present volt assignment is derived from absolute ohm and ampere determinations and is uncertain to the same extent as the latter (5 ppm or more). However, a direct volt determination should be free from some of the systematic errors of past ampere determinations. Furthermore, there is no conversion of electrical energy to heat, which may have affected dimensional results and balance operation in past ampere determinations. Thus is hoped that a direct determination of the volt may reduce the uncertainty in its assigned value.

Current Activities

Our volt balance consists of a vertically aligned coaxial-cylinder electrode system with the low-voltage electrode in the annular space between an inner and outer high-voltage electrode, and suspended from the balance beam. The vertical electrical force on this suspended electrode is compared by substitution to the mechanical force produced by a known mass. The relation between electrical and mechanical forces,

$$E^2\frac{\partial C}{\partial z} = 2mg$$

requires that capacitance be measured against vertical electrode displacement; and the high-voltage electrode system is mounted on a carriage which can be moved vertically on three guide rails, position being determined using a laser interferometer.

It has been shown that horizontal electrical forces which are present if the system is not truly symmetrical about a vertical axis may translate into a quasi-vertical force if the knife-edges of the balance beam are not in a horizontal plane. Thus it is extremely important that the electrode system be accurately symmetrical (within a few micrometers) about an axis that is vertical (within a few seconds of arc); the carriage movement of the high-voltage electrode system must also be vertical within the same constraint.

A mechanical disturbance to the central system can cause the suspended electrode to oscillate as a pendulum about its central position. When voltage is impressed on the electrometer, there is a lateral electrical force acting on the displaced suspended electrode tending to increase its displacement during pendulous motion. This is opposed by the centering force of gravity. If operational stability is to be retained, the value of impressed voltage is limited, but can be increased by lowering the center of gravity of the suspended electrode. At the present time our system is stable for a 1 g force, but not for voltages corresponding to 2-5 g forces which we would like also to employ. Francis Hermach recently suggested the possibility of axial stabilization of the suspended electrode by using the repulsive force between like poles of permanent magnet pairs, one magnet fixed to the upper rim of the suspended electrode, and its companion to the fixed shielding ring that surrounds the upper end of the electrode. If such a magnetic stabilization scheme can be realized, it will remove the need to lower the center of gravity of the suspended system for force measurements above the 1 g level. A model of the suspended electrode system has been constructed so that we may study the possibilities of magnetic stabilization.

Accomplishments

Determinations of $\partial C/\partial z$ have shown undesireably large uncertainties, amounting to several ppm in a series of 10 determinations. It has been assumed that the O-ring carriage bearings could be binding against the steel rails modifying the position and attitude of the electrode system supported by the carriage. Since O-ring pressure against the rail can be modified, a study of the effect of this pressure on $\partial C/\partial z$ is being made. Clearly, it would be desirable in any future construction to use a central bearing system rather than a group of bearings located at the rim of the carriage.

Preliminary experiments with the magnetic stabilization model are promising; and a system for precisely controlling magnetic positions is under development.

Future Plans

Study of $\partial C/\partial z$ will be continued in an effort to reduce its uncertainty. The magnetic stabilization study will be continued in our model.

REALIZATION OF THE SI FARAD AND OHM

(J. Q. Shields, L. H. Lee, G. R. Jones, Jr.,
G. W. Small (GW), H. P. Layer)

Objectives

The objectives of this project are to build, maintain, and operate equipment for calibrating the NBS standards of capacitance and resistance in terms of their SI definitions to an accuracy of 1 or 2 parts in 100 million, and to assure the compatibility of these standards with those of other countries.

Accurate realizations of the farad and ohm are required to assure the compatibility of instruments (via resistance, inductance, and capacitance calibrations) that are manufactured within the U.S. and for the determination of certain fundamental constants. The NBS absolute farad and ohm measurements make use of a calculable cross capacitor and a series of bridges for comparing capacitors and resistors. The result of the measurement sequence is an absolute calibration of the NBS reference standards of capacitance and resistance that is accurate to a few parts in 10^8. These measurements can also be considered as fundamental constant determinations, with applications to questions concerning the adequacy of quantum electrodynamic theory and to the determination of more exotic constants. For example, a reliable value of the ratio of the NBS ohm to the SI ohm is required in order to obtain a value for the fine-structure constant from a measurement of the proton gyromagnetic ratio and 2e/h as measured via the Josephson effect; and from a measurement of the quantized Hall resistance in a two dimensional electron gas. It is also necessary for the new NBS absolute ampere experiment.

Current Activities

The current calculable capacitor was completed a number of years ago and is among the best in the world; a value for the NBS farad and ohm in terms of the SI farad and ohm accurate to a few parts in 10^8 was obtained in 1974. Work is presently concentrated on the preparation of this equipment for a new determination of the absolute farad and ohm with slightly improved accuracy. Other current activities include maintenance of the NBS unit of capacitance at the 10 pF level, and participation in international comparisons of capacitance and resistance standards.

Accomplishments

The major task this year in the present realization of the SI farad and ohm has been the evaluation of the many corrections and systematic errors associated with the calculable cross capacitor and its related measuring equipment. Most of the corrections and systematic errors have now been evaluated and it is expected that final results of the SI farad determination will be available sometime during the first quarter of 1987. Preliminary results show that the NBS unit of capacitance, as maintained by a group of 10 pF fused silica dielectric capacitors, has been changing at an average rate of 0.01 ppm/year since 1974.

The SI farad project has benefitted greatly from a three month working visit by Greig Small of the National Measurement Laboratory in Australia. With the help of Greig and Howard Layer of the Length and Mass division, a major disassembly of the calculable cross capacitor in which both the upper and lower guard tubes and the entire upper guide assembly were removed was undertaken. The disassembly was necessitated by a number of factors: (1) an abnormal pattern in the optical fringes indicated the presence of foreign matter on the optical flats which form the built-in Fabry-Perot interferometer; (2) capacitance gauge measurements showed horizontal movement of the upper guard tube as it was raised and lowered, thus indicating the need for a larger diameter PTFE guide ring; (3) reduction of the uncertainty in the frequency correction for the calculable capacitor required that a number of internally distributed inductances and capacitances be measured; and (4) uncertainty in the alignment of the electrical and optical axes required a realignment of these axes.

The primary vehicle for international capacitance comparisons continues to be a set of three 10 pF capacitors of NBS design and construction which exhibit good stability while being shipped via commercial carrier. The shipment of the capacitors to NML in Australia in early FY 86 was timed to coincide with the NBS measurement of three 1-Ω resistors which were hand-carried from NML. The double comparison showed good agreement between the measurement sequences whereby each laboratory obtains the unit of resistance in terms of the unit of capacitance.

Future Plans

A comparison of the NBS units of capacitance and resistance will be repeated while keeping the calculable capacitor in operation. This should yield an SI ohm realization with an uncertainty of less than 0.1 ppm by the middle of CY 87. Subsequent work will concentrate on reducing the uncertainties in the measurements to the few parts in 100 million level and to improving and otherwise upgrading the apparatus to make the measurements easier to carry out. Absolute realizations of the ohm will be coordinated with the NBS quantized Hall resistance measurements to ensure the closest possible tie between the two. Another comparison of capacitance units between NBS and NML is also planned, and possibly comparisons between NBS and other national laboratories as well.

QUANTIZED HALL RESISTANCE

(M. E. Cage, C. T. Van Degrift, R. F. Dziuba, W. J. Bowers, T. E. Kiess, B. F. Field)

Objectives

To develop techniques for bringing the quantum Hall effect (QHE) in semiconductor devices to the point where it can be used to: (1) determine the fine-structure constant α with the unprecedented accuracy of a few parts in 10^8, thereby allowing the unequivocal testing of quantum electrodynamic (QED) theory; and (2) to establish a reproducible resistance standard of the same accuracy.

The quantum Hall effect has the potential of providing the most accurate QED-independent value of α, as well as a resistance standard based on fundamental constants of nature, to replace the present resistance artifacts. It would thus permit a definitive test of QED as well as allow NBS to maintain the U.S. unit of resistance in SI units continually to a very high accuracy, rather than at multi-year intervals via the very difficult calculable cross-capacitor experiment.

Current Activities

The method for achieving the goals involves measurements of the quantized Hall resistance R_H in a two-dimensional electron gas realized, for example, in the inversion layers of semiconductor devices such as silicon MOSFETs (metal-oxide-semiconductor field-effect transistors) or GaAs-AlGaAs heterojunction when these devices are operated at temperatures at or below 4.2 kelvin, and in the presence of a strong magnetic field perpendicular to both the current flow and the Hall voltage.

At each Hall step the resistance R_H (defined by $R_H = V_H/I$) is quantized, and can be expressed as $R_H = h/e^2 i = \mu_0 c/2\alpha i$ 25.812.80/i ohms, where h is the Planck constant, e is the elementary charge, i is a quantum number, μ_0 is the permeability of vacuum, c is the speed of light, and α is the fine-structure constant.

Currently we are: (1) performing QHE measurements on GaAs heterojunction samples with an 8 T magnet; (2) using the quantum Hall effect to monitor the national unit of resistance; (3) constructing a new QHE laboratory which will allow us to continue monitoring the national unit of resistance in a 13 T magnet and 0.3 K He-3 refrigerator system while enabling us to expand our basic standards using a second system capable of attaining magnetic fields of 15 T and temperatures down to 30 mK with a dilution refrigerator.

Accomplishments

Four steps are required to use the QHE to maintain the "NBS Ohm" or U.S. Legal Ohm, Ω_{NBS}. First, each device is thoroughly studied for magnetic field, temperature, and current dependence. Second, the 6453.2 Ω quantized Hall resistance (i=4) is transferred to a room temperature resistor of nearly the same value. Third, a Hamon series parallel resistance network is used to transfer that value to a 100 ohm standard. Fourth, another Hamon device is used to complete the transfer to the set of five NBS one-ohm resistors which comprise Ω_{NBS}.

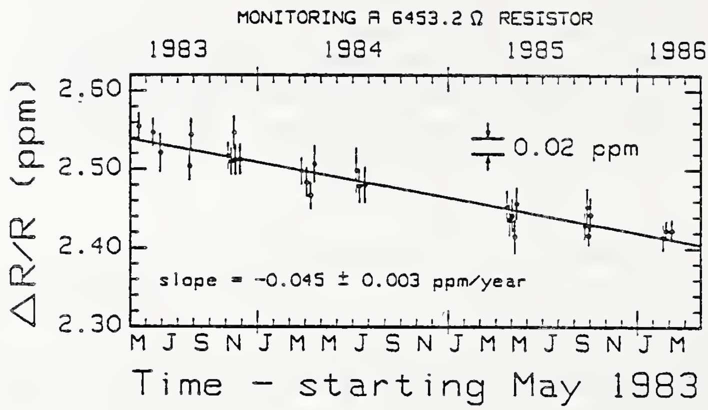


Figure 1. Relative comparisons as a function of time of the resistance of the i = 4 steps of three different quantum Hall devices with that of a nominal 6,453.20 Ω wire-wound reference resistor. $\Delta R/R = (V_H - V_R)/V_R$. The value of this particular resistor is increasing by (0.045 ± 0.003) ppm/year.

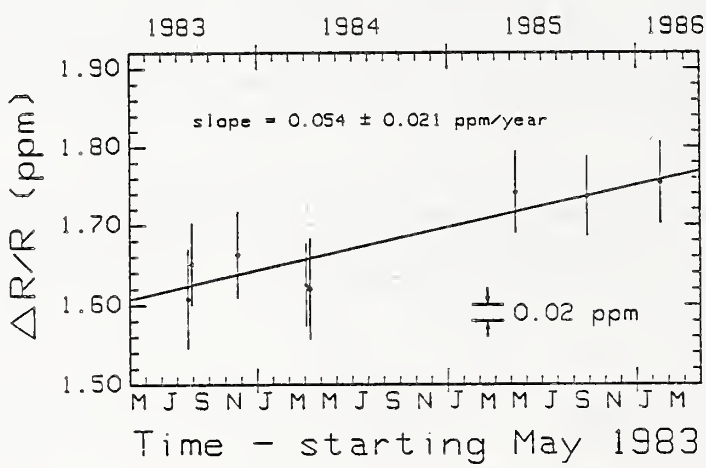


Figure 2. Monitoring as a function of time the value of $R_H(4)$ expressed as a difference in ppm from a reference value of 6,453.20 Ω_{NBS}. These data indicate that the U.S. Legal Ohm, Ω_{NBS}, is decreasing by ~ (0.054 ± 0.021) ppm/year.

Figure 1 displays the latest results of these comparisons. Two different automated measurement systems are now being used for step 2: a modified Wheatstone bridge system and a potentiometric comparator constructed during the FY by G. M. Reedtz, a Guest Scientist from the Electrotechnical Institute in Turin, Italy. These measurements have typical one standard deviation total uncertainties of ± 0.02 ppm. The figure also shows that the value of the 6453.2 Ω reference resistor is increasing at a rate of (0.045 ± 0.003) ppm/year. This increase occurs even though the resistor is hermetically sealed, is continuously temperature-controlled to within ± 0.002 °C, and has not been moved.

Figure 2 shows the result of steps 2 and 3 using a second, transportable, 6453.2-Ω reference resistor. These data provide the first direct evidence that Ω_{NBS} is drifting; its value is apparently decreasing at the rate of (0.054 ± 0.021) ppm/year. The uncertainty in this drift rate is quite large, but should be further reduced as a result of our continued measurements using the quantum Hall effect.

The National Measurement Laboratory (NML), Australia, invited M. E. Cage to assist them in their QHE experiments during the FY. NML has been maintaining the unit of resistance for the world over the last twenty years using their calculable cross-capacitor, but had been unable to locate any satisfactory quantum Hall devices. This visit provided a direct comparison of the national resistance units of Australia and the U.S. via a quantum Hall device. The 6453.2 Ω (i=4) step of the device designated GaAs(9) was chosen as the transfer standard. This device has very flat Hall steps and is one of the three devices that has been used to monitor Ω_{NBS} over the last 2 1/2 years. Its Hall resistance was compared with Ω_{NBS} to within ± 0.05 ppm in September, 1985, before being hand-carried to Australia. It was found that $\Omega_{NML} - \Omega_{NBS}$ obtained from the QHE measurements and from a comparison using 1 Ω transportable resistors carried out at the end of October 1985 agreed to within 0.02 ppm. This is a very satisfying result.

Ω_{NML} is maintained in SI units using a calculable cross-capacitor. The assigned uncertainty is ± 0.062 ppm. An absolute determination of Ω_{NML} was made during this visit. The measurements for both i=2 and i=4 Hall steps of GaAs(9) indicate that the value of R_H is (0.383 ± 0.078) ppm larger than a nominal value of 25,812.80 Ω.

The new QHE laboratory is nearing completion. During the FY, the basement rooms selected for the new QHE laboratory underwent the necessary major modifications. Two massive vibration-isolated pits were built into the floor, one 2.5 m long by 1 m wide and 4 meters deep for the 15 tesla research magnet and a second 0.5 m square and 3.5 m deep for the 13 tesla standards magnet. Installation was completed for the support simultaneous operation of a He-3 refrigerator for the 13 tesla magnet and a dilution refrigerator for the 15 tesla magnet. Although, we still await delivery of the 15 tesla magnet, we have begun construction of its dilution refrigerator insert.

Future Plans

During FY 87, we will make the new QHE laboratory operational. The top-loading dilution refrigerator for the 15 tesla system will be completed and tested, and the high accuracy Hall resistance measurement systems will be relocated in the new laboratory. Several months of extensive testing will be necessary to certify that the resistance measurements in the new laboratory and the temperature measurements are not degraded by the magnetic field.

While continuing to monitor Ω_{NBS}, we will use our new capabilities to make a careful measurement of the temperature dependence of R_H (at i=2 as well as i=4) from 30 mK to 4 K. We should be able to accurately trace the transition between the "activation" and the "multi-range hopping" temperature regions. Previous temperature dependence measurements have had inadequate temperature accuracy and resistance precision to provide a definitive test of the various theoretical predictions.

GAMMA-P AND THE FINE-STRUCTURE CONSTANT
(E. R. Williams, P. T. Olsen, W. D. Phillips,
G. R. Jones, Jr., Zhu Te-ming)

Objectives

To carry out an improved determination of the gyromagnetic ratio of the proton in H_2O, γ_p', to an accuracy of a few parts in 100 million, thereby obtaining a value of the fine structure constant α to an accuracy of 0.02 - 0.03 ppm. This will extend the precision with which quantum electrodynamics (QED), the Josephson effect, and the quantum Hall effect, can be tested. It will also provide a test of our ability to monitor and maintain the NBS units of voltage and current.

The present approach to redetermining α is based on improving the inductive dimensional measurement method developed in our laboratory for determining the pitch and diameter variations of a precision solenoid and used to carry out a 0.2 ppm determination of γ_p' reported previously. The NPL in England and the VNIIM in the USSR have reported values of γ_p' that are in complete disagreement with our earlier result (10-15 standard deviation discrepancies). The Chinese value obtained at NIM, Beijing, agrees with our value. The Japanese at ETL have recently reported an intermediate value. We expect that a new determination of γ_p' will resolve these major disagreements.

Current Activities

The gyromagnetic ratio of the proton is defined as the ratio of the angular precession frequency ω_p'/B (the prime indicates the proton is in a spherical, pure, H_2O sample at 25 $^\circ$C). The precession frequency is measured by standard nuclear magnetic resonance methods. The magnetic field is calculated from the measured physical dimensions of a single-layer solenoid, wound on a precision-ground quartz from, with a known (in terms of NBS standards) electric current in the turns of wire. The location of each turn of the solenoid is found by an inductive pick-up probe and a laser interferometer which locates the position of the probe. We have constructed a new solenoid and measuring apparatus that reduces the sources of error in the previous experiment. The new experiment has the following improvements: (i) improved axial symmetry of the inductive pick-up probe; (iii) an improved straightedge used to guide the probe; (iv) an improved laser measuring system; (v) the means to measure all six degrees of freedom of the probe; (vi) increased S/N ratio for the NMR signal; (vii) improved temperature control; and (viii) improved calibrations for the length and electrical standards. These advances should produce nearly an order of magnitude improvement over our previous determination. The quantum Hall effect, which provides an independent value of α, provides additional incentive for completing the γ_p' measurement in the near future.

Accomplishments

The first part of the year was spent carefully testing and checking the dimensional measurement system because of an unexplained shift in the measured pitch. Finally, we found the source of the problem to be one lock-in amplifier that was very nonlinear when operating near full scale. The exercise resulted in extensive testing for systematic errors and several small improvements.

A complete dimensional measurement set including a laser calibration was completed during the winter. Figure 1 shows the latest measurements, where the lower graph is a plot of the changes in the radius as a function of the wire position, and the upper graph is a plot of the changes in the axial position (pitch) after a uniform pitch of 1.058588 mm/turn is subtracted from the value measured by the laser interferometer reading. In this figure, each wire was measured four times, and the standard deviation of the measurements is represented by the error bars. This one measurement set required about 50 hours of data taking, and seven such sets were obtained. From each set we calculate the correction to the magnetic field at the center due to these imperfections (see Fig. 2). Notice that the large uncertainty in the pitch of wires −610 to −1050 does not contribute significantly to the uncertainty in the calculated magnetic field. These large uncertainties are a result of the necessity of measuring these wires without a vacuum for the interferometer path.

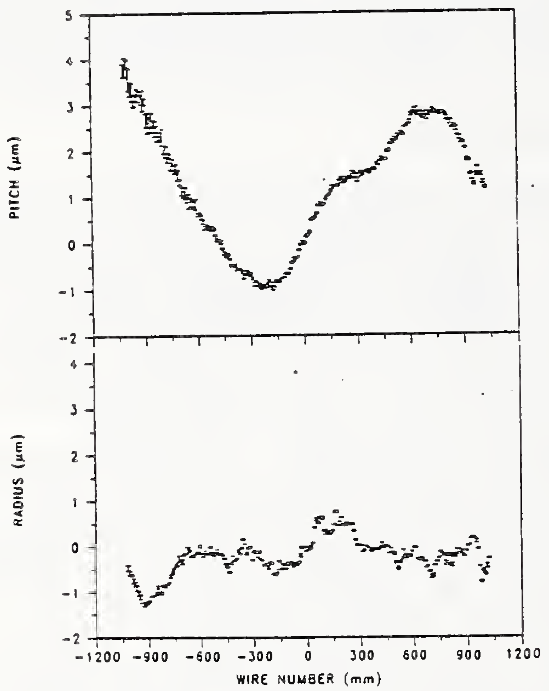


Fig. 1. Radial variations (bottom) in μm and axial position variations (top) in μm versus wire number (~1 mm/wire number). The radial variations are with respect to the center wires. For the axial variations a uniform pitch of 1.0585880 mm/turn has been subtracted from the laser interferometer reading at each wire.

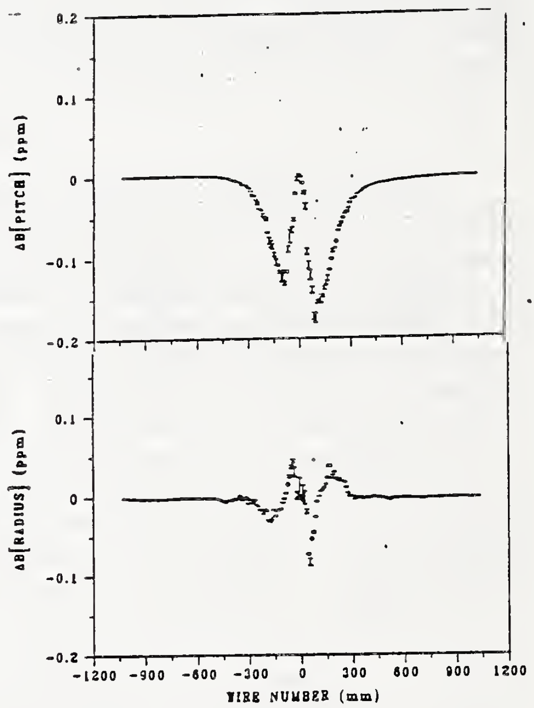


Fig. 2. Again using the data of Fig. 1 we calculate the expected magnetic field gradient along the solenoid axis near its center.

We were encouraged by our dimensional measurement results. The average of the calculated field (correction to a nominal value) for the seven sets is (0.051 ± 0.02) ppm (σ_m = 0.008 ppm) for the radius and (−4.69 ± 0.12) ppm (σ_m = 0.04 ppm) for the pitch. Further improvements in the pitch measurements are expected during the next measurement cycle. We were thus optimistic when we went to the NMR part of the experiment for which we needed only to repeat our previous precision of 0.02 ppm to obtain a 0.1 ppm value of γ_p'. We had all the usual problems and ended up rebuilding most of the previous NMR electronics, but still had time to make the measurements in time for their presentation to the 1986 Conference on Precision Electromagnetic Measurements. However, a new and totally unexpected systematic error has arisen; we obtain a good NMR line but on reversing the solenoid current, then returning immediately back to the original current direction, the NMR frequency shifts by up to 10 ppm and then slowly returns toward the original frequency with a time constant of 50 minutes. No serious data can be taken until this effect is understood and eliminated.

One additional accomplishment was relatively easy and fun. We measured the correction to the calculated magnetic field due to the iron in the earth by inductive techniques similar to those used in measuring the solenoid. We designed a primary coil system that produces as large a field as possible at a distance (i.e., has a large magnetic dipole moment). A large detector coil is rigidly connected to these primary coils and positioned so that the signal in the detector coil from the primary coils is nearly zero. Then the signal due to the induced magnetic moment in the iron contaminated earth is measured as a function of the distance of the coils above the earth. The data obtained fit beautifully to the expected cubic dependence. From this data we now can predict the correction for the iron in the area to be (-0.12 ± 0.03) ppm. This is a large effect. If the earth were made of solid steel, the correction would only be 50 times larger.

Future Plans

Of course, we will continue to look for the cause of the present systematic error in the NMR. It is a very large effect, and we should be able to find its source relatively easily. However, it is so large that it most likely must be eliminated, not just measured, when we understand its origin.

The Japanese are also nearing completion of their γ_p' experiment (at lower accuracy). Dr. Williams has been invited to spend two months at ETL working on this experiment. Upon his return in December, he will proceed to obtain the 0.1 ppm value from the NBS experiment by solving the NMR problem. After the NMR is working properly, one to two year's worth of testing and measuring will be required to achieve the few parts in 100 million uncertainty of which this experiment is capable. Although this latest NMR effect is disappointing, a good deal of progress has been made in the dimensional measurements this past year. With a little good fortune, the project should achieve its ambitious goal.

LASER COOLING AND TRAPPING OF NEUTRAL ATOMS
(W. D. Phillips, A. L. Migdall, P. L. Gould, H. J. Metcalf (GS))

Objectives

The basic objectives of this project are to decelerate and cool a neutral atomic beam, and to confine and further cool neutral atoms in traps.

A major motivation for this work is that cooling and trapping provide solutions to motional effects, such as Doppler and transit time, which limit the performance of high resolution spectroscopy. This work is complementary to the trapped/cooled ion work in the Time and Frequency Division. Both efforts concern spectroscopy, but neutral atoms present some different opportunities, such as studies of atoms in electric fields. These could test theories of Stark effect or provide a new determination of the fine-structure constant from Stark splittings. Spectroscopy of neutral atoms also has possible applications to frequency standards, other fundamental constants, and the search for electric dipole moments and failure of time-reversal-symmetry. Cold or trapped atoms may be applied to the study of quantum collective effects such as Bose-Einstein condensation, trapping of neutral antimatter, atom-surface interactions, surface probes, atomic collisions, and sensitive deflection experiments to study photon statistics or charge neutrally of matter.

Current Activities

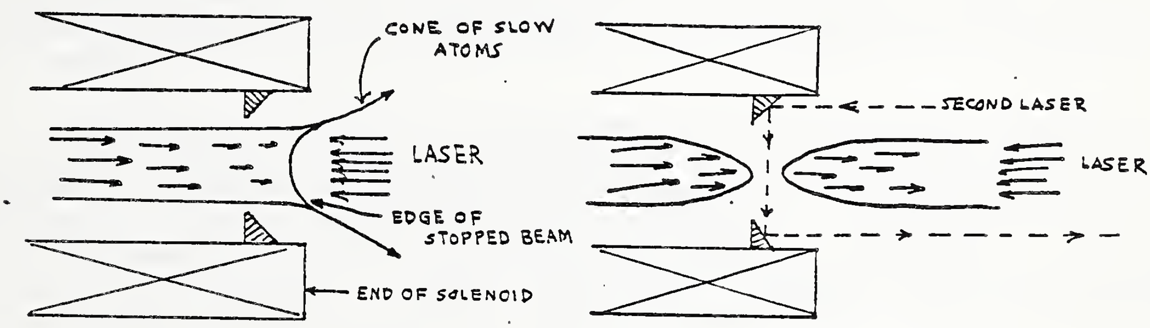
A thermal sodium beam is decelerated by the radiation pressure of a resonant laser. The changing Doppler shift of the decelerating atoms is compensated by the Zeeman shift of the spatially varying magnetic field of a solenoid so as to keep the atoms in resonance. Atoms are brought to rest continuously, and can be extracted by turning off the laser and allowing the atoms to drift out of the field. In our work to date the atoms are stopped by a pulse of light and have been trapped, by virtue of their permanent magnetic dipole moment, in an inhomogeneous magnetic field. The atoms have been trapped for an average time of 0.8 s, limited by collisions with background gases.

Accomplishments

During the past year we have redesigned the vacuum apparatus and the magnetic traps to improve the quality of the vacuum, the trapping time, and the density of trapped atoms. Improved instrumentation also has allowed faster switching of the magnetic field of the trap, which should permit experiments on multiple loading and cooling of trapped atoms, as well as more accurate measurements on the trapped atoms and more efficient loading of the trap. The new vacuum system has improved the base pressure by about an order of magnitude. Two new traps have been constructed: a clean, liquid nitrogen cooled trap and a liquid helium cooled superconducting trap. The latter should provide significant additional cryopumping, and an even more improved vacuum. The new traps are now ready for installation and testing.

We have also developed a new technique for extracting continuous beams of very slow atoms from the solenoid. Because the sodium ground state is split by hyperfine structure, great care must be taken in cooling to avoid loss of atoms to the "wrong" hyperfine state. By using another laser we can deliberately pump atoms into this wrong state and thus interrupt the cooling. This causes the atoms to exit the solenoid continuously with velocities as low as 40 m/s.

The figure shows a drawing representative of the visual observations we have made during the extraction of a slow beam by optical pumping. The first drawing shows the atomic beam, visible by the laser induced fluorescence, coming to rest near the end of the varying-field solenoid. Streams of atoms which wander out of the last beam as the atomic beam comes to rest are seen as a separate cone emerging from the solenoid. When the second laser is directed across the atomic beam, it removes atoms from the cooling process before they stop, causing the fluorescence to disappear at that point, the cone of slow atoms disappears, and the main atomic beam exists the solenoid at a low velocity where the fluorescence reappears as the atoms are pumped back into near resonance with the laser.



In a separate experiment, we have attempted to observe the collection and concentration of slow atoms in a vapor cell by optical molasses, a three dimensional arrangement of cooling laser beams. The apparatus for this has been constructed, and while an initial attempt was hampered by poor optical quality windows, a new apparatus is now ready for another attempt. Coupled with these efforts has been a theoretical investigation, using MonteCarlo techniques, of the properties of optical molasses, and particularly of the process of loading atoms into the molasses. These studies have been important in designing the cell molasses experiments and in designing experiments for loading slow atomic beams into molasses.

Future Plans

The continuous beam of slow atoms produced by the optical pumping technique is slow enough that it can be easily deflected out of the cooling laser beam and put into optical molasses. Since the residence time for atoms in optical molasses can be a second or longer, and we have achieved an atom flux of $10^{10}/cm^{-2}\cdot s^{-1}$, it may be possible to build up a density of $10^{10}/cm^{-3}$ in the molasses, which would be about 10^4 times bigger than presently reported densities for optical molasses. Such high densities could be used to load optical dipole or magnetic traps. Densities implied for optical dipole traps are in the interesting range for Bose condensation, although other effects such as molecule formation might also be expected. We will be pursuing these areas as well as optical molasses in a cell and further development of magnetic trapping techniques.

FUNDAMENTAL CONSTANTS DATA CENTER
(B. N. Taylor)

Objectives

The principal objectives of this project are to provide an international information center within the U.S. for work in the general area of precision measurement and fundamental constants, to analyze the consistence of measured values of the fundamental constants, to analyze the consistency of measured values of the fundamental constants that are obtained from different experiments, and to obtain sets of recommended values of these constants for international use.

The close relationships that exist between the fundamental constants and precision measurements, basic measurement units such as the ampere, volt, and ohm, fundamental physics, and state-of-the-art measurement technology, makes the subject a natural one for NBS involvement. One of the purposes of this project is to provide assistance and guidance in the general area of precision measurement and fundamental constants to both NBS staff and university scientists, in particular, to advise them on the potential impact of the various experiments they are considering carrying out and to keep them informed of related work currently underway in various laboratories throughout the world.

Self-consistent sets of "best values" of the fundamental constants, obtained by means of least-squares adjustments, are required for a variety of purposes in science and technology, for example, in accurate calculations of the energy levels of atoms that are of importance in nuclear fusion, or for critical comparison of theoretical calculations with experiment. Furthermore, as the basic invariants of nature, they can be expected to form the basis of a system of reproducible, artifact-independent measurement units. Such a system is an ultimate long-range goal of metrology.

Current Activities

Current activities in the precision measurement-fundamental constants (PMFC) field include (1) keeping apprised of and maintaining a complete reprint collection of the latest accomplishments throughout the world in PMFC; (2) carrying out new least-squares adjustments of the fundamental constants to obtain sets of recommended values; (3) participating in the work of national and international groups (for example, the CODATA Task Group on Fundamental Constants and the NAS/NRC Advisory Committee on Fundamental Constants); (4) publishing the quarterly "Preprints on Precision Measurement and Fundamental Constants" (PPMFC) for the Office of Standard Reference Data (this publication lists preprints as well as reprints of PMFC papers); (5) attending and organizing national and international conferences on PMFC, visiting laboratories carrying out work in this field, and giving talks and preparing papers on the present status of the fundamental constants; and (6) answering inquiries from both within and without NBS relating to the PMFC field.

Accomplishments

By far the most important accomplishments this fiscal year has been the completion of the 1986 CODATA least-squares adjustment of the fundamental physical constants (LSAFC 86). Initiated six years ago in collaboration with E. R. Cohen of Rockwell International and under the auspices and guidance of the CODATA Task Group on Fundamental Constants, this lengthy undertaking was pronounced finished when the CODATA Task Group, at its June 22, 1986 meeting just prior to the 1986 Conference on Precision Electromagnetic Measurements (CPEM 86) held at NBS June 23-27, met and approved of the work Cohen and I had done; and when the CODATA General Assembly, at its annual meeting held this year in Ottawa on 17 and 18 July, approved our final recommended values. The CODATA report which will give the final results and describe how they were arrived at, and which will be published as CODATA Bulletin No. 64 by Pergamon Press, is rapidly nearing completion as of this writing. Bulletin No. 64 should be available by the end of calendar year 1986. The new adjustment represents a major advance over that carried out in 1973 as the following table shows:

Quantity	1986-1973 value (ppm)	1986 uncert. (ppm)	1973 uncert. (ppm)
α^{-1}	-0.34	0.045	0.82
e	-7.4	0.30	2.9
h	-15.2	0.60	5.4
m_e	-15.9	0.59	5.1
N_A	15.2	0.59	5.0
m_p/m_e	0.65	0.020	0.38
F	7.8	0.30	2.8
2e/h	7.7	0.30	2.6

It should be noted that the 1986 CODATA set of recommended values is based on all the data available through 1 January 1986.

Other FY 86 accomplishments include organizing, chairing, and reviewing the papers for a session at CPEM 86 entitled "Precision Physical Tests;" preparing and presenting a paper at CPEM 86 on the history of the present value of 2e/h used internationally for volt maintenance purposes; coauthoring a paper for the CPEM proceedings with K. Jaeger, Lockheed Missiles and Space, on the U.S. perspective on possible changes in the electrical units; and helping to organize and generate data summaries for the September 1986 meeting of the Consultative Committee on Electricity (CCE) at which the CCE will consider the questions of adopting (1) a new value, consistent with the SI, for the Josephson frequency-voltage ratio 2e/h to be used by every national standards laboratory which employs the Josephson effect to define and maintain its laboratory unit of voltage; and (2) a value of the quantized Hall resistance R_H, consistent with the SI, to be used by every national standards laboratory which employs the quantum Hall effect to define and maintain its laboratory unit of resistance.

Future Plans

The goals for FY 87 include (1) completing the long, detailed report on the LSAFC86 for publication in the J. Phys. Chem. Ref. Data; (2) disseminating widely the 1986 recommended values; and (3) beginning the up-dating of LSAFC 86 by including data which had become available during 1986 and which becomes available during the first half of 1987.

PRECISION MEASUREMENT GRANTS

(NBS Precision Measurement Grants Committee; B. N. Taylor, Chairman

Objectives

The current annual objectives of this project, which was first initiated in 1970 and is funded by the NBS Director, are to award two new Precision Measurement Grants of $30 k (renewable for two additional years at the option of NBS), and to renew four existing grants. The grants are awarded to scientists in academic institutions in order to (i) promote and encourage fundamental research in the field of measurement science in colleges and universities and train future measurement-oriented scientists, and (ii) foster contacts between NBS scientists and those researchers in the academic community who are actively engaged in such work.

The importance of research in the precision measurement-fundamental constants field has been covered in the project report entitled FUNDAMENTAL CONSTANTS DATA CENTER. While NBS has a strong interest in this area and much experimental work underway, it cannot do it all - there is much expertise and relevant work in the colleges and universities. It is the purpose of this project to tap this reservoir and to foster the training of students who might eventually become NBS staff by awarding grants to a selected number of outstandingly qualified, academic researchers. Only those individuals working in areas of immediate of potential future benefit to ongoing NBS programs are chosen to receive awards. Thus, the work carried out by the grant recipients serves to compliment the efforts of the Bureau's own staff in closely related areas. Selection is based primarily upon the originality of the work proposed as described in formally submitted proposals.

Current Activities

The research supported under the PMG program includes experimental and theoretical studies of fundamental physical phenomena which may lead to improved or new measurement methods and standards; the determination of important fundamental physical constants; and general research and development on basic measurement techniques and instrumentation. To simplify the selection process, candidates are first requested to submit a biographical sketch and preproposal summary outlining the objective of their proposed research, why they believe it to be important, and the general approach to be used, including some indication of what they expect to accomplish in the three year time period covered by the grant. On the basis of this material, four to eight candidates are selected by the NBS Precision Measurement Grants Committee (consisting of four senior university professors) to submit more detailed proposals. The same committees evaluate these, and on the basis of this evaluation, the recipients are finally selected. The criteria used in evaluating the preproposals and full proposals include the importance of the proposed research to science, the feasibility of the research, and the past accomplishments of the applicant.

Accomplishments

The procedures outlined above for selecting candidates, which were first instituted in FY 77, were again used successfully in FY 86. Proposals were openly solicited via an advertisement in Physics Today, announcements in appropriate trade journals and newsletters, and the mailing of a brochure to the physics departments of all of the colleges and universities in the U.S. which grant bachelor's degrees in physics (about 850). Excellent proposals were received from 35 candidates, five of whom were chosen to submit final, full proposals. The following are the two recipients selected, their institutions, and project titles:

Frederick R. Raab, University of Washington
Atomic Physics Tests of Gravity and the Equivalence Principle

Daniel R. Stinebring, Princeton University
High Precision Timing of Millisecond Pulsars

The aim of Raab's research is to improve by at least a factor of 100 a test of whether the local vacuum is Lorentz invariant as required by Einstein's statement of the Equivalence Principle. The phenomenon to be used is nuclear spin resonance in mercury isotopes. These 'nuclear' clocks will be tested for frequency shifts when their orientation with respect to distant Lorentz frames is altered. Also to be investigated is a nuclear spin gyro based on xenon and helium 3 atoms to check for precessions as the gyro's internal spin structure is oriented differently relative to gravitational fields. The gyro will test if all spins in gravitational fields are equivalent, independent of internal structure. A spin splitting of 4×10^{-30} eV may eventually be observable.

The aim of Stinebring's research is to search for primordial gravity waves by observing millisecond pulsars with a timing precision 3 to 5 times better than is currently attainable. This will allow the testing of the leading theories for the generation of such waves, for example, the phase transition from quarks to nucleons or an inflationary stage in the early universe. A second goal is to establish a 'flywheel' pulsars time standard that complements atomic time standards.

For FY 86, the NBS Precision Measurement Grants Committee consisted of Drs. Deslattes, Hall, Taylor, and Wineland; the Outside Advisory Committee of Professors Crampton, Metcalf, Ritter, of CBS and Williams.

The following grants are renewed in FY 86: T. E. Chupp, Harvard U., A Test of Local Lorentz Invariance Using Polarized ^{21}Ne Nuclei; M. J. Levine, Carnegie-Mellon U., Precision Calculation of the Anomalous Magnetic Moment of the Electron Using a Specialized Computation Engin; G. Gabrielse, University of Washington, Injection of Protons, Antiprotons, and Heavy Ions into a Penning Trap for Precision Mass Measurements; L. R. Hunter, Amherst College, A New Method to Search for the Electric Dipole Moment of the Electron.

The work of W. N. Hardy and A. J. Berlinsky, U. of British Columbia, on the development of a cryogenic hydrogen maser, was especially successful this year -- they demonstrated the operation of such a maser for the first time (their Grant was initially awarded in FY 85).

Future Plans

FY 87 plans naturally focus on renewing the four eligible current grants and awarding two new grants. Current and past recipients will be invited to visit NBS and to present talks as appropriate, and visits to current and past recipients will be made by NBS staff in conjunction with other travel.

Electricity Division Sponsored Seminars/Workshops

Workshop on Electrical Measurement Assurance Programs, held October 27 - Nov. 1, 1985, Rosemont, IL.

Invited Talks

N. B. Belecki, "Present and Future Calibration Uncertainties in the NBS Electricity Division," 1986 Measurement Science Conference, Irvine, CA, January 1986.

M. E. Cage, "The Quantum Hall Effect and its Application as a Resistance Standard," Commonwealth Scientific and Industrial Research Organization Colloquium, Sydney, Australia, November 1985.

M. E. Cage, "Features of the Quantum Hall Effect," Solid State Physics Colloquium, University of New South Wales, Sydney, Australia, December 1985.

M. E. Cage, "The Quantum Hall Effect and its Application as a New Resistance Standard," Bull. Am. Phys. Soc. II, 31 (1986) p. 61 (Atlanta Meeting of the American Physical Society, January, 1986).

M. E. Cage, "Features of the Quantum Hall Effect," Department of Physics Colloquium, University of Maryland, Baltimore County Campus, Cantonsville, Maryland, March 1986.

M. E. Cage, "The Quantum Hall Effect and its Application as a Resistance Standard," 1986 Kieval Lecture in Physics, Cornell University, Ithaca, New York, April 1986.

M. E. Cage, "The Quantum Hall Effect," Society of Physics Students Invited Lecture, American Physical Society Meeting, Washington, D.C., April 1986.

M. E. Cage, "The Quantum Hall Effect," Department of Physics Colloquium, California State University, Sacramento, California, September, 1986.

B. F. Field, "NBS DC Voltage Dissemination Services," 1986 Measurement Science Conference, Irvine, CA, January 1986.

P. L. Gould, "Momentum Transfer to Atoms from Light," Helsinki Summer School on Cooling and Trapping, Helsinki, Finland, 1986.

P. L. Gould, "Experiments with Stopped Atoms," Helsinki Summer School on Cooling and Trapping, July 1986.

J. R. Kinard, "AC-DC Difference Calibrations at NBS," 1986 Measurement Science Conference," Irvine, CA, January 1985.

H. J. Metcalf, "Electromagnetic Trapping of Neutral Atoms," International Quantum Electronics Conference, San Francisco, CA, June 1986.

H. J. Metcalf, "Magnetic Traps," Helsinki Summer School on Cooling and Trapping, Helsinki, Finland, July 1986.

A. L. Migdall, "Models, Magnets and Molasses," Helsinki Summer School on Cooling and Trapping, Helsinki, Finland, July 1986.

A. L. Migdall, "Laser Cooling of Atom/Ion Beams," Workshop on Atomic Physics with Stored Cooled Heavy Ion Beams, Oak Ridge, TN, January 1986.

W. D. Phillips, "Trapped and Laser-cooled Particles," Committee on Atomic and Molecular Science Workshop on the Laser-Atomic Frontier, National Academy of Sciences, Washington, D.C., October 1985.

W. D. Phillips, "Laser Cooling and Electromagnetic Trapping of Neutral Atoms," Plenary Session, First International Laser Science Conference, Richardson, TX, November 1985.

W. D. Phillips, "Cooling, Stopping and Trapping Atoms," Physics Department Colloquium, University of Chicago, December 1985.

W. D. Phillips, "Cooling, Stopping and Trapping Atoms," Physics Department Colloquium, University of Iowa, January 1986.

W. D. Phillips, "Early History of Light Pressure," Helsinki Summer School on Cooling and Trapping, Helsinki, Finland, July 1986.

W. D. Phillips, "Experimental Techniques for Laser Cooling Atomic Beams," Helsinki Summer School on Cooling and Trapping, Helsinki, Finland, July 1986.

W. D. Phillips, "Stopping and Trapping Atoms," Helsinki Summer School on Cooling and Trapping, Helsinki, Finland, July 1986.

R. L. Steiner, "Maintenance of the U.S. Legal Volt using Josephson Junction Devices," 1986 Measurement Science Conference, Irvine, CA, January 1986.

B. N. Taylor, "History of the Present Value of 2e/h Commonly Used for Defining National Units of Voltage and Possible Changes in National Units of Voltage and Resistance," Conference on Precision Electromagnetic Measurements, National Bureau of Standards, Gaithersburg, MD, June 1986.

C. T. Van Degrift, "The New NBS Quantum Hall Effect Laboratory," Low Temperature Physics Seminar, Cornell University, Ithaca, New York, May 1986.

Publications FY 86

1. <u>In Print</u>

P. L. Gould, G. A. Ruff, and D. E. Pritchard, "Diffraction of Atoms by Light: The Near-Resonant Kapitza-Dirac Effect," Phys. Rev. Lett. 56, 827 (1986).

C. A. Hamilton, R. L. Kautz, R. L. Steiner, and F. L. Lloyd, "A Practical Josephson Voltage Standard at 1 V," IEEE Trans. Electron Device Lett. 6-12, 623 (1985).

J. R. Kinard, E. S. Williams, and T. E. Lipe, "Automated Thermal Voltage Converter Intercomparisons," Proc. IEEE 74, 105 (1986).

A. Migdall, T. Bergeman, J. Dalibard, H. Metcalf W. Phillips, J. Prodan and I. So, "Cooling, Stopping and Trapping Atoms," in Laser Spectroscopy VII, Ed. by T. Hansch and Y. Shen (Springer-Verlag, Berlin, 1985), p. 10.

A. L. Migdall, "Laser Cooling of Stored Beams," in Proceedings of the Workshop on Atomic Physics with Stored Cooled Heavy Ion Beams, (National Technical Information Service, 1986) CONF-860144, p. G-1.

J. Niemeyer, L. Grimm, C. A. Hamilton, and R. L. Steiner, "High Precision Measurement of the Resistive Slope of Josephson Array Voltage Standards," IEEE Tran. Electron Device Lett., 7-1 44 (1986).

W. D. Phillips, "Laser Cooling and Trapping Neutral Atoms," Ann. Phys. Fr. 10, 717 (1985).

W. D. Phillips, J. V. Prodan, and H. J. Metcalf, "Laser-cooling and Electromagnetic Trapping of Neutral Atoms," J. Opt. Soc. Am. B2, 1751, (1985).

W. D. Phillips, A. L. Migdall and H. J. Metcalf, "Laser Cooling and Electromagnetic Trapping of Neutral Atoms, in Advances in Laser Science I, Eds. by W. Stwalley and M. Lapp (AIP Conference Proceedings No. 146, New York, 1986) p. 362.

W. D. Phillips, "Trapped and Laser Cooled Particles," in Physics at the Laser-Atomic Frontier, (National Academy Press, Washington, 1986), p. 21.

N. N. Tadros and L. B. Holdeman, "Thin Film Cryogenic Resistors from Aluminum Alloys," Cryogenics 25, 709 (1985).

B. N. Taylor, "Possible Changes in the U.S. Legal Units of Voltage and Resistance," NCSL Newsletter 25, No. 3, 12 (Sept. 1985); PMA Newsnotes Vol. II, 15 (1985).

2. <u>In Press, In Review, or Nearing Completion</u>

L. S. R. Becker, B. F. Field, and T. E. Kiess, "Ten Volt Round-Robin Test Conducted on a Solid-State DC Voltage Standard," IEEE Trans. Instrum. Meas., to be published.

M. E. Cage, The Quantum Hall Effect, Chapter II: "Experimental Aspects and Metrological Applications of the Integer Quantum Hall Effect," Eds. R. E. Prange and S. M. Girvin (Springer-Verlag: Berlin), in press.

M. E. Cage, R. F. Dziuba, B. F. Field, T. E. Kiess, and C. T. Van Degrift, "Monitoring the U.S. Legal Unit of Resistance via the Quantum Hall Effect," IEEE Trans. Instrum. Meas., IM-36, to be published 1987.

G. M. Free and A. Muciek, "An Unbalanced Bridge Technique for Comparing Impedance Standards," in preparation.

C. A. Hamilton, R. L. Kautz, F. L. Lloyd, R. L. Steiner, and B. F. Field, "The NBS Josephson Array Voltage Standard," IEEE Trans. Instrum. Meas. IM-36, to be published 1987.

F. L. Hermach, J. R. Kinard, and J. R. Hastings, "Multi junction Thermal Converters as the NBS Primary AC-DC Transfer Standards for AC Current and Voltage Measurements," IEEE Trans. Instrum. Meas. IM-36, to be published 1987.

K. B. Jaeger and B. N. Taylor, "U.S. Perspective on Possible Changes in the Electrical Units," IEEE Trans. Instrum. Meas., IM-36, to be published 1987.

H. J. Metcalf and W. D. Phillips, "Laser Cooling and Magnetic Trapping of Atoms," submitted to McGraw-Hill Yearbook of Science and Technology.

H. J. Metcalf and W. D. Phillips, "Electromagnetic Trapping of Neutral Atoms," to appear in Metrologia.

H. J. Metcalf and W. D. Phillips, "Cooling and Trapping Atoms," in preparation for Scientific American.

W. D. Phillips, A. L. Migdall, P. L. Gould, and H. J. Metcalf, "Laser Cooling and Trapping Neutral Atoms," in preparation for Science.

B. W. Ricketts and M. E. Cage, "Quantized Hall Resistance Measurements at the National Measurement Laboratory, Australia," IEEE Trans. Instrum. Meas., IM-36, to be published 1987.

B. N. Taylor, "History of the Present Value of 2e/h Commonly Used for Defining National Units of Voltage and Possible Changes in National Units of Voltage and Resistance," IEEE Trans. Instrum. Meas. IM-36, to be published 1987.

B. N. Taylor, "Possible Changes in the Electrical Units," J. Res. Natl. Bur. Stand. 91, to be published 1986.

Technical and Professional Committee Participation and Leadership

N. B. Belecki, member, ANSI S82, American National Standards Institute Committee on Electrical Standards, Instrumentation, and Devices.

N. B. Belecki, member, National Conference of Standards Laboratories Measurement Assurance Committee.

N. B. Belecki, member, National Working Group, OIML (International Organization of Legal Metrology) Pilot Secretariat 13, Measurement of Electrical and Magnetic Quantities; and Co-chairman, U.S. National Working Group, OIML (International Organization of Legal Metrology) Reporting Secretariat 13.1, International Compatibility of National Primary Standards Used for Instrument Verification.

N. B. Belecki, member, TC-2, DC and LF Standards, Instrumentation, and Measurements Committee of the Instrumentation and Measurement Society, Institute of Electrical and Electronics Engineers (IEEE).

N. B. Belecki, member, National Conference of Standards Laboratories Measurement Requirements Committee.

N. B. Belecki, member, National Conference of Standards Laboratories Education Liaison Committee.

G. M. Free, member, ASTM E7, American Society for Testing and Materials, Nondestructive Testing; ASTM E7, SC.7, Electrical and Magnetic Methods (vice chairman); E7, SC.9, Materials Inspection and Testing Laboratories; E7, SC.9, Editorial Review; E7, SC7.02, Glossary (chairman); E7, SC7.01, Nonmagnetic Applications (chairman).

G. M. Free, secretary, American Society for Nondestructive Testing, C2, Electrical and Magnetic Methods Committee

G. M. Free, member, American Society for Nondestructive Testing, C2, Electrical and Magnetic Methods Committee.

J. R. Hastings, member, TC-2, DC and LF Standards, Instrumentation, and Measurements Committee of the Instrumentation and Measurement Society, Institute of Electrical and Electronics Engineers (IEEE).

J. R. Kinard, member, TC-2, DC and LF Standards, Instrumentation, and Measurements Committee of the Instrumentation and Measurement Society, Institute of Electrical and Electronics Engineers (IEEE).

W. D. Phillips, member, NBS Research Advisory Committee.

W. D. Phillips, member, Steering Committee for the NBS Discussion Group on Atomic Physics.

W. D. Phillips, member, Editorial Board of Progress in Quantum Electronics.

W. D. Phillips, member, Advisory Committee on Fundamental Constants of the Division of Chemistry and Chemical Technology, Numerical Data Advisory Board, National Academy of Sciences/National Research Council/National Academy of Engineering.

W. D. Phillips, member, Steering Committee of the American Physical Society Topical Group on Laser Science.

B. N. Taylor, member, Advisory Committee on Fundamental Constants of the Division of Chemistry and Chemical Technology, Numerical Data Advisory Board, National Academy of Sciences/National Research Council/National Academy of Engineering.

B. N. Taylor, Chairman, NBS Precision Measurement Grants Committee.

B. N. Taylor, NBS representative, Consultative Committee on Electricity (CCE), International Committee on Weights and Measures.

B. N. Taylor, member, ANSI C-42, American National Standards Institute Committee on Definitions of Electrical Terms.

B. N. Taylor, member CODATA (Committee on Data for Science and Technology Task Group on Fundamental Constants.

B. N. Taylor, Technical Advisor (Chairman, U.S. National Working Group) OIML (International Organization of Legal Metrology) Pilot Secretariat 13, Measurement of Electrical and Magnetic Quantities; and Co-chairman, U.S. National Working Group, Reporting Secretariat 13.1, International Compatibility of National Primary Standards Used for Instrument Verification.

B. N. Taylor, NBS representative to Conference on Precision Electromagnetic Measurements (CPEM) Executive Committee and Comptroller, CPEM.

Collaborations, Consulting, Miscellaneous Activities

N. B. Belecki and R. F. Dziuba are collaborating with metrologists from six Southern California Companies (Beckman Instruments, Electrical Standards Repair Service, Ford Aerospace & Communications, Lockheed of California, Rockwell International Anheim, and TRW) in a pilot experiment to develop metrology for a "self-help" group MAP in resistance. The goal is a procedure by which companies could set up and run their own MAP, including data reduction and error analysis, using NBS's calibration services and their own transport standards. Some of the equipment is being furnished by the NCSL Measurement Assurance Committee.

N. B. Belecki served as Chairman of the Technical Program Committee of the 1986 Conference on Precision Electromagnetic Measurements held at NBS in June, 1986.

M. E. Cage, C. T. Van Degrift, R. F. Dziuba, and B. F. Field are collaborating with S. M. Girvin of the Surface Science Division (541) on the theoretical aspects of the quantized Hall resistance experiment.

M. E. Cage, C. T. Van Degrift, R. F. Dziuba, and B. F. Field are collaborating with D. C. Tsui of Princeton University, and A. C. Gossard and H. L. Stormer of Bell Laboratories, on quantized Hall resistance measurements of GaAs-AlGaAs heterojunctions.

M. E. Cage, C. T. Van Degrift, R. F. Dziuba, and B. F. Field are collaborating with M. Razeghi of Thomson-CSF, France, on quantized Hall resistance measurements of GaInAs-InP heterojunctions.

M. E. Cage, C. T. Van Degrift, R. F. Dziuba, and B. F. Field are collaborating with E. Mendez of IBM on quantized Hall resistance measurements of GaSb-InAs heterojunctions.

R. F. Dziuba served as Editor of the Program Digest for the 1986 Conference on Precision Electromagnetic Measurements held at NBS in June, 1986.

B. F. Field is collaborating with a number of companies (John Fluke Mfg. Co., National Semiconductor, Standard Reference Labs) on the evaluation of improved solid-state voltage standards.

B. F. Field and T. E. Kiess are collaborating with personnel from the DoD Primary Standards Laboratories (Redstone Arsenal, North Island Naval Air Station, Washington DC Navy Yard, Newark Air Force Station) on the use of commercial 10 V solid-state voltage standards as MAP transfer devices.

G. M. Free is collaborating with N. M. Oldham of the Electrosystems Division, CEEE, NEL, on the design, construction, and testing of binary inductive voltage dividers.

G. M. Free provided technical quidance and advice to Reynolds Aluminum Company researchers on the design and construction of eddy current instrumentation.

P. L. Gould is collaborating with the group of D. E. Pritchard at MIT on the deflection of atomic beams by light.

T. E. Kiess collaborated with N. Erickson of the Surface Physics Division on the precise measurement of high-voltage surface potentials.

J. R. Kinard is collaborating with personnel from the Navy Metrology Engineering Center, Pomona, CA, and the John Fluke Mfg. Co. on the evaluation of solid-state thermal converters.

J. R. Kinard is collaborating with personnel from the Navy Metrology Engineering Center, Pomona, CA, and Ballantine Laboratories on the evaluation of automatic programmable ac to dc converter instruments.

J. R. Kinard is collaborating with N. M. Oldham, NBS Electrosystems Division, Center for Electrical and Electronics Engineering (CEEE), NEL, in the study of possible transport standards of ac voltage and current.

P. T. Olsen is collaborating with personnel of the Navy's Primary Standards Laboratory, East (Washington Navy Yard) on the calibration of magnetometers.

W. D. Phillips is collaborating with M. G. Littman of Princeton University on the spectroscopy of Rydberg atoms in electric fields and applications to the measurement of the fine-structure constant.

W. D. Phillips is collaborating with J. Dalibard and C. Cohen-Tannoudji of Ecole Normale Superieur, Paris, on the laser trapping of neutral atoms.

W. D. Phillips is collaborating with H. J. Metcalf, I. So and T. Bergeman of S.U.N.Y. at Stony Brook on laser deceleration (cooling) and magnetic trapping of sodium atoms.

W. D. Phillips, A. L. Migdall, and P. L. Gould are collaborating with H. J. Metcalf of SUNY, Stony Brook, on laser cooling and magnetic trapping of atoms.

W. D. Phillips served as the American organizer of the Helsinki Summer School on Laser Cooling and Trapping.

W. D. Phillips organized two sessions on trapping and cooling for the Second International Laser Science Conference, Seattle, October 1986.

W. D. Phillips is serving as a member of the Program Committee for IQEC 87.

R. L. Steiner and B. F. Field are collaborating with C. A. Hamilton, R. L. Kautz, and F. L. Loyd of the Cryoelectronics Group of the Electromagnetic Technology Division, CEEE, NEL, NBS/Boulder, and J. Niemeyer of the Physikalisch-Technische Bundesanstalt, West Germany, on the development of 1 V Josephson array voltage standards.

R. L. Steiner and B. F. Field, with C. A. Hamilton of NBS/Boulder, is collaborating with K. Jeager, Lockheed Missles & Space Co., B. Barnaby, Sandia Laboratories, and G. Trinite, Navy Metrology Engineering Center, Pomona, CA, on the construction of and operational procedures for Josephson array voltage standards at their respective laboratories.

B. N. Taylor is collaborating with E. R. Cohen, Rockwell International, and the CODATA Task Group on Fundamental Constants, on a new least-squares adjustment of the fundamental physical constants to be completed in 1986 for international adoption by CODATA.

J. Toots is collaborating with Kim In Seon, Korean Standards Research Institute, on the implementation of a Josephson voltage standards at KSRI by fabricating Josephson tunnel junctions.

E. R. Williams is collaborating with H. Nakamura of the Electrotechnical Laboratory (ETL), Japan on their proton gyromagnetic ratio and absolute ampere experiments. He has received a research fellowship from the Japanese Industrial Technology Association for a two month stay at ETL to support the collaboration.

E. R. Williams is collaborating on the realization of the SI volt with Prof. V. Bego of the Electrotechnical Institute, University of Zagreb, Yougoslavia under the Joint U.S. Yugoslavia Joint Board on Science and Technology.

TEMPERATURE AND PRESSURE DIVISION
SUMMARY OF ACTIVITIES
FISCAL YEAR 1986

I. HIGH TEMPERATURE SCALE RESEARCH
(M. Reilly, J. Schooley, R. Edsinger, and W. Bowers)

The temperature range covered here extends from 904 K (the upper limit of the platinum resistor scale) to approximately 2400 K (the approximate upper limit of NBS thermocouple calibrations). This temperature range is presently defined by standard thermocouples and radiation thermometers using the Planck Law. For a variety of technical reasons, errors in temperature measurement using these devices can become unacceptably large (as much as 0.5 K for standard thermocouples, as large as 3 K for Planck-Law radiation thermometers). Accordingly, the Division has initiated a program to address this problem. The goal is to develop a temperature scale accurate to 20 ppm by comparing two instruments based on two physical laws: the ideal gas law and the Planck radiation law. A further consideration is to develop transfer standards based on special platinum resistance thermometers or on the optical fiber thermometer. Development of the optical fiber thermometer using the Planck radiation law is coordinated with the other Division projects - gas thermometry and high-temperature PRT's - as will be explained below.

I.A. OPTICAL FIBER THERMOMETER

The goals of the Optical Fiber Thermometer (OFT) program are to (I) establish accurate values for the thermodynamic temperature of the thermometric fixed points, silver (962 °C) and gold (1064 °C), relative to that of aluminum (660 °C) and to (II) provide a means of interpolating temperature between these fixed points with an uncertainty not exceeding 20 ppm. Through its development and use as a primary thermometer, we hope that the OFT can provide the basis for the formulation of a more accurate temperature scale over the interval 630 to 1064 °C.

The OFT, as offered commercially at this time, is a self-contained measurement system with a high-temperature probe of single-crystal sapphire rod (nominally 1 mm diameter and 30 cm long) with a metallic blackbody cavity sputtered on its tip. The low-temperature end of the probe is coupled directly to a silicon photodiode detector via a compound narrow-band interference filter (nominally an 800 nm peak wavelength with a 100 nm bandwidth). When the cavity is heated, the radiant flux emitted within the narrow wavelength band can be used to determine its temperature. Since the temperature ratio is determined by a fundamental physical law (Planck law), the OFT is capable of measuring thermodynamic temperatures over its entire useful range (perhaps 600 to 1600 °C) using one calibration point.

The OFT being studied in the current NBS program <u>does not</u> have the metallic cavity on the tip of the high-temperature probe. As a consequence, this version of the OFT is rather like an optical pyrometer having a long slender lens which penetrates directly into the hot zone to capture and transmit the radiant flux. There are two reasons for choosing this configuration: (1) the OFT will be used with existing Division thermometric blackbody sources so that the metallic cavity is unnecessary and (2) we want to eliminate any error associated with the unknown (at present) thermal radiative properties of the metal-to-sapphire interface that forms the sputtered cavity.

There are three major sources of error which limit the accuracy with which the OFT can measure thermodynamic temperature. In order of their importance these are: (1) uncertainties in the optical properties of the probe, (2) uncertainties in the spectral response characteristics of the optical system (particularly the interference filter and detector), and (3) uncertainties in the linearity of the detector and the associated electronic circuitry.

The optical properties of the probe that lead to temperature errors in measurement are: (a) the reflectivity at the air-to-sapphire interface, (b) the attenuation of the transmitted radiant flux due to absorption in the probe, and (c) loss of the transmitted flux (and likely gain of unwanted background flux) due to scattering at the cylindrical surface of the probe. These properties must be known for the temperature range of interest as well as for the wavelength range within the passband of the interference filter.

Concerning the first problem, the reflectivity at the air-to-sapphire interface relative to that at room temperature has been determined for temperatures from 400 to 1060 °C and for wavelengths of 633 and 799 nm. The results were published in May 1986. This leaves two remaining problems.

At present, we believe that dominant source of error is that due to scattering and self-emission processes which occur <u>near the cylindrical surface</u> of the rod. Rods are cut from single-crystal sapphire boules and then centerless ground to approximate diameter before the cylindrical surface is finished by either mechanical or flame polishing procedures. The grinding process leaves a finite damage layer of complex microfractures which propagate in the material to a depth (perhaps to several hundred micrometers) which depends upon the details of the operation. This damage layer, which is the major cause of the scattering and self-emission, must be eliminated.

Since 1983, when the program began, the two principal fabricators of sapphire rods have been steadily improving the quality of their product, especially the surface finish. Several new sapphire rods were tested during FY86. The best of these (finished by the Accufiber Corp.) exhibited scattering/self-absorption properties which are an order of magnitude less than any sapphire rod previously tested. The rod was comparable in quality to the best synthetic vitreous silica rods we have tested. Even better results are expected from new rods which are being prepared from a sapphire boule that is grown by a different method--one which is known to yield material having significantly less bulk scattering.

Through FY'86, the results of these scattering/self-absorption tests have been qualitative, allowing the characteristics of the various rods to be compared relative to one another. A new experimental method, designed to quantify the error due to scattering, is now being set up and tested. A state-of-the-art experiment to determine the linearity of the OFT detector is also being assembled.

Before July 1986, all experimental work on the OFT program was done in temporary laboratory space provided by the Radiometric Physics Division (534). A new, permanent laboratory is now being set up for the OFT program in the Temperature and Pressure Division space.

I.B. HIGH-TEMPERATURE GAS THERMOMETRY

This project involves the evaluation of the differences between the Kelvin Thermodynamic Temperature Scale (KTTS--the scale that unifies all scientific measurements involving temperature) and the International Practical Temperature Scale of 1968 (IPTS-68). The region of interest is 457 °C to 660 °C, connecting gas thermometry reported earlier from NBS (L. A Guildner and R. E. Edsinger, J. Res NBS, 80A, 703, 1976) with the range wherein spectral radiation thermometry can provide equivalent thermometric accuracy. The resulting thermodynamic data will provide the basic information needed to replace the IPTS-68 with a superior temperature scale.

During the past fiscal year, we completed a set of measurements over the intended range using a 0-°C gas-bulb filling pressure of 13.5 kPa. Use of this pressure kept the corrections for both gas imperfection and thermal transpiration below 30 mK. The much larger correction resulting from thermal expansion of the gas bulb was estimated on the basis of earlier thermal expansion measurements. The determinations of t(KTTS) - t(IPTS-68) derived in this fashion are shown in the accompanying figure.

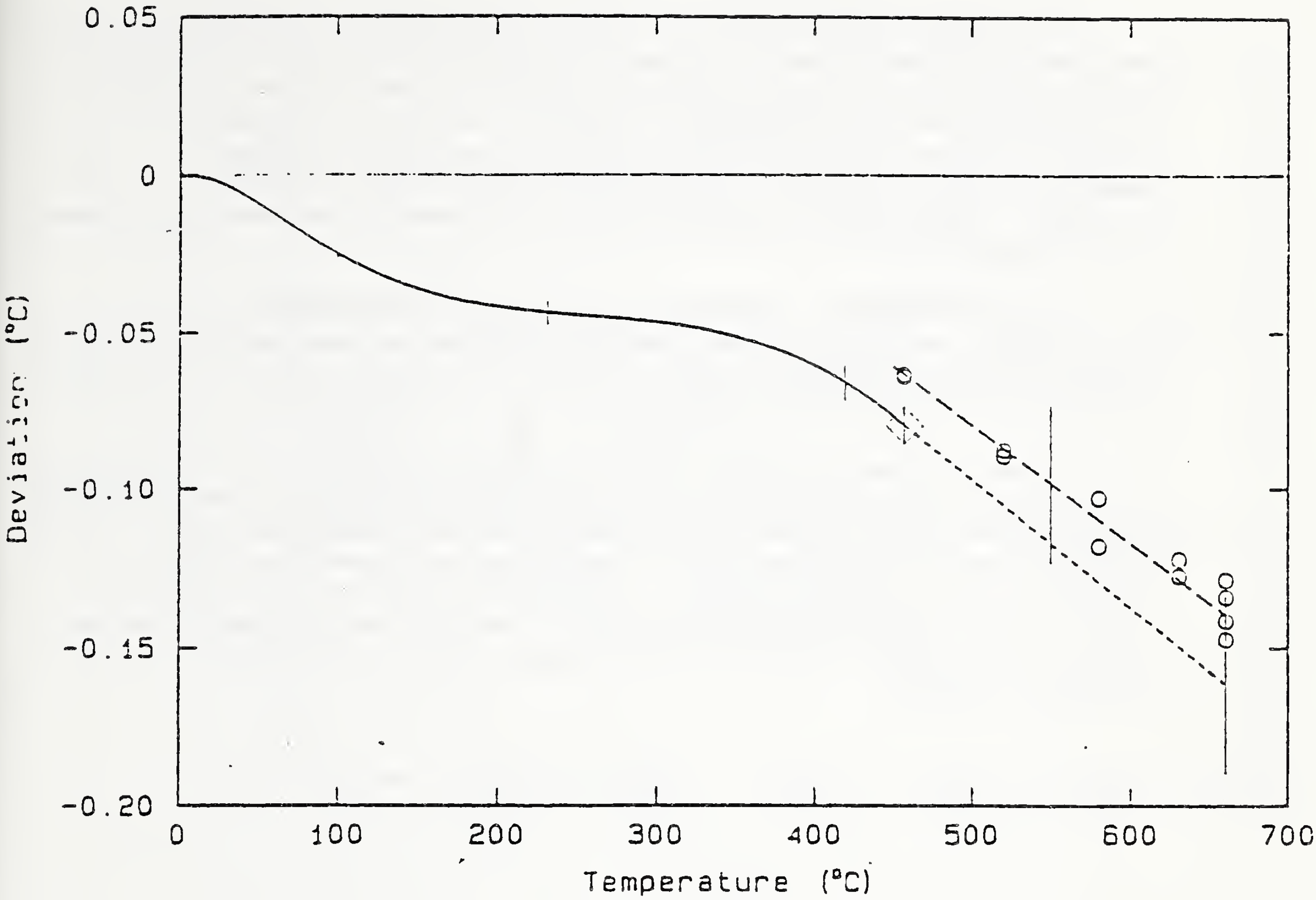


Fig. 1. Solid Curve - Guildner-Edsinger Gas Thermometry (NBS)

Dotted Curve - Jung-Radiation Thermometry (PTB)

Dashed Curve & Circles - Edsinger-Schooley Latest Gas Thermometry (NBS)

The figure shows the small (15 mK) discrepancy between the present NBS results at 457 °C and the results published previously from NBS. It also shows the close agreement between the present results and those of Jung (PTB Berlin) obtained by spectral radiation thermometry (H. J. Jung, Metrologia, 20, 67, 1984); had Jung selected the recent determination of the 457 °C difference rather than the earlier one as his basis temperature, his results and the present ones would have been indistinguishable.

We have prepared a report on the present results for publication. The stated uncertainty of the results, ± 20 mK, arises mainly from our uncertainty regarding the proper values of thermal expansion to employ in correcting the gas-bulb pressure ratios.

In the process of examining existing data on the thermal expansion of the gas-bulb materials, we have prepared a publication that provides for the first time details of the apparatus and techniques used in this work some years ago. Included in the discussion are data obtained on 100% Pt, on Pt/12 wt% Rh, and on Pt/20 wt% Rh over the range -20 °C to 560 °C. The relatively high quality of the data can be seen from the accompanying figure showing the deviations of the data from the fitted curve for 100% Pt.

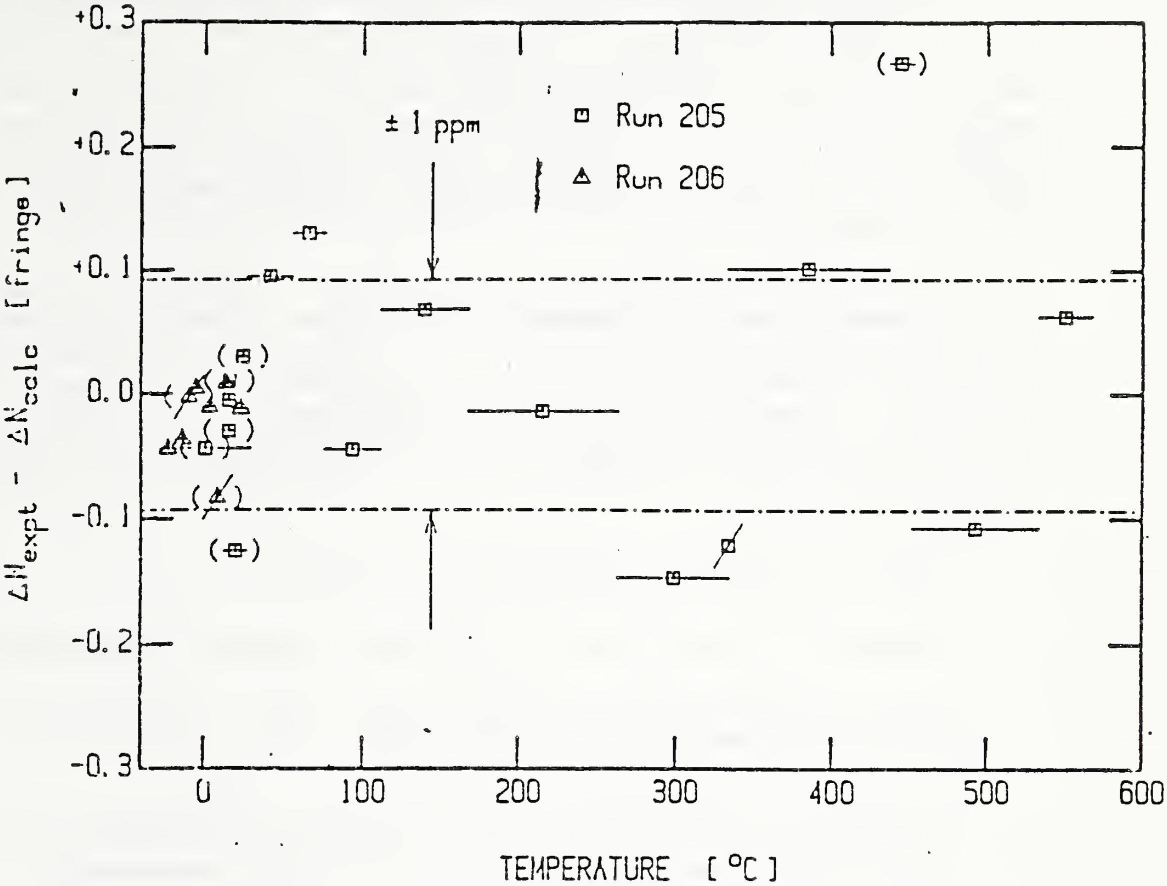


Fig. 2. Deviation of a fourth order polynomial fit to the measured thermal expansion of Pt. Data from two separate measurements (Run 205 and 206) are shown. The fit is seen to be within 1 ppm.

Because of the extreme sensitivity of our gas thermometry results to the thermal expansion of the gas bulb, we intend to measure the thermal expansion of several samples of the Pt-Rh alloy gas bulb which was used to obtain the results shown in Fig. 1. To that end, we have begun to re-activate the thermal expansion measurement apparatus. This process mainly involves upgrading the equipment by introducing a heat pipe into the furnace of the apparatus. At the present time, the heat pipe has been procured and the furnace modification has been started.

In response to a long-standing need for a comparison between a high-accuracy pressure reference and the gages currently in use in the NBS piston-gage calibration program, we have provided access to the Gas Thermometer manometer system and have collaborated with Pressure Group personnel in accomplishing an extensive comparison. The activity has been pursued over a five-month period; it has resulted in a significant advance in the level of understanding of piston-gage calibration (see Section VI.B.).

Our plans for FY'87 include the following:

Complete the rebuilding of the thermal expansion apparatus;

Test the apparatus and re-measure the thermal expansion of one or more samples measured earlier;

Coincident with the first two activities, complete gas thermometric measurements using lower filling pressures and lower furnace temperatures. Completing these measurements will permit us to examine the adequacy of present thermal transpiration corrections and to examine further the level of agreement between the present procedures and those used in earlier NBS gas thermometry;

Dismantle the present gas-bulb system; cut and measure thermal expansion samples from the gas bulb; and evaluate the thermal transpiration correction for the gas-bulb capillary by direct measurement.

I.C. HIGH-TEMPERATURE PLATINUM RESISTANCE THERMOMETRY

The purpose of this project is to develop high-temperature platinum resistance thermometry as a long needed and more precise replacement for thermocouple thermometry in defining a practical temperature scale. The program consists of the design and testing of thermometers, electrical measuring systems, thermometric fixed points, and interpolating formulations, with the goal of achieving 10 mK or less uncertainty over the full range 630 to 1064 °C. The retirement of

John Evans has brought this NBS project to a halt. NBS will depend on other national standards labs to continue this research.

II. INTERNATIONAL PRACTICAL TEMPERATURE SCALE (IPTS-68)

(B. Mangum, G. Burns, M. Scroger, W. Bigge, J. Wise, G. Evans, E. Pfeiffer, and G. Furukawa)

II.A. THERMOCOUPLES

These cover the range from 273K to 2400K; the thermocouple laboratory is managed by G. W. Burns with the assistance of M. G. Scroger. The activities generally fall into two categories: routine calibrations and non-routine tests.

1. Routine Calibrations.

Approximately 220 thermocouples were calibrated for 100 customers during FY86 producing approximately $100 k in test fees.

Documentation of the procedures, apparatus, and uncertainties involved in thermocouple and thermoelement calibration services offered by NBS was completed this FY. The document covers calibrations over the range −196 to 2100 °C for all commonly used types of thermocouples and thermocouple materials including the new automatic thermocouple calibration system used for all type S, R, and B thermocouples calibrated by comparison with a reference thermocouple.

2. Non-routine tests.

a. IMGC-NBS Collaboration on Tungsten-Rhenium Thermocouples.

As part of a continuing program of scientific cooperation between the NBS and the Instituto di Metrologia "G. Colonnetti" (IMGC) in Torino, Italy, a transfer standard optical pyrometer was constructed at the IMGC by Dr. Righini for the NBS Temperature and Pressure Division. Construction of the new pyrometer was completed early in 1986, and it was subjected to extensive evaluation tests at the IMGC. This instrument, which has two interference filters (one at 655 nm and a second at 900 nm) was subsequently calibrated at the IMGC and delivered to the NBS in July. Mr. G. C. Bussolino of the IMGC came to NBS in mid-September to assist G. W. Burns with the initial setup and operation of the instrument. During Bussolino's 4-week stay at NBS, he and G. Burns will be working primarily on assembling the hardware needed for pyrometer measurements, checking the calibration of the instrument against NBS standards, and developing the software required for pyrometer operation. This instrument, when fully operational, should greatly enhance the capabilities of the NBS thermocouple calibration laboratory for achieving improved thermocouple standards at temperatures above 1000 °C.

b. ASTM Committee Work.

To assist ASTM Committee E20.04.02 with the development of a new standard specification covering NiCrSi/NiSi thermocouple wire (Type N), some emf stability tests with Type N and Type K thermocouples made from 0.128, 0.064, and 0.032 inch diameter wires were carried out in accordance with procedures specified in Draft No. 3 of the proposed ASTM standard, E20-D-16. The changes in the emf of Type N and Type K thermocouples were determined during heating in air for 24 hours at 1250 °C, as described in section 5.3.5.3 of the proposed standard. The emf changes of the Type N and Type K thermocouples were also determined when they were thermally cycled between room temperature and 550 °C, as described in section 5.3.5.2 of the proposed standard.

The Type N thermocouple wires were furnished for the emf stability tests by three manufacturers of base-metal thermocouple alloys: Driver-Harris Alloys, Inc.; Hoskins Manufacturing Company; and Carpenter Technology. One of the manufacturers also provided samples of Type K thermocouple wires to include in the tests for purposes of comparison.

The measured changes in the Type N thermocouples of all three wire sizes after heating them for 24 hours at 1250 °C in air were found to be less than the allowable change of 0.200 mV specified in the proposed standard. However, the changes in the emf of Type N thermocouples made from the 0.032 and 0.064 diameter wires measured at 550, 400, and 300 °C after heating them for 1 hour in air at 550 °C, exceeded, in some cases, the allowable change of 0.015 mV specified in the proposed standard.

A detailed report covering the test procedures, apparatus used, and the results obtained was prepared, and it was presented at the ASTM Committee E20.04.02 meeting on May 14, 1986, in Philadelphia. The results of the tests were reviewed by the Committee and were used to make modifications in the test procedures and requirements specified in the standard. The Committee requested that the NBS conduct similar tests with Type N thermocouples made from smaller diameter wires to obtain test data to allow broadening the scope of the standard specifications.

3. Thermometry for Jet Engines

This project was initiated in May of 1984 with support from the U. S. Navy Metrology Engineering Center. The overall objectives are 1) to investigate and evaluate present Department of Defense calibration support of jet engine temperature measurements, 2) to provide a comprehensive report that details the present system and demonstrates several alternative methods to provide the calibration support required, and 3) to develop the support system that is mutually agreed upon to optimize performance by means of automation. The essential task is to develop reliable standards and procedures for the accurate calibration of JETCAL heater probes, which are small electrically-heated furnaces specially designed to test the thermal response of jet engine thermocouples. The probes are required to be calibrated with an accuracy of ±4 °C or better at a temperature usually near 600 °C.

During the first year of the program, NBS examined the calibration and use of JETCAL heater probes both by the Navy and by the various jet engine manufacturers. In 1985 we submitted a report which outlined our findings and recommended both long- and short-range goals for upgrading procedures and improving the accuracy of the calibration of the heater probes. We subsequently developed a priority listing of those probes for which there is a definite need for calibration standards of improved reliability. We also proposed that we investigate possible causes of the unsatisfactory results obtained with several probes known to be difficult to calibrate.

In March 1986, NBS was asked to develop a calibration procedure for one of the JETCAL heater probes selected from that list (Howell Instruments, BH 14101-40). This heater probe is specifically designed to test the thermocouple harness of T400-CP-400 and T400-WV-402 jet engines which power the Navy UH-1N and the Marine Corps AH-1J helicopters. The harness itself is composed of eight matched sheathed thermocouples that are connected in parallel. A complete test of the performance of the harness requires eight heater probes operating simultaneously. The BH 14101-40 heater probe is particularly difficult to calibrate because it has an immersion depth of about one inch and the specified calibration temperature is 900 °C.

We are developing a two-piece standard thermocouple assembly. One piece is the thermocouple itself which, except for length, will be made to the exact specifications of the thermocouples in the T400 harness. The length of 18 inches will guarantee that the thermocouple can be calibrated in the tin, zinc, aluminum, and silver freezing-point cells without significant immersion errors. The second piece is an adapter which will be attached to the thermocouple after calibration. It will provide proper immersion as well as insure that the whole assembly matches the thermal loading of the T400 thermocouple. In this way, the proper heat balance will be obtained when the assembly is inserted into the JETCAL heater probe during its calibration.

Although the active element in the T400 harness thermocouple is Type K wire (Chromel-Alumel), we plan also to test standard thermocouples made from Type N (Nicrosil-Nisil) wire; it should be more stable than the Type K thermocouples. We are also testing a single engine thermocouple (i.e. not a part of a harness) which not only matches the external dimensions but also has the same location of its measuring junction relative to the sheath end closure as do the individual thermocouples of the T400 harness. We want to investigate the suitability of these latter thermocouples as secondary standard instruments.

II.B PLATINUM RESISTANCE THERMOMETRY

The objectives of this program are (1) to maintain the IPTS-68(75) in the range 13 K to 904 K (the region of the scale in which the standard instrument is the SPRT); (2) to make improvements in the realization of that scale; (3) to disseminate the scale (through calibrations, precision measurement seminars, MAPs, lectures, publications, interactions with standards-writing organizations, etc.); and (4) to prepare for a new international temperature scale.

The following table outlines the SPRT calibration procedure.

SPRT Calibration Procedure

13 K to 500 K	Capsule SPRTs	Calibrations by comparison against reference standards
78 K to 904 K	Long-Stem SPRTs	Calibrations by comparison against reference standards at 90 K and by use of fixed points (TP H_2O, Sn, and Zn).

In the future, capsule PRTs will be calibrated in the EPT-76 automated laboratory, although during this fiscal year some were calibrated in the manually-operated calibration system in the PRT laboratory.

The new semi-automated laboratory for long-stem PRTs is still under construction.

Some specific accomplishments this FY include:

(1) Dr. G. T. Furukawa completed the analysis of data obtained on the triple point of oxygen. A paper on the results was submitted to the NBS Journal of Research and is in the galley-proof stage.

(2) The documentation of the platinum resistance thermometer calibration service was completed.

(3) The remaining apparatus and electronic equipment required for modernization and semi-automation of the SPRT Calibration

Laboratory were ordered. Most but not all of these have been received.

(4) Tin and zinc fixed-point cells are used in the calibration of SPRTs. Since there is a critical shortage of these in the PRT Laboratory, construction of several new cells of each were begun. Crucibles for 9 new cells (7 for long-stem and 2 for capsule SPRTs) of tin and for 7 new cells of zinc were filled with 99.9999+ % pure metals (SRMs 741 and 740, respectively). The remaining part of the preparation and the testing of the new cells will be completed next year.

(5) A new zinc-point, 3-zone furnace was put into operation in the PRT Calibration Laboratory, replacing one that had burned out.

(6) Evaluation of three new SPRTs suitable for use to the silver point and purchased from Chino Works America, Inc. was begun. One of these is being used in evaluating some lower-accuracy high-temperature PRTs on a contract with the Navy and the others are undergoing a general evaluation as stable precision thermometers.

(7) The design of a new apparatus, incorporating an argon triple-point cell, that is to be used in the calibration of long-stem and capsule SPRTs was completed. The apparatus has been under construction by the NBS shops. This apparatus will accommodate 7 long-stem SPRTs and 6 capsule SPRTs. When construction of this apparatus is completed and it has been tested, it will replace the comparison apparatus currently used at the oxygen point.

(8) We have a continuing MAP on calibration of SPRTs. A MAP was completed this year with the Boeing Aerospace Company.

(9) Since the zinc-point furnace burned out last year, there was only one operating furnace left for use with both the tin and zinc cells prior to March 1986. Nevertheless, as of the end of August of FY86, there were 22 calibrations of the type 7.3B and 47 of the type 7.3C, for a total of 69 long-stem SPRTs calibrated. In addition, we have on hand 10 SPRTs for the type 7.3B calibration and 5 SPRTs for the type 7.3C calibration. Furthermore, 4 capsule PRTs were calibrated over the range 13 K to 600 K (type 7.3E calibration) and 6 were calibrated over the range -183 ^{o}C to 300 ^{o}C (type 7.3F calibration). We have on hand an additional 7 capsule PRTs for type 7.3F calibration. This gives a grand total of 79 SPRTs calibrated by the end of August of this year with 22 on hand for calibration.

During the calibrations of these SPRTs, further comparisons were made between the manually-operated Guildline dc Current Comparator Bridge and the automatic Cutkosky dc-Pulse Bridge in preparation for automation of the measurement and analysis processes in the calibration of SPRTs.

(10) The "old" computer (1108) programs which derived calibration coefficients from calibration data obtained on capsule PRTs in the temperature range 12 K to 300 °C and on long-stem PRTs in the range -183 °C to 420 °C were adapted to run on an IBM - XT personal computer.

(11) The PRT Laboratory (suitable for a wide range of experiments relating to platinum resistance thermometry) on the third floor of the Physics Building was vacated. A much smaller laboratory on the second floor of the Physics Building was equipped with the utilities necessary for research and development supporting the PRT Calibration Laboratory and some of the equipment of the third floor moved into it. Some of the equipment required for measurements at the silver and gold points was moved into another lab and some required for evaluation of the high-temperature industrial platinum resistance thermometers for the Navy was moved into a third lab in the Physics building.

(12) The contract with the Navy (of CCG) for the NBS to evaluate the "best" commercial IPRTs (i.e., non-SPRT) up to 650 °C was not funded until the middle of April 1986. Following receipt of that money, a furnace was adapted for that work and the appropriate insert and insulation necessary for temperature equilibration and uniformity was constructed and tested. The evaluation of the selected IPRTs is in progress now and it is anticipated that the experimental aspects of that contract will be completed by the end of September 1986.

II.C. LABORATORY THERMOMETERS

Approximately 500 liquid-in-glass thermometers and 18 thermocouples were calibrated by Ms. J. Wise. The number of additional thermometers calibrated as special tests, including thermistors, industrial platinum resistance thermometers and digital thermometers, was approximately 45.

The printed version of NBS Monograph 174, "A Model for State Calibration Laboratories", by Jacquelyn A. Wise and Robert J. Soulen, Jr., was received. With the help of this monograph, a state or industrial organization should be able to establish a laboratory to calibrate temperature measuring instruments in the range of 0 °C to +200 °C with an accuracy of 0.1 °C.

J. Wise participated in the semiannual Precision Thermometry Seminar and continued to work with ASTM as Secretary of Committee E-20, Thermometry. She is also Secretary of Subcommittees E-20.90, Advisory, and E-20.05, Liquid-in-Glass Thermometers and Hydrometers. J. Wise serves as a member of ASTM Subcommittees E-20.91, Editorial and Nomenclature and E-20.08, Medical Thermometry.

J. Wise completed the Documentation Project for laboratory thermometers.

III. LOW TEMPERATURE SCALE

(E. Pfeiffer, J. Schooley J. Colwell, H. Marshak, W. Bowers, and W. Fogle)

This project is divided into two parts: (1) the temperature region covered by the EPT-76 (0.5 K -30 K) and (2) the region below 0.5 K covered by the temperature scale NBS-CTS-1 (0.010 K - 0.5K).

III.A. EPT-76: TEMPERATURE SCALE

Goal: The primary goal of the EPT-76 laboratory has been to establish at NBS the Provisional 0.5 K to 30 K Temperature Scale (EPT-76) and to provide a calibration service based on that scale. Secondary goals include a thermometric evaluation of the various resistance thermometers which presently serve, or may be candidates to serve in the future, as secondary reference standards in the EPT-76 region. Such evaluations would address such factors as sensitivity, stability, durability, and smoothing or interpolation methods. Another secondary goal is the development of automated calibration procedures for transfer to other temperature calibration laboratories. An added goal in 1985 was evaluating the feasibility of performing automated calibrations of capsule platinum resistance thermometers (PRT's) on IPTS-68 between 13.81 K and 273.15 K in the EPT-76 comparison cryostat, with a view toward transferring such calibrations out of the PRT calibration lab.

Progress in FY86: E. Pfeiffer completed an assessment of these goals named above and prepared a special document describing the service.

No calibrations were performed in FY86. Two customers were scheduled for FY87 while Mr. Pfeiffer devoted the major part of this past FY to assisting in the establishment of the new PRT calibration lab.

III.B. EPT-76: SUPERCONDUCTING FIXED POINTS

SRM 767a contains six metallic samples (Nb, Pb, In, Al, Zn, and Cd). The transitions between the normal and superconductive states of those samples provide reference temperatures that are reproducible within ± 0.3 mK. The devices are used in thermometer calibration laboratories and by individual scientists for the calibration of thermometers below 10 K.

Apart from supplying approximately 6 - 10 calibrated devices per year for distribution through the NBS Standard Reference Materials program, it is necessary to complete the characterization of the samples and to document the procedures to be used in employing the devices for precision thermometry. During FY86, six devices were prepared for the OSRM and preliminary measurements of the dependence of the superconducting transition temperatures on the applied magnetic field were obtained. As usual, a variety of requests for information and for special tests were answered.

Our plans for FY87 include the completion of the magnetic critical field measurements and writing of a publication describing the device characteristics and recommended measurement procedures.

III.C. NBS-CTS-1

This scale, developed at NBS and distributed worldwide via SRM 768, does not have international sanction. Research along parallel lines at other national standards laboratories (KOL; PTB-Berlin; Helsinki) should bring confirmation and the possibility of adoption of a provisional temperature scale from 1 mK to 500 mK by the CCT when the next scale is formulated.

The scale is based on a comparison of two (thermodynamic) thermometers: noise and nuclear orientation. Research in both of these areas this past year has been directed at understanding all systematics so that ultimately a scale accurate to 0.1% will evolve. To these two primary thermometers are added two secondary thermometers: the melting curve of He-3 and the paramagnetism of cerium magnesium nitrate (CMN).

For distribution of the scale to other laboratories, a superconductive fixed point device, SRM 768 is calibrated versus the NBS temperature scale.

1. Secondary Thermometers

A CMN thermometer was designed and constructed. Before it can be tested, a gas handling system and mutual inductance bridge must be constructed.

Two He^3 melting curve thermometers were tested this FY. The first was compared with a SRM 768 unit to determine the reproducibility. The results are shown in the accompanying table.

Superconductive Material in SRM 768 (Serial #7)	Number of Measurements	Standard Deviation Inferred from Melting Curve Thermometer (μK)
Tungsten	7	13
Beryllium	3	78
Iridium	5	48
$AuAl_2$	7	29
$AuIn_2$	4	30

These results testify to the high level of precision and reproducibility which may be obtained with a melting curve thermometer.

A second melting curve thermometer proved to be mechanically unstable and will be retested.

Critical to the success of the thermometry effort is the ability to stabilize temperature to 0.01% from 0.005 K to 3 K for periods as long as 24 hours. Careful use of the melting curve thermometer as the sensing element at low temperatures and carbon resistors as the sensing element at higher temperatures allowed us to achieve this goal.

2. Noise Thermometer.

Several improvements in the Josephson junction noise thermometer were made. In addition, the new He^3-He^4 dilution refrigerator was completed. In order to check for systematic errors induced by these changes, the noise thermometer was used to remeasure the superconductive transition temperatures (Tc) of a SRM 768 unit. The results are given below.

Material	Tc Before Changes (mK)	Tc After Changes (mK)
W	15.544(.03)	15.522(0.01)
Be	22.672(0.05)	22.710(0.02)
Ir	99.236(0.02)	99.157(0.07)
$AnAl_2$	159.8(0.1)	160.4(0.2)
$AuIn_2$	204.0(0.03)	204.4(0.1)

The results for the three lower Tc materials agree within the one-standard- deviation statistical uncertainties ("1 sigma") of the measurements (given in parentheses in the Table), whereas the two highest Tc results agree within 2 sigma. Thus no systematic uncertainties were introduced by the changes.

3. The apparatus used for the thermometry experiments, by virtue of its unique properties (magnetic and EMI shielding, stable temperature control), has proved to be helpful to other Divisions at NBS:

J. Colwell, W. Fogle, R. Soulen of Division 522 collaborated with M. Cromar and R. Ono of Division 724 on a study of the physics of very small area Josephson junctions at very low temperatures. The junctions exhibited some new features which has stimulated a conference report and publication.

J. Colwell, W. Fogle, R. Soulen of Division 522 collaborated with A.Clark and J. Moreland of Division 724 on tunneling experiments in "heavy electron" systems at low temperatures.

The results were reported at the March APS meeting. More experiments are planned to explore this area.

4. NUCLEAR ORIENTATION THERMOMETRY

a. The collaborative (NBS-Freie Universitat Berlin-Bonn Universitat) research work on the low temperature magnetic properties of the rare earth system consisting of radioactive ^{160}Tb in ^{159}Tb single crystals has been very fruitful this past year. In Berlin, we have successfully carried out the first nuclear magnetic resonance (NMR) on this system; in fact, this is the first successful NMR to be performed on a rare earth impurity in a rare earth host. The terbium single crystal system that we are studying is very interesting in that, in addition to having a very large nuclear magnetic dipole interaction (the internal magnetic field is 305 Tesla), it also has an extremely large electric quadrupole interaction. Thus, the single dipole resonance line is split into widely spaced subresonances separated by more than 300 MHz. By measuring these subresonance frequencies one can obtain very precise values for both the dipole and quadrupole interactions. This situation, coupled with very precise data on the nuclear decay scheme of ^{160}Tb, makes this system a very useful absolute nuclear orientation thermometer for use in the temperature region from ~10 to ~100mK. Moreover, the large magnetic hyperfine field makes this thermometer rather insensitive to applied magnetic fields, in contrast to most gamma-ray thermometers now in use. We have measured the lowest subresonance (transitions between the m=+3 and +2 spin substates) frequency and found it to occur at 480.0(4) MHz. These results were published (Phys. Rev. Lett. 56,1976(1986)).

New terbium single crystal samples were prepared at NBS and shipped to Bonn Universitat where the ^{160}Tb was implanted. These new samples are presently being used in Berlin where we are searching for the second subresonance (transitions between the m=+2 and +1 spin substates). This resonance should occur at about 800 MHz.

We have also investigated a "bulk" ^{160}Tb^{159}Tb single crystal sample here at NBS. This sample was prepared at the NBS reactor by neutron activation. In this experiment, the dipole and quadrupole interactions are determined by fitting gamma-ray anisotropy versus temperature measurements in on the various gamma rays. The temperature scale used was generated by calibrating carbon thermometers in-situ using a special magnetically shielded 6-element superconducting fixed point device that provided access to NBS-CTS-1 (NBS Cryogenic Temperature Scale-1). The analysis of this experiment is currently under way and results should be forthcoming shortly.

A short report on the ^{160}Tb^{159}Tb nuclear orientation thermometer is being presented at the Europhysics Study Conference "Refrigeration and Thermometry Below 1 Kelvin".

b. A new computer based (IBM-AT) data acquisition system is being programmed for use with the $^{60}Co^{59}Co$ nuclear orientation thermometer. This system will be used in our final comparison experiment with the noise thermometer. Most of the new ^{59}Co single crystal samples that were prepared last year for use as nuclear orientation thermometers were found to be damaged. New ones will now be produced and tested for use in the comparison experiment.

c. The NATO supported collaborative (Dr.G.Eska,Walther-Meissner Institute, Garchung, West Germany; Prof.B.G.Turrell,University of British Columbia, Vancouver, Canada; Dr.R.M.Mueller,I.F.F. der KFA, Julich, West Germany and H. Marshak, NBS) experiment to measure the A-transition in ^3He using nuclear orientation thermometers was started this winter in Garching, using Dr. Eska's nuclear demagnetization refrigerator. Problems that were encountered (leaks, faulty counting equipment, etc.) are being solved. Work is continuing and it is expected that a measurement of the A-transition with an imprecision of 2-3 percent will evolve.

IV. MEDICAL THERMOMETRY (B.W. Mangum and G. Evans)

The goal of this program is to develop a set of temperature fixed points and a means of using them to calibrate transfer standards for the temperature region of interest (0 - 200 °C) to the medical community.

The following table outlines the temperature fixed point program (T_f indicates the transition temperatures of the materials listed).

Medical Temperature Fixed Points

Material	T_f (°C)	Status
Indium	156.635	SRM 1971 50 cells tested
Succinonitrile	58.0805 +/- 0.0015	SRM 1970 115 cells tested NBS J.Res. paper published SP 260-101 published
Phenol	40.92	under study
n-Lauric acid	43.95	under study
n-Docosane	43.6	under study
Rubidium	39.303 +/- 0.005	SRM 1969 SP 260-87 published
Ethylene carbonate	36.32	alternative to Rb under study publication prepared
Gallium	29.772 +/- 0.001	SRM 1968 several papers published

Specific accomplishments this FY include:

(1) We believe that an organic material, sealed in glass cells, with a fairly large heat of fusion would be easier for clinical laboratory personnel to use than the rubidium triple-point standard which by its nature must be sealed in stainless steel. With this in mind, some melting/freezing experiments on 2 large cells and several small cells of ethylene carbonate (melting point 36.324 °C) were conducted to evaluate the suitability of this material to serve as a temperature fixed point near body temperature (37 °C). We have shown that ethylene carbonate can be sufficiently purified and that it is sufficiently stable that it can be used as a temperature reference point. Both melting and freezing experiments have been conducted on both large and small cells; from these experiments it was found that the freezing method, using the slush technique, yields results which are more reproducible than those obtained by the melting method. The material can be sufficiently purified that either method may be used for realizing the fixed point. However, the freezing method is the simpler one to use. A collaboration with Dr. John Cox of NPL, involving a study on 2 large cells with SPRTs and also with thermistors, was completed. Both the NBS and the NPL groups determined the triple-point temperature of the same cells by the same techniques and obtained the result that T(NBS) - T(NPL) = 0.3 +/- 0.2 mK, (that is, a maximum difference of 0.5 mK), using 3 SPRTs at NBS and 8 SPRTs at NPL. In addition, we made a preliminary investigation of the time dependence of the approach to equilibrium after creating a mush condition following super-cooling of the ethylene carbonate. A compilation of our data has been made and a paper written and submitted to Metrologia. Further investigations of the melting and freezing behavior of more small cells of this material are planned in order to ascertain not only the agreement among cells of a given lot but also that among cells of different lots. The amount of purification necessary to produce cells with freezing points within a sufficiently narrow range of temperatures to make this material suitable as an SRM must be determined also.

(2) Just as there is a special need for a temperature fixed point near body temperature, so there is a special (even critical) need for two fixed points bracketing the hyperthermia range used in cancer therapy. Those two points should occur at about 41 or 42 °C and 44 or 45 °C. Several materials have been selected as possible candidates for those temperatures, and several small cells of phenol, n-lauric acid and n-docosane have been obtained. More cells of these materials have been ordered. We continued the study of the small triple-point cells of these materials during the year; all of these materials look promising. Since hyperthermia is used in cancer therapy, some discussion with personnel of the National Cancer Institute took place regarding their funding some of this work and they solicited a proposal from Dr. Mangum, which was submitted in June 1986. The funding by the NCI, if successful, may become available in October 1986.

(3) The investigation of the melting/freezing behavior of high-purity indium in small Teflon cells, conducted during the previous year, showed the feasibility of using this point (and realized in such small cells) as a temperature fixed point and as an SRM. During the first quarter of FY86, the NBS instrument shops constructed 100 cells appropriate for the indium SRM (SRM 1971). Those cells were filled with 99.9999+ % pure indium and sealed under an atmosphere of dry argon. Fifty of the cells will have been tested for suitability to serve as SRM 1971 by about the end of September 1986. The remaining 50 cells will be certified next year.

In addition to the possible use of indium as an SRM temperature fixed point, there is the possibility of using it as a temperature fixed point for the International Practical Temperature Scale. In fact, a fixed point at about the melting point of indium is urgently needed for the calibration of capsule SPRTs, to provide a more accurate calibration of long-stem SPRTs for the most accurate and precise work needed in research, and to provide a check on the routine calibration of SPRTs. With this in mind, we are proceeding to make a thorough investigation of the indium melting/freezing behavior and of the reproducibility of the melting/freezing-point temperature. We have two large cells of indium filled with 99.9999% pure indium, the cells being of sizes sufficient for use with long-stem SPRTs and capsule SPRTs. Preliminary results on the large cells indicate that the pressure dependence of indium is 4.95 +/- 0.04 mK/std.atm. A preliminary value of the freezing-point temperature of one of the cells is 156.635 $^{\circ}$C. We plan to continue measurements on the cells during the coming year.

(4) NASA needs to make surface temperature measurements of air foils in the temperature range from about 77 K to about 335 K. Since NASA wanted an independent and unbiased evaluation of some small thermometers for that purpose, they made a contract with us to investigate the reproducibility and stability of some small silicon diode thermometers over the temperature range of interest. That investigation was successfully completed in January 1986 and a report written to NASA.

V. DYNAMIC PRESSURE AND TEMPERATURE
(G. Rosasco, W. Hurst and R. Dove)

Goal: The goal of this project is to develop the means of measuring P and T with high temporal response (10 ns) and high spatial resolution (mm^3). A laser diagnostic technique based on nonlinear optical spectroscopy is used. Specifically the project is designed to develop the algorithms for inferring P and T from spectral lineshapes and intensities. A second goal is to accumulate reference data and develop predictive theory for selected gases of importance in diagnostic applications.

Accomplishments FY1986:

Raman pump laser: Experiments, begun in FY85, to test the feasibility of using injection-seeded, flashlamp-pumped dye lasers as Raman pump sources of high peak power and very narrow-bandwidth were completed in early FY86. In FY85 we had succeeded in using injection-seeding techniques to produce approximately 5 mJ pulses, 1μs duration, TEM_{00} spatial mode, with bandwidths under 8 MHz, and very low out-of-band light levels (peak to baseline of better than 1000:1). The goal for the last stage of the work was to boost the energy of the laser developed in our prior work by a factor of approximately 20, while preserving the spectral and spatial mode characteristics of the laser. The only way found that would allow us to reach this goal was to use at least two stages of single pass, high energy flashlamp-pumped amplifiers. Injection-seeding a second, high-energy oscillator did not yield the required spectral purity, although we could get the required energy level. This three stage system, while feasible and manageable in the laboratory, would represent a major investment in order to develop a reliable 10 Hz repetition rate system. Dr. Kermit C. Smyth, NBS Center for Fire Research, participated, as a guest worker, in these studies. We decided to halt further development and gain experience with the only other alternative known to us at this time, i.e. the use of injection-seeded, single mode Nd:YAG lasers to provide Raman pump lasers. These are described in the FY84 Annual Report. The system we used is housed at the National Combustion Research Facility, Sandia National Laboratories, Livermore, CA. Their Raman pump laser currently is the best in the world in terms of spectral bandwidth (45 MHz), pulse energy (20 mJ), and repetition rate (18 Hz). The pulse is temporally smooth and stretched to approximately 20 ns duration. This laser system relies on the use of a very sophisticated, injection-seeded, single-longitudinal mode Nd:YAG laser which they developed over the last 4 years. The Nd:YAG system includes a diode-laser pumped, miniature, monolithic Nd:YAG master oscillator, a slave oscillator, and a three-stage, single-pass post amplifier system. This laser is frequency doubled, and used to pump a three stage dye laser amplifier (also built at Sandia) which is seeded with the output of a tunable, single frequency (<1 MHz bandwidth) commercial cw-dye laser. The equipment investment required to produce and operate this Raman pump laser currently is beyond the scope of our project at NBS. Thus, where possible, measurements which require this type of Raman pump laser source will be done in collaboration with the Sandia staff.

Spectral Effects of Velocity Changing Collisions: Experimental and theoretical analysis of spectra in which the velocity distribution makes a considerable contribution to the spectral profile, via the Doppler effect, has received a great deal of attention this past year. As explained in prior reports, this component in the spectrum is of increasing importance as the temperature is increased (particularly for pressures up to a few atmospheres). Additionally, we will be studying the spectrum of H_2 as a function of temperature, collision partner, and pressure under our ARO contract. For the last-mentioned molecule, velocity-changing collisions, which lead to Dicke narrowing, are the dominant cause of pressure-dependent changes in the linewidth for pressures less than 5 atm, even at room temperature. There are two "standard", analytically solvable models which we have been testing against our measurements of the pressure dependence of the Q-branch spectrum of D_2:X(X=D_2,H_2, He, Ar, and CH_4). These models differ in the details of the collision kernel employed; however, they both are solutions of the Boltzmann equation for the spatially and temporally dependent velocity distribution function. One of the most significant results of our research is the discovery of a second component in the Q-branch spectrum of D_2 which we ascribe to a coupling of the internal degrees of freedom to the translational motion of the molecules. The additional component, a small Lorentzian feature which is broader than the main component, is shown in Figure 3 and 4. This is the first direct vidence of the failure of the Boltzmann equation as traditionally applied to describe the effects of velocity-changing collisions on the spectrum of an internal mode. It is known that the appropriate equations for systems with internal degrees of freedom are either the Wang Chang-Uhlenbeck or Waldmann-Snider equations. The essential physics which produces the additional feature in the spectrum involves the fact that the basic dephasing (broadening) process in the Q-branch is a rotationally inelastic collision. Because of the large energy gaps between rotational levels in the hydrogenic molecules, there is a possibility of a large energy defect associated with a dephasing collision. Because of the small mass of these molecules, there can be large changes in velocity coupled to a dephasing collision. A plausible analytical description for this coupling has been proposed and shown to be in agreement with the measurements. An improved agreement with and most importantly a more reliable prediction of the spectrum of D_2:X has resulted from this work. The improved predictive capability is illustrated in Figure 5, where the width of the main (as opposed to additional) component as a function of density is compared to a theoretical prediction. The concepts and theory developed in this study will be important for the prediction of the spectrum of H_2, N_2, and CO as functions of temperature and collision partner. Professor A. David May, University of Toronto, Dr. Larry Petway, Howard University, and Dr. Smyth participated, as guest workers, in these studies. Professor May primarily is responsible for the physical model which underlies the additional component in the spectrum.

J and Collision Partner Dependence of Line Broadening in D_2: The studies discussed above also have provided data which allow an assessment of the J and collision-partner dependence of line broadening in hydrogenic systems. Our measurements are the most extensive and most accurate for these systems and have provided some critical tests of theory. In particular, our work with Professor May on HD:HD has demonstrated remarkable agreement with first principle calculations. Our studies of D_2:X have allowed us to test the relative roles of elastic vibrational dephasing and rotational inelasticity in the broadening of the Q-branch. A summary of some of our data, and the predictions of a theory based on an exponential gap model for the rates of state-to-state rotationally inelastic collisions (see below) are summarized in Figure 6. Rotationally inelastic collisions dominate the linewidths in these systems, the vibrational dephasing contributions being (in units of 10^{-3} cm^{-1}/amagat) 0.47(D_2), 0.86(He), 2.2(Ar), and 2.6(CH_4). These results should be contrasted to those for H_2 in which noble gas collision partners are thought to produce only vibrational dephasing and essentially no rotationally inelastic collisions. Researchers at Johns Hopkins University Applied Physics Laboratories are performing first-principle calculations to better understand the results in Figure 6. Dr. Smyth also has collaborated on this part of the research.

Application of Exponential- Gap Laws to Predict Q-branch Spectra: In the first years of this project we studied the spectra of simple diatomic molecules, in particular N_2 and CO, because of their importance in diagnostic applications. The fact that the Q-branch spectral lines are broadened almost entirely by rotationally inelastic collisions and further that individual Q-branch transitions are mixed by specific state-to-state transitions leads to a complex, collisionally collapsing (with increasing pressure) spectrum. Without an appropriate theoretical model (which in this case involves an n x n relaxation matrix), and a great deal of information about the various molecular parameters which enter this model, we cannot accurately predict the Q-branch spectrum as a function of temperature and pressure. Conversely, we showed that the temperature and pressure information derived from the spectrum were very inaccurate. In our early work we showed that simple energy-gap models for rates of state-to-state rotationally inelastic collisions could be used to determine the Q-branch spectrum. In recent years, a great deal more work has been devoted to understanding this problem. Most of this work came from researchers in diagnostic labs because of the importance of these effects in temperature and pressure measurements. Recently, researchers at the National Combustion Research Facility proposed a modified exponential gap model (MEG) for the rates of state-to-state rotational energy transfer. This model was derived primarily from semi-classical molecular dynamics calculations of rotational inelastic collisions in N_2. They used this rate law to express the entire relaxation matrix and fit the predictions to experimental spectra of the N_2 Q-branch as a function of pressure. Excellent agreement was found. The temperature dependence of the linewidth was then measured and an empirical fitting function added to the rate law. This simple 4-parameter model can be used to calculate the spectrum at all values of T and P. In the course of our research at Sandia, we tested the predictions of this model for the collapse of the N_2 Q-branch at 1000 K, and for pressures up to 20 atm. The results were very good. The latter observation is critical because there have been a number of other rate law models which accurately predict line broadening, but do not accurately account for line interference, (which leads to narrowing and collapse of the Q-branch). In addition to the work on N_2, we made an extensive study of CO as a function of temperature (at 1 atm and below) while at Sandia National Labs. This work directly supports of our ARO contract; its goals were to verify the utility of the MEG law to predict the collapse of room-temperature CO Q-branch spectra (determined in our early work) and to determine the temperature dependence of the line broadening coefficients of CO. The last mentioned data allow test of the use of the T-dependent MEG law to predict the linewidths in CO. The results of our work, to date, show excellent agreement of the model with the room temperature spectra and with the T-dependence of the widths. Parameters similar to those of N_2 also were found. Some of these results are summarized in Figure 7. All our previous studies of N_2 and CO have been substantiated by the most recent studies of these systems. Most important, however, is the fact that we now have a simple, reliable, and microscopically justifiable predictive equation for the spectra of the simple diatomics which are important in diagnostic applications.

Figures

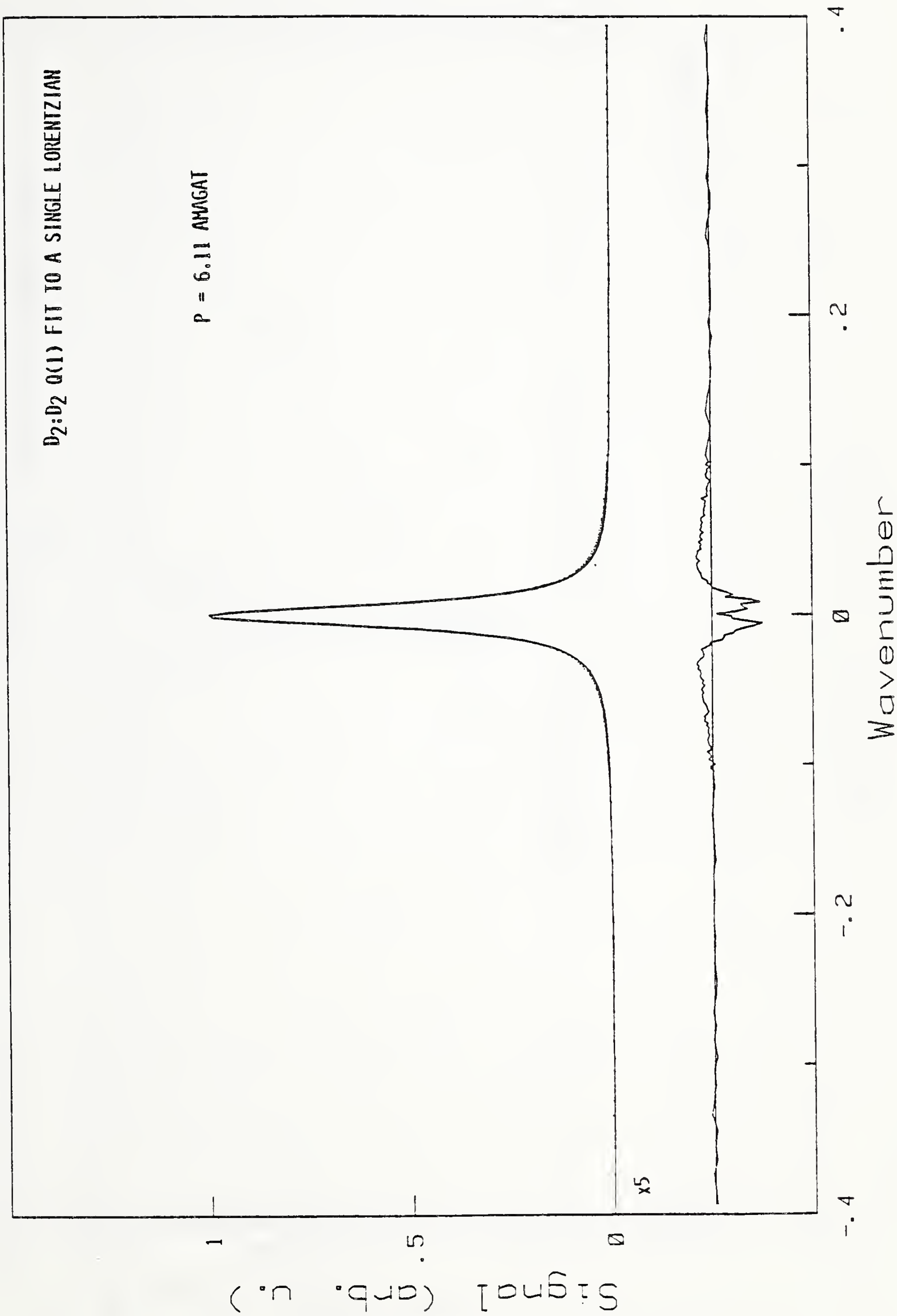
Fig. 3. D_2 (Self-broadened) Q-branch line of J=1, fit to a single Lorentzian, with constraint that the area of the Lorentzian curve equals that of the data. The deviation of the fir (scale expanded x5) is shown below the spectrum and represents the additional component in the spectrum.

Fig. 4. Same data as in Fig. 3 fit to the sum of two Lorentzians. The second, broad component (scale expanded x5) is given by the top curve and is seen to be a Lorentzian. The deviation of the fit from the sum of the two Lorentzians (scale expended x5) is given by the bottom curve.

Fig. 5. Density dependence of the width (HWHM) of the narrow Lorentzian component for the D_2 (self-broadened) Q-branch line of J=1. The curve is a fit of the data to a Dicke-like expression D/p + p*gamma, where D is given by the diffusion constant and gamma is the pressure broadening coefficient.

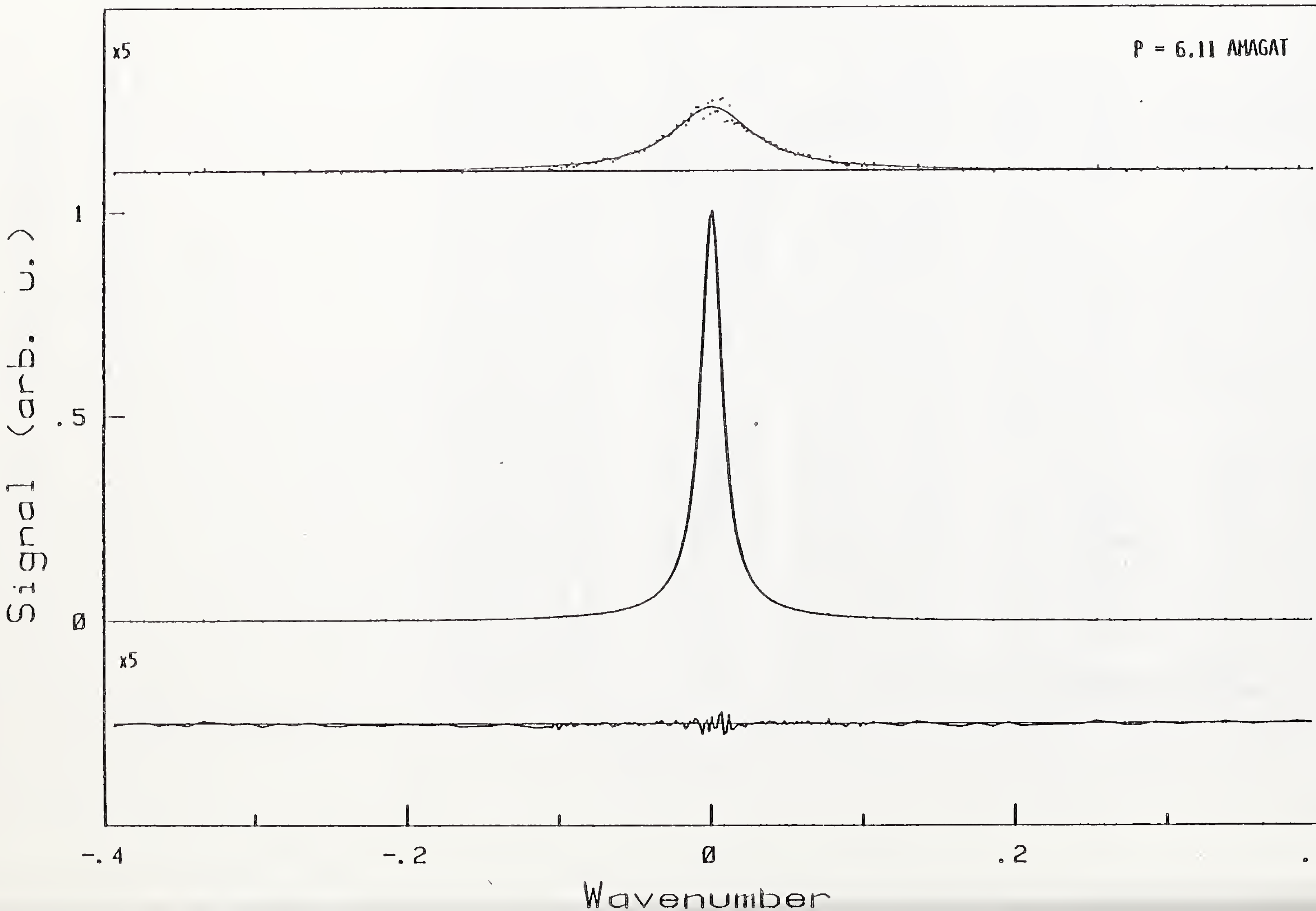
Fig. 6. Pressure broadening coefficients from our measurements of D_2 broadened by X (X = D_2, He, Ar or CH_4), for lines J=0 to 5. The lines indicate predictions of theory based upon a modified exponential gap model.

Fig. 7. Pressure broadening coefficients (HWHM) determined from the measurements of CO (self-broadened) at 295, 701 and 1504 K, for lines J=0 to 38. Symbols indicate coefficients extracted from fits to the data. The curves indicate the predictions of the modified exponential gap (MEG) rate law for the line width.



D2:D2 Q(1) FIT TO A SINGLE LORENTZIAN
P = 6.11 AMAGAT
x5
-.4
-.2
0
.2
.4
Wavenumber
0
.5
1
Signal (arb. u.)

Fig. 3.


P = 6.11 AMAGAT
x5
x5
1
.5
Ø
Signal (arb. u.)
-.4
-.2
Ø
.2
.4
Wavenumber

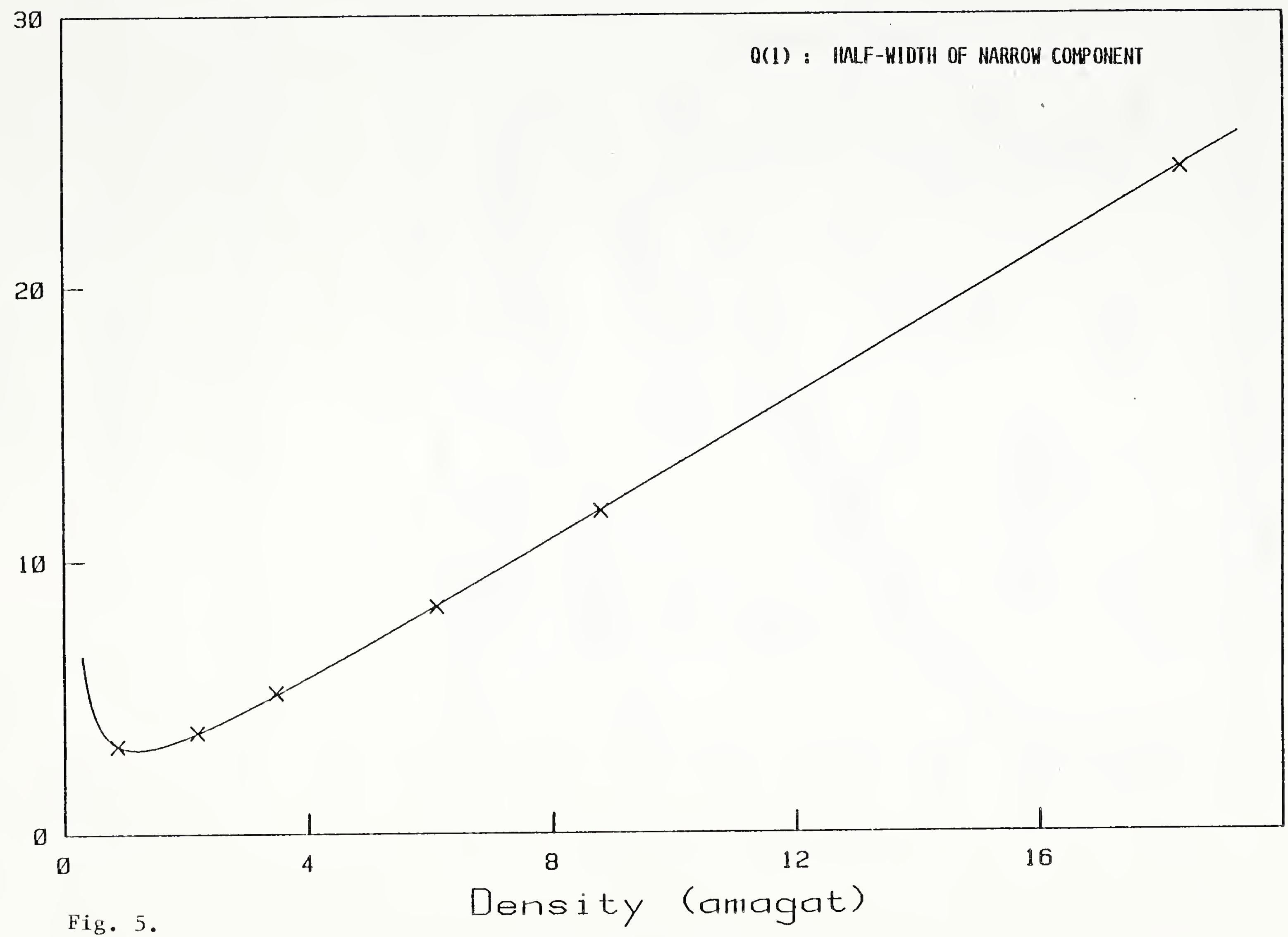
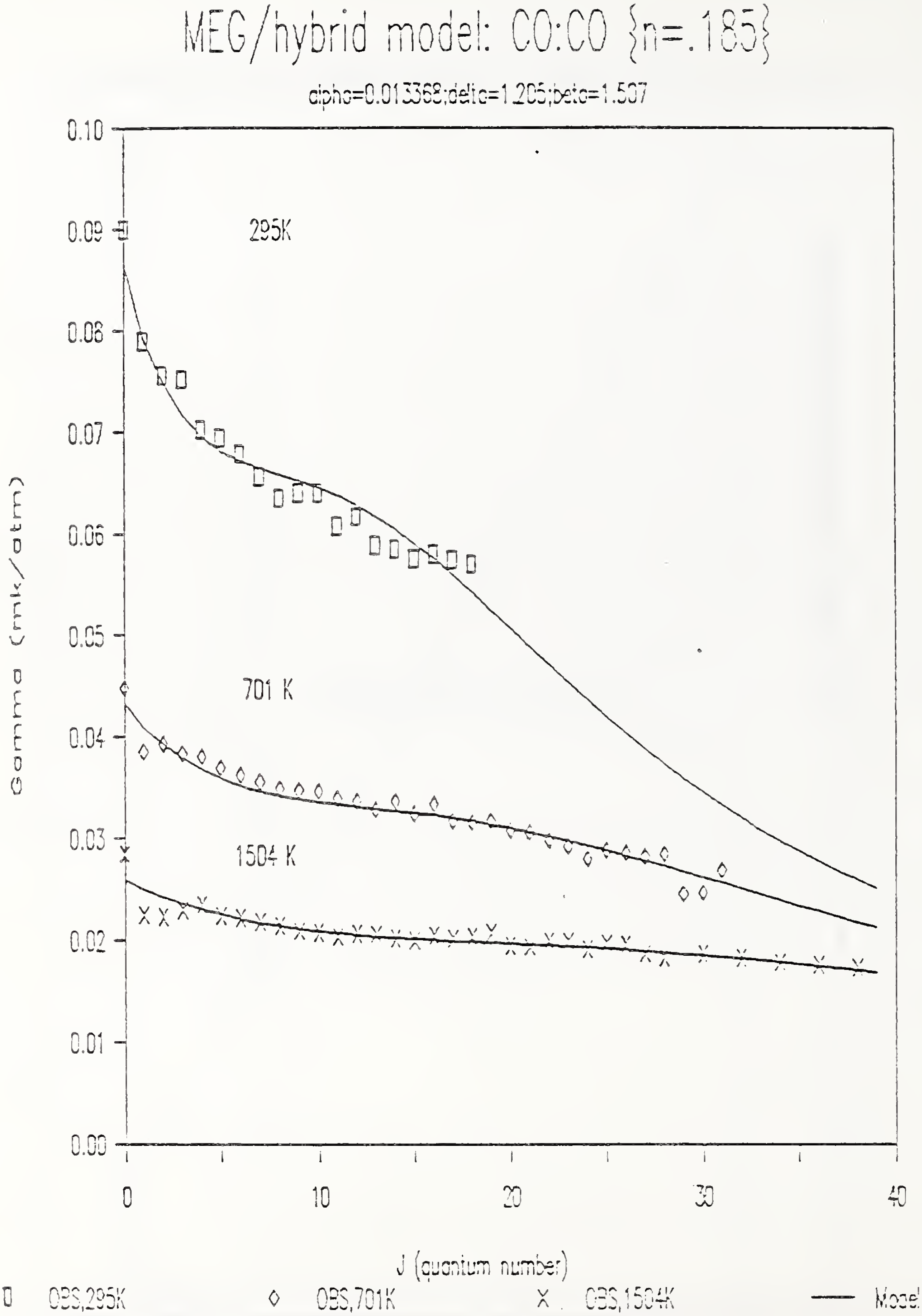
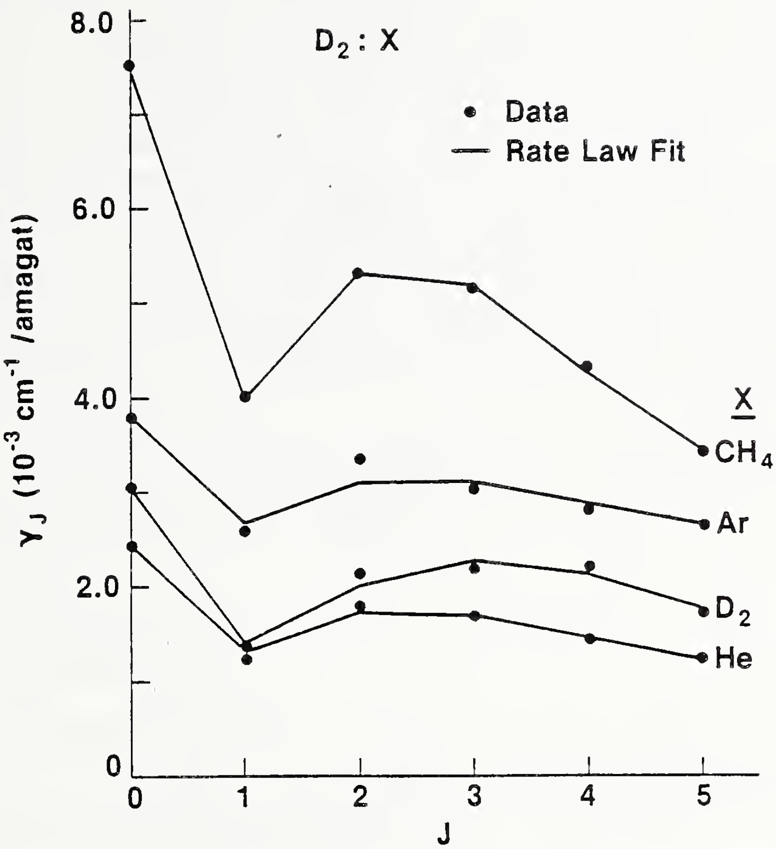

Q(1) : HALF-WIDTH OF NARROW COMPONENT
30
20
10
0
mK
0
4
8
12
16
Density (amagat)

Fig. 5.



MEG/hybrid model: CO:CO {n=.185}
alpha=0.013368;delta=1.205;beta=1.507
295K
701 K
1504 K
Gamma (cm-1/atm)
J (quantum number)
OBS,295K
OBS,701K
OBS,1504K
Model

Fig. 6.



8.0
6.0
4.0
2.0
0
Y_J (10^{-3} cm^{-1} /amagat)
D_2 : X
Data
Rate Law Fit
X
CH_4
Ar
D_2
He
0
1
2
3
4
5
J

Fig. 7.

VI PISTON GAGES

(V. Bean, G. Driver, W. Markus, B. Welch, and J. Houck)

Goal: The piston gage is the standard instrument for precise pressure measurements in the range above the limits of manometry. The instrument consists of a carefully made piston fitted into a matching cylinder which is, in turn, connected to a pressure generating system. The piston is loaded with measured weights, floated by adjusting the cylinder pressure using a transmitting fluid, and rotated to relieve friction and to assure concentricity. The pressure is calculated as the ratio of the downward force, due to the weights and the piston, to the effective area of the piston-cylinder combination. Our goal is to determine the effective area at atmospheric pressure A_o, and the change in the effective area with pressure, with an accuracy sufficient to: (A) provide American piston gage manufacturers with the needed calibration services to keep their products competitive in the world market; (B) meet the need for increased accuracy requested by our calibration service customers, such as the DoE and DoD laboratories; (C) participate effectively with other national standards laboratories in setting international standards for pressure calibrations.

Commercially available gages span the range from 2 kPa to 1.4 GPa and may be designed for use with gases or condensed fluids in appropriate parts of the range.

Accomplishments during FY 86

A. Calibration Services

We have calibrated 79 units for an income of $ 120 k.

At the suggestion of members of NCSL, the pressure calibration report has been greatly simplified. The software to support the new report is under development.

Considerable effort this past year has gone into documentation of our piston gage calibration services. The document was completed this FY.

B. New Primary Standard for Low Pressure

Historically, the primary standard for the gas-operated, low-pressure calibration service has been a controlled-clearance piston gage. We are now in the process of changing the standard to a mercury manometer which was originally developed at NBS for gas thermometry. Four thoroughly studied piston gages are currently being calibrated using the manometer. One of the four will be installed in the calibration bench for direct use in the calibration service; it will also be used to calibrate the other standards on the bench. The other three piston gages will be used only in international intercomparisons and periodically to check the standards on the bench.

Great care has been taken to obtain a precise comparison of these piston gages and the manometer. Shown below (Fig. 8) is a plot of the measured variation in A_0 for one of the piston gages as a function of the number of measurements taken at 96 kPa and 62 kPa using helium in the absolute mode. Each plotted point is the average of 15 measurements. The standard deviation of all 150 measurements is 0.26 ppm and is indicative of the precision that was achieved. The manometer has an estimated uncertainty of 2 ppm as a primary pressure reference. Our goal of reducing the uncertainty from 50 to 10 ppm or less in the pressure range up to 4.9 MPa in the calibration service appears to be attainable by this change in the primary standard.

In conjunction with the new primary standard, this past year we have designed and constructed a new calibration bench for gas-operated piston gages. It is equipped with automatic check standards which are expected to be a great help in spotting any problems with the customer's gage or with the calibration process. We expect this improved calibration service to be in place by early 1987.

C. Distortion of Piston Gages at High Pressure

As pressure increases, the leading source of uncertainty in pressure measurement is lack of knowledge of how the effective area of the piston gage changes with pressure. A pressure intercomparison in the pressure range of 20 to 100 MPa, involving LNE, PTB, IMGC, NPL, and NBS, demonstrated a lack of agreement among these labs in evaluating the pressure coefficient of the effective area of the transfer-standard piston gage used in the intercomparison. NBS and PTB have initiated research programs to reexamine piston gage distortion. Briefly, the NBS program goals are:

1. Develop the capability of calculating the piston-cylinder distortion from theory without resorting to the usual approximations which are:
    a. The cylinder is infinite in length.
    b. The pressure is uniform.
    c. There are no shear stresses between thin planes passed through the cylinder normal to the cylindrical axis.

   The problem involves solving a biharmonic equation with appropriate boundary conditions, using the pressure profile between the piston and the cylinder as an input parameter.

2. For two cylinders of calculable but different geometry and made of different materials, make measurements of the change of outer diameter of the cylinder as a function of pressure and cylinder length. These measurements will provide a check on the theory.

3. Make the best possible estimates of the distortion coefficients for the effective areas of the two gages.

4. Test those values by cross-floating the two gages to determine the pressure dependence of the ratio of their effective areas. How constant the ratio appears to be as a function of pressure will provide a measure of the correctness of our understanding of the distortion coefficients.

The necessary solution for the biharmonic equation has been obtained using the NBS computer. Extensive measurements of the changes in the outer diameters for the two cylinders have been completed this past year using a special capacitance probe mounted on a micrometer head. Measurements with and without the piston in place clearly demonstrate that assumption c above is not appropriate. (It is obvious that assumption a and b are also not appropriate for a piston gage).

Analysis of the measurements and calculations using the theory both require knowledge of the pressure profile between the piston and the cylinder. We have shown earlier that the pressure profile can be calculated from the measured clearance between the piston and cylinder. Both pistons have been measured by Division 738. However, the cylinder bores have not been measured, as the necessary instrument has been out of commission for several months due to the unavailability of parts. We are developing our own capability of making the cylinder-bore measurements using a capacitance probe mounted on an air bearing.

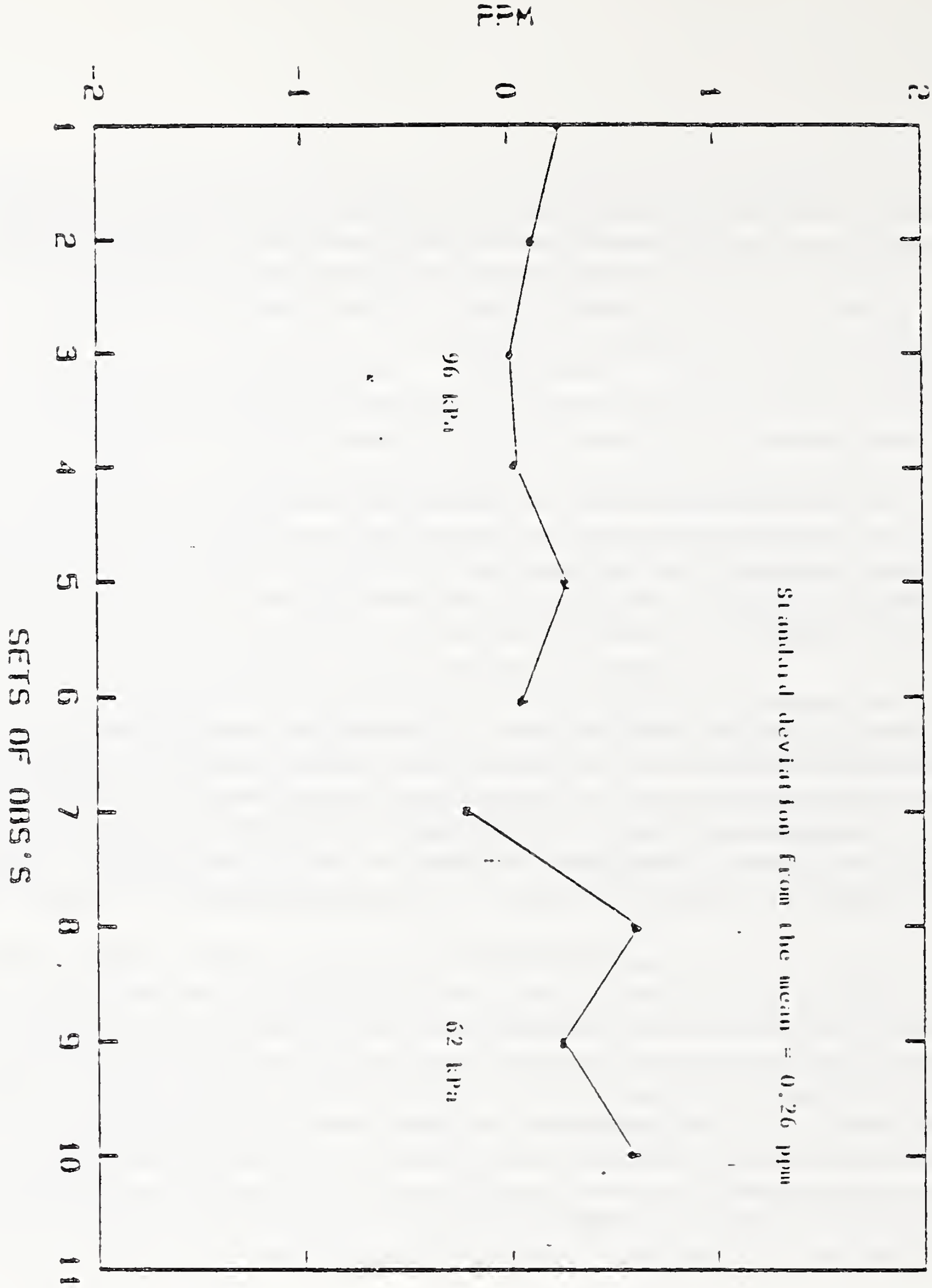


Fig. 8. Deviation is area of one piston gage as determined by the gas thermometer manometer plotted as a function of the sets of observations. Each point on the plot is the average of 15 measurements.

It is expected that these new techniques will be useful up to modest pressures, about of 100 - 150 MPa. At higher pressures the rate of leakage of the pressurizing fluid past the piston can increase to the extent that the float time is too brief to make the gage useful. Under these conditions, controlling the flow by controlling the clearance between the piston and the cylinder via an auxiliary pressure on the outer surface of the cylinder can be a distinct advantage; the "controlled-clearance piston gage" provides this capability.

D. New Controlled-clearance Primary Standard Piston Gages.

During this past year we have designed two new controlled-clearance primary standard piston gages: one for service up to 280 MPa to provide a 1:1 range correspondence with our calibration service standard in this industrially important pressure range; the other for service up to 700 MPa to meet the needs of DoE laboratories and the increasing demand from industry. The gages are very similar in design; both incorporate as many commercially available parts as possible. The 700 MPa gage has been assembled and is undergoing testing to determine its characteristics.

E. InSb Pressure Transfer Standard

Both NBS and the DoE laboratories need a sensitive and stable pressure transducer operating in the 700 MPa range for use in the characterization measurements of controlled-clearance primary standard piston gages. The DoE laboratories and BIPM are also interested in a transfer-standard-quality transducer for the 700 MPa range for laboratory intercomparisons.

Currently, the most sensitive gage in this pressure range is based on the electrical resistance of a length of manganin wire; however, the manganin gage does not have sufficient sensitivity for the characterization of controlled-clearance gages.

During this past year we have looked into the feasibility of making a pressure gage based on the change of resistance of a small band gap semi-conductor, InSb. The calibration equation for such a gage is of the form

$$P = A \ln R/R_o$$

which has the fortunate and unusual feature that the sensitivity increases as the pressure increases. Here P is the pressure, A is a constant and R and R_o are the resistances at pressure and at atmospheric pressure respectively. At 700 MPa, the InSb gage has a sensitivity that is 70 times greater than that of manganin.

Stability tests to date have been limited to 280 MPa. Repeated measurements over a 4 hour period had a standard deviation of 60 ppm, an encouraging result. Further work awaits the availability of the 700 MPa primary standard mentioned above.

F. Basic Research on Gas-operated Piston Gages

The careful study of the four gas-operated piston gages mentioned in Section B above is leading us into new and unexplored areas. Last year we reported that when two gas-operated gages having areas differing by a factor of four were balanced in the gage mode and then the space surrounding the weights was evacuated so the gages were operating in the absolute mode, we found that the resulting out-of-balance condition was not fully accounted for by the air buoyancy correction for the weights. The effect at one atmosphere for nitrogen amounts to 23 ppm and is a function of pressure, the gas, and the clearance between the piston and the cylinder. Gas flow conditions in this narrow space are in the transition regime between viscous and molecular flow. If momentum transfer from gas molecules colliding with the sides of the piston were the responsible mechanism, then one would expect the magnitude of the effect to be a monotonic function of the gas molecular weight; however, this correlation for the six gases studied is very poor.

To explore the physics behind this effect, we are now building an apparatus to measure the change in the gas density in the annular space as a function of length along the cylinder of an operating piston gage using several gases and in both the gage and absolute modes. This project is being carried out by Akira Ooiwa, a guest scientist from NRLM, Japan.

G. Pressure Fixed Points

Pressure fixed points are valuable not only for laboratory intercomparisons but also as an invariant against which standards can be checked as a function of time. Two pressure fixed points are currently under consideration at NBS by Dr. Noel Bignell, a Guest Scientist from CSIRO, Australia. They are the CO_2 vapor pressure at the temperature of the triple point of water which is about 5 MPa and the ice Ih-ice III-water triple point at about 200 MPa. Several measurements have been done to investigate the suitability of the ice Ih-ice III-water triple point. For these measurements, the water sample was contained in a stainless steel bellows, the motion of the free end of which was tracked using capacitance measurements. The triple point cell is now being designed based on that experience.

VII. VACUUM AND LEAKS

(B. Dove, C. Ehrlich, A. Fillippelli, R. Hyland, F. Long, D. Martin, K. McCulloh, C. Tilford, and S. Wood)

VII.A Overview

The objectives of this group are to develop primary standards and measurement techniques, evaluate the performance of transfer standards and improve them where necessary, and provide calibrations and assistance to the technical community.

Vacuum measurements currently cover nine decades of pressure that range from 10^{-6} Pa (10^{-8} Torr) to 1.6 x 10^{5} Pa (1.6 atmospheres) with a gap between 10^{-1} and 10 Pa. The low vacuum (10-1.6 x 10^{5} Pa) standard is a high resolution mercury manometer of NBS design, employing a 10 MHz acoustic technique (ultrasonic interferometry) to measure the mercury column lengths. The high vacuum (10^{-6} to 10^{-1} Pa) standard is of the orifice-flow type, generating known pressures by passing a known flow of gas through a calculated conductance. Leak (low flow rate) measurements currently extend from 10^{-12} to 10^{-8} moles/sec (10^{-8} to 10^{-4} std cc/s). Leak rate standards are grouped with vacuum standards because important parts of the primary standards, most notably the flowmeter, can be shared and most leak measurement users employ vacuum techniques.

Members of the group and their primary responsibilities are Bruce Dove - mechanical technical support; Charles Ehrlich - leak standards; Albert Filippelli - ultra high vacuum (less than 10^{-6} Pa) standards; Richard Hyland - low vacuum and leak standards; Fred Long - electronic technical support; Donald Martin - mechanical technical support; Charles Tilford - overall coordination; Sharrill Wood - high vacuum (10^{-6} to 10^{-1} Pa) standards. For most of this past year Bernd Lindenau, a guest scientist from KFA-Julich, worked with us in further characterizing the spinning rotor gage, a high vacuum transfer standard. During this year K. McCulloh concluded his work on vacuum standards.

Compared to the previous year, the emphasis this year was less on the construction of equipment and facilities and much more on the evaluation of our standards and the extension of services to users. A major amount of time was spent in the preparation of required documentation for the low and high vacuum calibration and special test services. Complementary to this effort was the preparation of several manuscripts for archival publication with descriptions of the high vacuum and leak standards and detailed error analyses. Large amounts of data had to be obtained or reviewed to support these efforts.

In addition to completion of the documentation and error analyses, significant accomplishments this past year include: the recent initiation of a special test service for helium leaks, an area where no national standards have previously existed; the extension of our high vacuum test services down by two decades to 10^{-6} Pa (10^{-8} Torr); and a measurement of the speed of sound in mercury with a 5 part per million uncertainty, allowing a major reduction in the uncertainty of our ultrasonic interferometer manometer standard.

Services to users are not confined to calibrations. A steady volume of telephone consultations is maintained, and members of the group spoke at a number of symposia and workshops and are active participants in several professional and standards-writing organizations. We have organized an international workshop on Ultra High Vacuum Gaging to be held the first week of November, 1986. As in the past we had "full house" attendance at two spinning rotor gage training courses. These courses are fairly intensive and require enough NBS effort that two courses were all we were able to offer without unduly interfering with our technical activities. However, our efforts are appreciated. A recent National Conference of Standards Laboratories review of NBS measurement services included the comment, "The NBS training course/seminar on the Spinning Rotor Gage must be commended as one of the better examples of NBS support to the calibration world." This is consistent with the private comments we received.

Technical activities this past year are discussed below in four areas; manometry, high vacuum, ultra high vacuum, and leaks. It should be kept in mind that these activities are all interrelated, sharing both personnel and equipment. This cooperation appears to be the most efficient way to address future problems as well; e.g., the ultrahigh vacuum and leak programs are both technically limited by hydrogen base pressures and the performance of ion gages and residual gas analyzers. Cooperative efforts are underway to address these issues.

During the coming year we expect our main activities, in addition to the continuation of existing services and refinement of existing standards, to be the efficient organization of the new leak test service, the extension of our leak standard range, continuation of the effort to reduce the base pressure in a ultra high vacuum standard, the fabrication of a new high vacuum standard that will accommodate more gages, completion and evaluation of the three ultrasonic manometers currently under construction, and extension of the speed of sound measurements over a wider range of parameters. If time and resources become available, we will start on a standard to cover the 10^{-1} to 10 Pa range.

VII.B. Manometry - Low Vacuum

The 160 kPa ultrasonic interferometer manometer (UIM) continues in use both as a primary pressure standard and as a research instrument.

In its capacity as a national standard, the NBS UIM was compared to pressure standards in the 0.1 to 1300 Pascal pressure range at the national laboratories in Germany (PTB - Berlin) and in Australia (CSIRO). The transfer standards are a set of 4 capacitance diaphragm gages. Evaluation of the results has not been completed. This intercomparison is part of an on-going round robin in this pressure range under the auspices of the low pressure working group of the BIPM.

The for-fee calibrations this year remained relatively constant at 14 units and $21 k in fees. Nine other units were calibrated for in-house use, largely to support the high vacuum and leak standards flowmeters.

The UIM has been used in its research capacity for the characterization of a type of dead-weight tester known as a ball gage. For the low range versions of these devices, enough data have been obtained on both the long-term stability and the non-linearity which exists over roughly the bottom 10% of their range to force significant revisions in the uncertainty statements which appeared in the customers' calibration reports.

The past year has seen a large effort toward the documentation of the general construction, use, and uncertainties of the current UIM. This effort has resulted in an updated error budget which includes a reduction in the systematic uncertainty from about 100 ppm to 18 ppm or less. This major reduction is the result of an improved measurement of the speed of sound in mercury. The measurement basically involves the comparison of an ultrasonic length measurement with a measurement of the same length using a frequency-stabilized laser, as illustrated in Fig. 9. A paper describing the work has been drafted and is currently undergoing internal review. Basically, the pressure, temperature, and length dependencies of the speed of sound have been obtained to permit its prediction with a maximum uncertainty of 5 ppm for mercury column lengths of 400 mm or less, and 10 ppm for lengths up to about 1000 mm. The results are better than expected, but the length dependence, presumably arising from acoustic near-field effect, is significantly larger than indicated by preliminary calculations. The present apparatus allows a maximum mercury column length of 400 mm, which is not long enough to determine if the speed of sound asymptotically approaches a far-field value. The apparatus is being modified to allow measurements for column lengths up to 1000 mm.

During the past year, considerable effort has gone into the construction of three new UIM's, two for outside sponsors and one for NBS. These instruments are of modified design intended to extend the measuring range to 300 kPa and improve performance. Complete error evaluations are planned for the three instruments upon their completion.

It should be noted that completion of the mechanical components for the new manometers has been significantly held up by delayed delivery and/or delivery of defective aluminum and glass tubing. However, a concurrent redesign of the electronics package has been successful, and awaits the marriage with the mechanical components for final debugging.

Other research begun this year involves the effect of helium on the behavior of differential quartz helix gages. This type of gage is widely used as a transfer standard in industrial standards laboratories, and there is widespread interest in its performance. Two gages have undergone repeated calibrations, alternating between the use of nitrogen and helium. Results are not yet available, although some preliminary work indicated no differences in behavior at the 100 ppm level.

The coming year should also see the start of an intercomparison between a special set of NBS-owned, high accuracy piston gages and the UIM, with the idea of tying together the low vacuum standard and the low pressure standards.It will also serve as an independent check on the overall accuracy of the standards in both ranges.

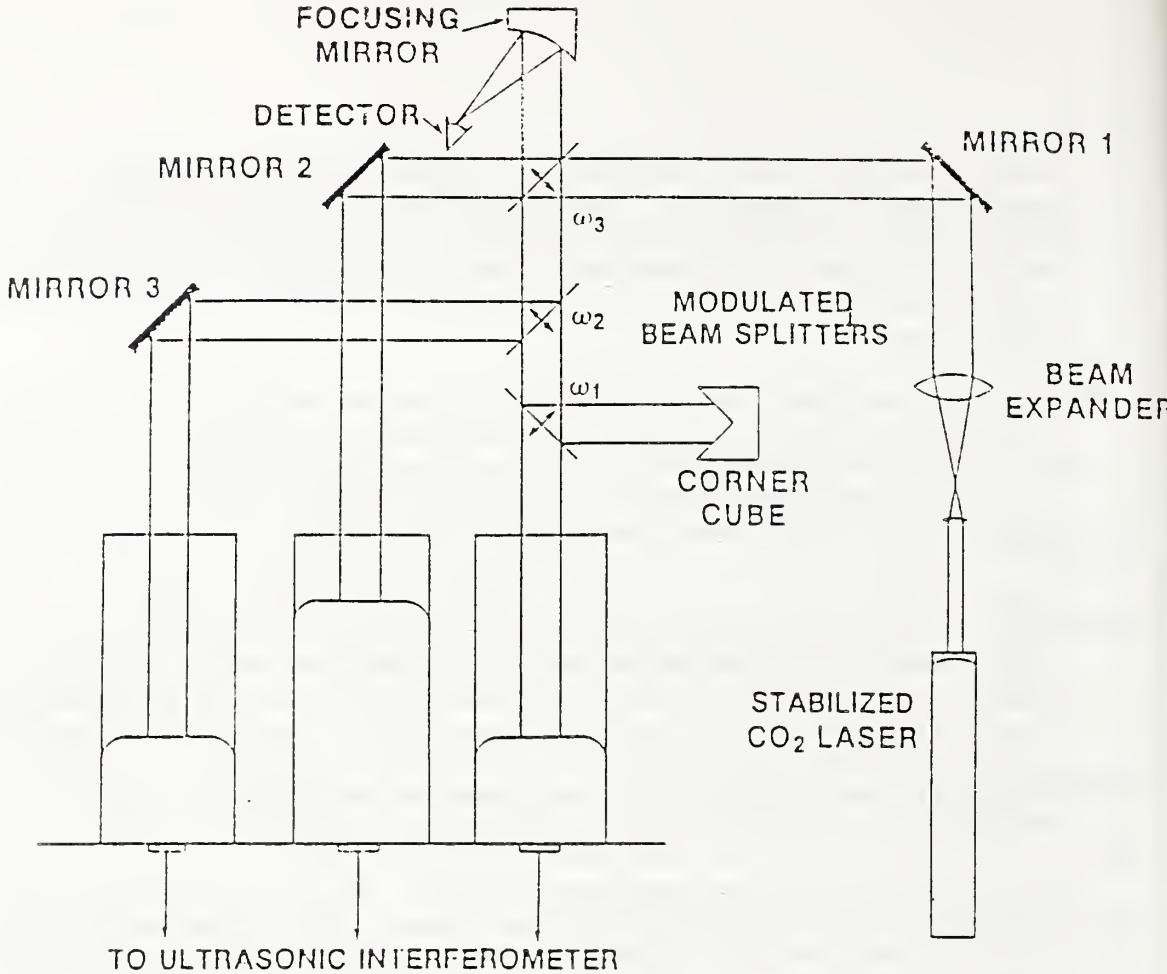


Fig. 9. Schematic of the speed of sound apparatus. The length of the center mercury column can be changed and this change simultaneously measured ultrasonically and by the optical interferometer. This determines the ultrasonic wavelength, and hence the speed of sound, in terms of the known wavelength of the frequency stabilized laser. The interferometers include provisions to correct for possible tilts and to align the measuring axis with the vertical.

VII.C. HIGH VACUUM STANDARDS

This year has been a busy one, characterized first by continuing growth in calibrations and second by a major effort to carefully document the primary high vacuum standard.

The calibration load has continued to expand as predicted. In FY84, 12 "for fee" calibrations were performed, in FY85, 24, and in FY86, 32 calibrations were performed, generating $52 k in fees. Eleven of these were ionization gages and 21 were spinning rotor gages (SRGs). The SRG continues to grow in popularity for use as a transfer standard with which to calibrate ionization gages in other laboratories and we anticipate that many of the new SRGs sold in the coming year will eventually come to us for calibration. Part of this work load may be picked up by vacuum calibration facilities being established at other laboratories. As an example, Sandia National Laboratories will soon be in a position to handle SRG calibrations for certain Department of Energy contractors. The expansion of our service down to 10^{-6} Pa and the growing awareness of the existence of the NBS high vacuum calibration service have lead to increased ionization gauge calibrations and we see no relief in this area. Two projects are scheduled for the coming year to increase our efficiency. The first is to install a new, larger chamber in the primary standard. This will permit more gages to be calibrated at one time. Secondly, the flowmeter, which forms one major component of the primary standard, will be automated to the extent that data will be taken and analyzed automatically. Customer controllers will still be read manually and calibration reports will continue to require individual attention.

Considerable effort went into the documentation of the primary high vacuum standard. Topics covered were the theory, design, construction, use and uncertainties in the orifice-flow system. Much of the analysis of the flowmeter came out of the leak standards program but all SRG and ionization gage data were examined in order to assess system performance - - in particular, systematic differences between various configurations of the orifice-flow system and between the primary standard and the SRG transfer standards. The final uncertainties were not very different from our first estimates - the total uncertainty (systematic plus three times random) is 1.5% between 10^{-4} and 10^{-2} Pa, rising to 2.6% at 10^{-1} and 7.2% at 10^{-6} Pa.

Preliminary work was done using the SRGs as transfer standards to assess flowmeter performance at very low flow rates by using a very small orifice in an auxiliary chamber. This work will complement the work done using leaks as transfer artifacts in this very low flow range.

A large set of data was taken last year for an international round robin under the auspices of BIPM but the results were inconclusive because the SRG rotors were damaged in transit and the resulting shifts in calibration were much larger than the anticipated uncertainties. The rotors are being returned to NBS this fall for further calibrations. The work was combined with a set of calibrations and a total of 14 SRGs was tested. In addition to the BIPM round robin, one ionization gage and two SRGs have been calibrated against the primary standard and will be exchanged with national laboratories in Japan and Italy.

We have spent considerable time studying the performance of the SRGs with emphasis on stability and performance at pressures as low as 10^{-4} Pa. The first part of this program has been to monitor long and short-term stability. In the course of our work, we have accumulated a very large bank of SRG data consisting of some 513 calibrations of 56 different rotors, some of which have been in use for as long as three years. Figure 10 is a histogram of the effective accommodation coefficients (calibration constants), S, of 46 smooth balls as determined by calibrations against the orifice-flow standard. This gives some idea of the errors that might occur when uncalibrated balls are used (i.e., S set to 1). We have also done some work using SRGs to check the non-linearity of the orifice conductance at higher pressures to establish error bounds at the upper limit of the orifice-flow standard.

In the second part of our characterization program, Bernd Lindenau from KFA in Julich, Germany spent last year with us working on SRG rotor properties which affect performance, particularly the stability of the residual drag. He examined rotors of several different materials and surface finishes in an effort to reduce frequency dependence and temperature sensitivity. This work will be presented at the American Vacuum Society (AVS) meetings this fall along with SRG performance data gathered at NBS. In view of the wide acceptance of the SRG as a transfer standard, we hope to continue work on the residual drag, the stability of which constitutes the limiting factor for low pressure work. However, this stability depends on the material, magnetic structure and geometry of the ball and we are, at this time, unable to predict the performance of individual balls without extensive testing.

Because the SRG is so new and its use is growing so rapidly, we have devoted substantial resources to educational activities and discussions with users. Toward this end, we conducted two Spinning Rotor Gage Workshops during the winter with both classroom discussion and hands-on training in the laboratory. In addition, NBS personnel moderate a Spinning Rotor Users Group at the American Vacuum Society meetings which provides an informal means of sharing information between users and potential users. Thirty to forty people attended the last meeting; another will be held this fall. Finally, one of our group members serves on the AVS Recommended Practices Subcommittee on the Use of the Spinning Rotor Gage as a Transfer Standard. The foundation of the recommended practice will be the NBS notes distributed at the Workshops.

This year, the national meeting of the American Vacuum Society and the International Vacuum Congress occur simultaneously in Baltimore, Md. We expect a large influx of visitors from both the U. S. and overseas. In order to tap this resource, we will host a meeting of standards laboratory personnel to discuss the SRG as a transfer standard.

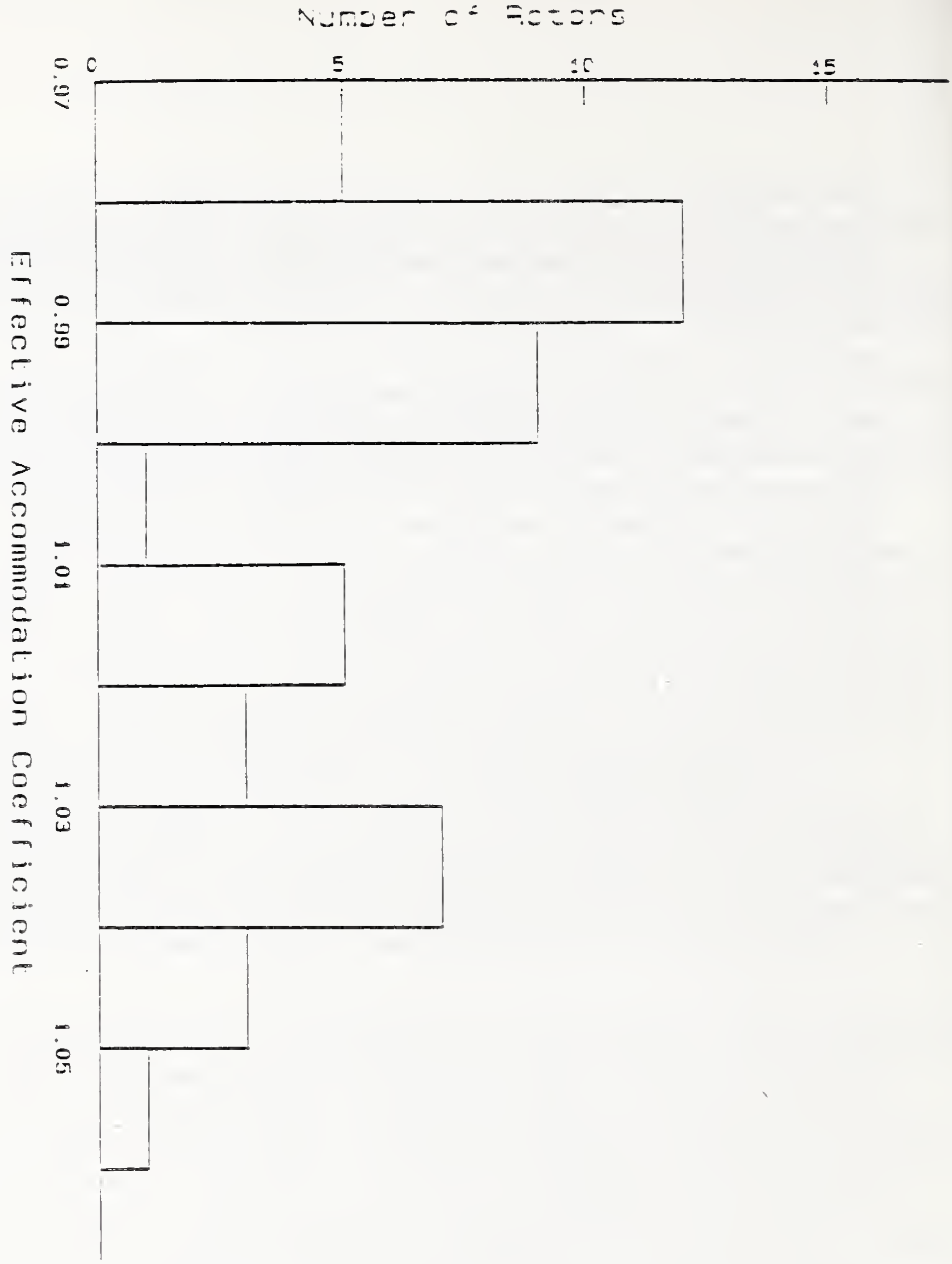


Fig. 10. Accommodation coefficients ("calibration constants") for 46 smooth spinning rotor gauge rotors indicating possible errors if an uncalibrated rotor is used and the accommodation coefficient is set to 1. Most of these rotors were new but many were customer gauges and may have been used before calibration.

VII.D. UHV STANDARDS AND GAGING

During the past year, our work in ultrahigh vacuum (UHV)standards and gaging has been concentrated in two areas: (1) UHV ionization gage characterization, and (2) development of a new UHV standard. In addition, we have (3) organized an ultrahigh vacuum gaging workshop and have (4) sponsored an investigation at Pennsylvania State University on a new type of UHV gage.

(1) Work is in progress to characterize and understand the behavior of a variety of commercial hot cathode ionization gages [here taken to include residual gas analyzers (RGA) with hot cathode ionizers] in the pressure region 10^{-6} to 10^{-2} Pa (3×10^{8} to 3×10^{12} molecules cm^{-3}). The emphasis is on the pressure dependence of gage response at fixed bias voltages and emission current, and on both the long and short term stability of this response.

(a) As part of this gage characterization program, several types of nude UHV Bayard-Alpert gages of both US and European manufacture (including a modulated gage and an extractor gage) have been calibrated on our existing high vacuum calibration apparatus. The data are being analyzed, and we intend to discuss them at an upcoming vacuum gaging workshop [See (3) below].

(b) The widespread and increasing use of residual gas analyzers in science and industry has prompted us to begin looking into the possibility and practicality of calibrating these instruments. To this end, over the past year and a half we have acquired eight instruments of the electric quadruple type and two of the magnetic sector type, all of differing manufacture. We are now in the process of learning to use these instruments and are obtaining some baseline data on the short and long term stability of their response.

Another motivation for investigating RGA's as UHV gaging instruments is that they may possibly allow us to calibrate helium leaks below 10^{-12} moles/second as progress is made with the development of our flowmeters, independently of progress made in reducing the residual hydrogen gas background in our vacuum vessels [See (2) below].

(2) The areas of UHV gaging and UHV standards are not independent. Characterizing and understanding ionization gages at pressures below the present lower limit (10^{-6} Pa) of our calibration facility depends

on having the means to generate these low pressures in a controlled and reproducible way. A very important use of a new (extended) UHV standard would be to directly measure and study the contribution of the pressure-independent X-ray current in conventional Bayard-Alpert gages, and to evaluate the techniques that have been used to account for this effect. A new chamber, under construction at the time of last report, has been completed. It was built principally to serve as a prototype for a new UHV standard. The 10^{-8} Pa residual gas background in the chamber of our present high vacuum standard limits our ion gage calibrations to pressures above 10^{-6} Pa. Our approach to solving this problem has been to begin with the same basic design as the existing standard and concentrate our efforts on ways to reduce the residual gas background (mostly hydrogen). Experiments planned or now underway with this new chamber include the following:

(a) Extended (5 days or longer) baking of the pumped chamber at 450 to 500 °C in a dry nitrogen external atmosphere. The idea is that the high temperature will increase the rate at which dissolved hydrogen diffuses out of the metal so that in a reasonably short time we may obtain a significant lowering of the concentration of dissolved hydrogen and a corresponding reduction in the rate at which the hydrogen comes out of the metal at room temperature. The external atmosphere of dry N_2 is to prevent introduction of more hydrogen from the H_2, H_2O, and CH_4 which are present in normal air.

(b) Experiments to determine how much of the background is due to permeation of the vacuum chamber wall by molecular hydrogen and water vapor in the ambient atmosphere.

(c) Experiments to determine how much of the residual hydrogen is coming from the turbomolecular pumps used on our vacuum chambers. Experiments with other kinds of pumps (i.e., cryopumps and getter pumps).

If these experiments do not lead to a reduction in the residual hydrogen pressure by at least a factor of 10, the most likely course we will follow will be to construct a second chamber out of aluminum, a material which is more difficult to work with from the standpoint of vacuum technology, but which is relatively impermeable to hydrogen and other gases.

(3) An ultrahigh vacuum gaging workshop organized by members of the vacuum standards group at NBS will be held November 3 and 4, 1986 at the Sheraton-Potomac Hotel in Gaithersburg, Maryland. The workshop will address UHV gaging needs in different areas of vacuum science and

technology, past and present gaging research, performance of UHV gages, and UHV standards. The emphasis will be on total pressure gages.

(4) The NBS is sponsoring work at the Pennsylvania State University on a UHV gage based upon the random (Brownian) motion of a very small particle suspended in a low pressure (< 10^{-4} Pa) gas. Some progress has been made. Three different particle levitation schemes have been successfully tried and a limited amount of computer modeling has been performed on particle motion as a function of pressure. This work is directed by one physics department faculty member and carried out by physics graduate students. Two of the students have expressed serious interest in continuing this work for their Ph.D. thesis. However, there are a number of issues to be resolved before the feasibility of a Brownian motion vacuum standard can be determined, and it is not clear what level of support the NBS can continue to provide.

VII.E. LEAK STANDARDS

Until this year there have been no nationally recognized standards in the area of leak rate (or very low flow rate of gas) available to U.S. industry. This has not been for lack of interest on the part of the leak measurement community. For example, a new subcommittee of the American Vacuum Society has been established to rewrite the antiquated standard AVS 2.2 (Method for Vacuum Leak Calibration), and have followed with considerable interest and anticipation the establishment of an NBS leak rate calibration service. In certain instances, such as the transportation of nuclear fuel, legal requirements for the traceability of leak measurements exist. The quantification of leakage rates can also improve the quality control of countless manufactured goods, from integrated circuits to refrigeration systems, inertial guidance systems to light bulbs. In 1984 NBS recognized that the area of leak rate standards would be an important addition to its calibration services and established the leak rate standards program in the Vacuum Group of the Temperature and Pressure Division.

After considerable effort outlined below, the NBS leak rate standards program has progressed this year to the point where a Special Test Service for fixed-reservoir helium permeation leaks was announced in July over the range 10^{-8} to 10^{-11} mol/s ($2x10^{-4}$ to $2x10^{-7}$ atm cc/s @ $0^{o}C$). The first two Special Test Reports were issued for NBS-owned artifacts that are being loaned to EG&G Idaho for use in cask leak detection at the Three Mile Island nuclear power plant site, and NBS personnel have also observed the use of artifacts at that site. By exploring our capabilities at the low-flow-rate end of our equipment, we found that we were able to provide these Special Tests at levels required to meet the ANSI N14.5 requirements for shipping casks. Work will continue on measuring leak rates of artifacts belonging to EG&G Idaho for use at TMI.

The data base required to offer this service to the public was established this year using the NBS-developed Primary Leak Standard. The standard consists of an orifice flow system connected to one of two flowmeters. One of the flowmeters is a direct piston motion type, while the other avoids gas leakage problems inherent in the first by having the piston displace oil in a reservoir, hydraulically linking the piston to a moveable bellows. This bellows flowmeter was tested extensively for the first time this year. Several fixed-reservoir artifacts have been investigated in detail over long time periods using both the piston and bellows flowmeters. The data provide information on the stability and long-term repeatability of both the artifacts and the entire system. An archival publication presenting the error analysis of the flowmeters has been written. We have basically been very pleased at the performance of the two flowmeters. Their performance has remained satisfactory to much lower flow rates than we initially thought possible. However, recent data indicate that we may have reached the point where errors have become intolerable and more complicated procedures must be employed to extend the leak range lower. The attached control chart (Fig. 11) for leak artifact serial number NBSL30 illustrates this point for a nominal flow rate of 6.5×10^{-13} mol/s (10^{-8} atm cc/s @ 0°C). For this flow rate the random errors are comparable to or larger than the systematic errors and will become progressively larger if the flowmeter is to be used below this point. The general industry requirement is $\pm 10\%$ imprecision at this flowrate, whereas we are presently at about $\pm 25\%$. We hope to be able to reduce this level in the coming year. Control charts have also been established to monitor the stability of other artifacts, and comparisons have been performed with other nationally and internationally recognized primary standards laboratories for several artifacts. Work has also begun in evaluating the performance of the residual gas analyzers that are an increasingly important component of the Primary Leak Standard at low flow rates. It is clear that instabilities are a problem, and we will need considerably more data before it can be addressed.

Investigations into the time and temperature dependence of fixed-reservoir helium permeation artifacts are continuing using the leak comparator system. Data have been taken from 0 to 50 $^{\circ}$C for 7 different artifacts in order to determine the range of parameters in the general temperature dependence equation

$$L = A\,T\,e^{-B/T}$$

where L is the leak rate of the artifact at absolute temperature T, A is a normalization parameter and B is a parameter that depends on the properties of the glass permeation element. The B parameter is consistently found to be in the 2700 - 3300 K range for commercial artifacts. We have also obtained data on the time response of the leakage rate to a sudden change in the back pressure of helium in the artifact reservoir. We will continue these artifact investigations next year.

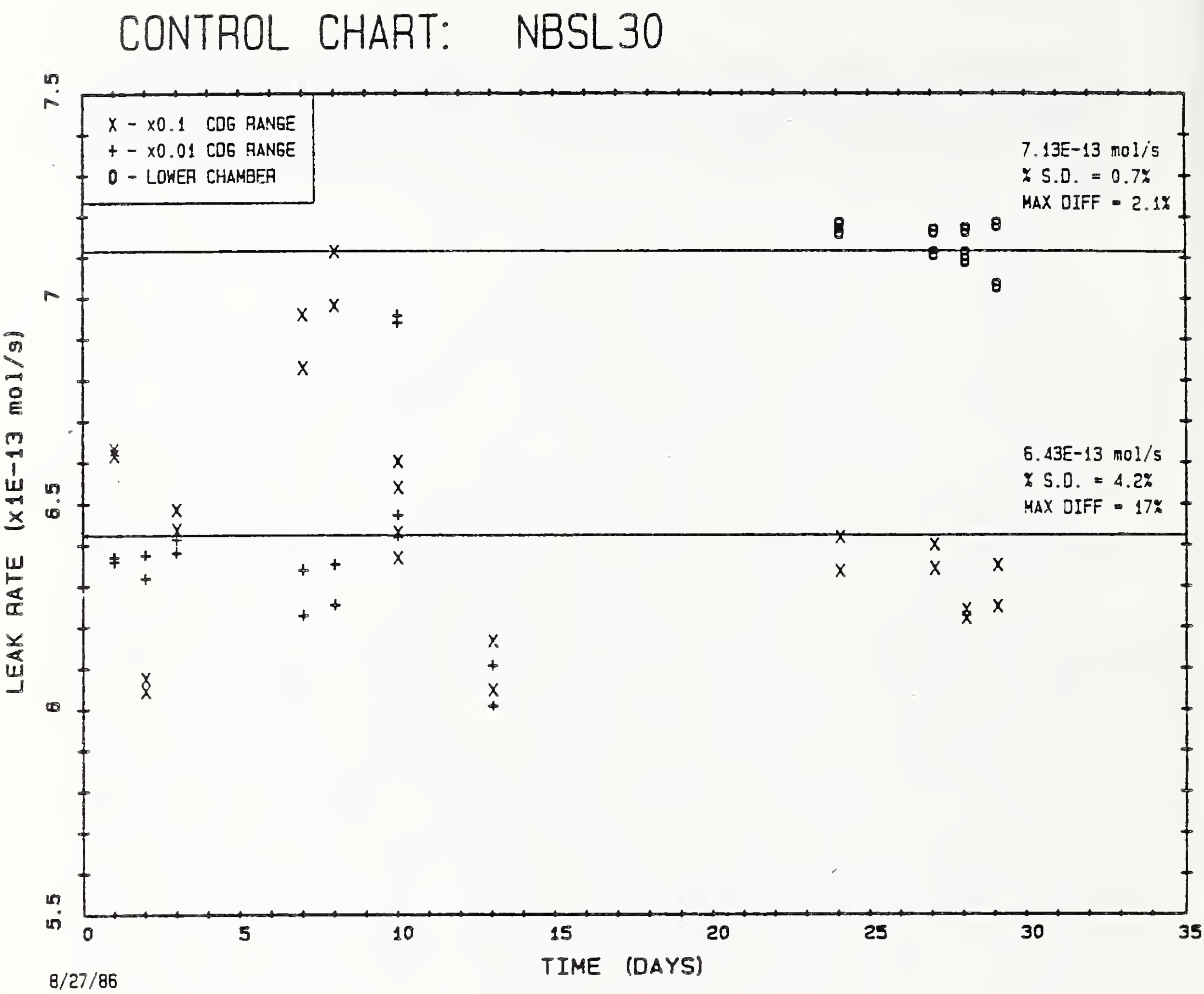


Figure 11. Repeat calibration data for a helium permeation leak. Data up to day 13 were obtained while the laboratory temperature was perturbed and the large scatter indicates a possible problem with temperature correction. Temperatures after day 13 were more normal and the data represented by X's have a significantly smaller scatter. The data represented by 0's were obtained using a flow division technique. Their systematic difference from the other data suggests flowmeter errors that may set the lower useful limit of the flowmeter.

INVITED TALKS

Temperature and Pressure Division (522)

Charles D. Ehrlich, "Present Status of the Leak Standards Program at the National Bureau of Standards," Sixth Annual Symposium of the Tennessee Valley Chapter of the American Vacuum Society, April 29, 1986.

Charles D. Ehrlich, "Status of the NBS Leak Standards Program," Fall Conference of the American Society for Nondestructive Testing, October 2, 1986.

B.W. Mangum, "Development of New Standard Reference Materials for Use in Thermometry," Measurement Science Conference, Irvine, CA, Jan. 24, 1986.

B. W. Mangum, "Resistance Thermometers," Beijing Glass Research Institute, Beijing, China, April 22, 1986.

B. W. Mangum, "Temperature Fixed Points Near Room Temperature," National Institute of Metrology, Temperature Measurement Laboratory, Beijing, China, April 23, 1986.

B. W. Mangum, "Temperature Fixed Points - Their Significance and Applications," Invited lecture sponsored by the Shanghai Municipality Society of Metrology and Measurements, delivered at the Shanghai Institute of Process Automation Instrumentation, Shanghai, China, April 26, 1986.

G. J. Rosasco, "Applications of Phase Modulated Stimulated Raman Spectroscopy," Physics Department, University of Toronto, Sept. 1985.

G. J. Rosasco, "Measurements of the Nonresonant Third-Order Susceptibility," First International Laser Science Conference, Dallas, Texas, Nov. 1985.

G. J. Rosasco, "The Effects of Velocity and State Changing Collisions on Raman Q-Branch Spectra," Eighth International Conference on Spectral Line Shapes, Williamsburg, VA, June 1986.

G. J. Rosasco, "Nonlinear Raman Spectroscopy with High-Resolution CW-Lasers," Tenth International Conference on Raman Spectroscopy, Eugene, Oregon, Sept. 1986.

Robert J. Soulen, "Recent Advances in Pressure and Temperature Measurements at NBS," National Institute of Metrology, Beijing, China, August 22, 1986.

Robert J. Soulen, "Fixed Points for Use Below 10 K," National Institute of Metrology, Beijing, China, August 22, 1986.

Robert J. Soulen, "Recent Advances in Pressure and Temperature Measurements at NBS," University of Science and Technology, Hefei, China, August 26, 1986.

Robert J. Soulen, "Recent Advances in Temperature Measurement," Tongji University, Sahnghai, China, August 30, 1986.

Robert J. Soulen, "Resistance Thermometry," Tongji University, Shanghai, China, August 30, 1986.

Robert J. Soulen, "Temperature Fixed Points for Use below 10 K," Tongji University, Shanghai, China, August 30, 1986.

Robert J. Soulen, "The Physics of Temperature," Zhejiang University, Hangzhou, China, Sept. 2, 1986.

Robert J. Soulen, "Temperature Fixed Points Below 10 K," Zhejiang University, Hangzhou, China, Sept. 2, 1986.

Robert J. Soulen, "Resistance Thermometry," Zhejiang University, Hangzhou, China, Sept. 3, 1986.

Robert J. Soulen, "He 3 Melting Curve Thermometry," Zhejiang University, Hangzhou, China, Sept. 3, 1986.

Robert J. Soulen, "Paramagnetic Thermometry," Zhejiang University, Hangzhou, China, Sept. 3, 1986.

Robert J. Soulen, "Recent Advances in Pressure and Temperature Measurements at NBS," Zhejiang University, Hangzhou, China, Sept. 4, 1986.

Robert J. Soulen, "SQUID Noise Thermometry," Zhejiang University, Hangzhou, China, Sept. 5, 1986.

Robert J. Soulen, "The Development of an International Temperature Scale Below 1 K," Physikalisch Technische Bundesanstalt, West Berlin, Germany, Sept. 13, 1986.

Charles R. Tilford, "Vacuum Gaging - Problems and Possibilities," 9th Annual Meeting of the Italian Vacuum Society, Florence, Italy, October 7, 1985.

Charles R. Tilford, "Aircraft Altimetry Metrology in the Real World", Instituto di Metrologia "G. Colonnetti, Turin, Italy, Oct. 14, 1985.

Charles R. Tilford, "Progress in Vacuum Standards at NBS," 1986 Measurement Science Conference, Irvine, CA, Jan. 23, 1986.

Charles R. Tilford, "Review of the Characteristics of High Vacuum Gages", 22nd Annual Meeting of the New Mexico Chapter of the American Vacuum Society, Albuquerque, NM April 26, 1986.

Charles R. Tilford, "Vacuum Standards and Gages," National Institute of Metrology, Beijing, China, May 9, 1986.

Charles R. Tilford, "Ultrasonic Manometry," National Institute of Metrology, Beijing, China, May 10, 1986.

Charles R. Tilford, "Properties of Vacuum Gages," Nanjing Institute of Technology, Nanjing, China, May 15, 1986.

Charles R. Tilford, "Vacuum Standards at NBS," Shanghai Institute of Metrological Technology, Shanghai, China, May 19, 1986.

Charles R. Tilford, "Properties of Vacuum Gages," Shanghai Institute of Metrological Technology, Shanghai, China, May 20, 1986.

Charles R. Tilford, "High Vacuum Standards at NBS", Korean Standards Research Institute, Taejon, South Korea, May 27, 1986.

Charles R. Tilford, "High Vacuum Gages: What to Look For", New England Chapter of the American Vacuum Society Workshop on Vacuum Technology for Micro-Electronic Processing, Nashua, NH, June 11, 1986.

Charles R. Tilford, "The National Bureau of Standards Vacuum Standards Program," ISA Symposium for Innovation in Measurement Science, Geneva, NY, August 5, 1986.

Charles R. Tilford, "Characteristics of Vacuum Transfer Standards," Southern California Chapter of American Vacuum Society Workshop on Vacuum Gage Calibration," Los Angeles, CA, August 14, 1986.

Charles R. Tilford, "Progress in Vacuum Standards", Southern California Chapter of American Vacuum Society Workshop on Vacuum Gage Calibration," Los Angeles, CA, August 14, 1986.

Sharrill D. Wood, "The Spinning Rotor Vacuum Gauge", ISA Symposium for Innovation in Measurement Science, Geneva, NY, August 5, 1986.

PUBLICATIONS

Temperature and Pressure Division (522)

IN PRINT:

1.Ruben J. Lazos-Martinez and **Vern E. Bean**, "Elastic Distortion of Piston Gages," Physica Vol. 139 and 140B, 785-787 (1986).

2.**Vern E. Bean**, "Pressure Metrology: Primary Standard Piston Gages," Physica, Vol. 139 and 140B, 739-742 (1986).

3.**V. E. Bean** (Chairman), S. Akimoto, P.M. Bell, S. Block, W. B. Holzapfel, H. Manghanani, M. F. Nicol, and S. M. Stishov, "Another Step Toward An International Practical Pressure Scale," 2nd AIRAPT IPPS Task Group Report, Physica, Vol 139 and 140B 52-54 (1986).

4.**C. D. Ehrlich**, "A Note on flow Rate and Leak Rate Units," J. Vac. Sci. Technol. A, Sept./Oct. (1986).

5.**Richard W. Hyland, Charles D. Ehrlich, Charles R. Tilford**, and Steve Thornberg, "Transfer Leak Studies and Comparison of Primary Leak Standards at NBS and SNL," J. Vac. Sci. Technol. A, Vol. 4, 334 (1986).

6.**B. W. Mangum**, "Development of New Standard Reference Materials for Use in Thermometry," Proceedings of 1986 Measurement Science Conference.

7.**B. W. Mangum**, and **G. A. Evans, Jr.**, "Stability of Some Epoxy-Encapsulated Diode Thermometers," NBSIR 86-3337 (NASA), DoC, NBS Feb. 1986. Prepared for the National Aeronautics and Space Administration, Langley Research Center, Hampton, VA 23665-5225.

8.**B. W. Mangum**, and S. El-Sabban, "SRM 1970: Succinonitrile Triple-Point Standard - A Temperature Reference Standard Near 58.08 °C," NBS Journal of Research, Vol. 90, No. 5, Sept/Oct (1985).

9.**B. W. Mangum**, "SRM 1970 - Succinonitrile Triple-Point Standard - and Its Use in Calibration of Thermistors," Temperature Measurement; Proc. International Symposium on Temperature Measurement in Industry & Science (China Academic Publishers, Beijing, China, pp. 170-175, 1986).

10.**B. W. Mangum**, "Stability of Thermistors," Temperature Measurement; Proc. International Symposium on Temperature Measurement in Industry

and Science, (China Academic Publishers, Beijing, China, pp. 170-175 1986).

11.**H. Marshak**, P. Roman, W. D. Brewer, E. Klein, K. Freitag, and P. Herzog, "Magnetic Resonance of ^{160}Tb Oriented in a Terbium Single Crystal at Low Temperatures," Phy. Rev. Lett., Vol. 56, No. 18 (1986).

12.**K. E. McCulloh, C. R. Tilford, S. D. Wood,** and **D. F. Martin,** "The National Bureau of Standards Orifice-flow Primary High Vacuum Standard," J. Vac. Sci. Technol, A4, 362 (1986).

13.R. R. Dils, J. Geist, and **M. L. Reilly,** "Measurement of the Silver Freezing Point with an Optical Fiber Thermometer: Proof of Concept," J. Appl. Phys. 59, 1005 (1986).

14.J. Tapping and **M. L. Reilly,** "Index of Refraction of Sapphire between 24 and 1060 °C for Wavelengths of 633 and 799 nm," J. Opt. Soc. Am A/Vol. 3, No. 5, May 1986.

15.**G. J. Rosasco,** and **W. S. Hurst,** "Phase Modulated Stimulated Raman Spectroscopy," J. Opt. Soc. Am. B2, 1485 (1985).

16.**G. J. Rosasco,** and **W. S. Hurst,** "Measurements of the Nonresonant Third-order Nonlinear Susceptibility, in Advances in Laser Science - I," ed. by W. C. Stwalley and M. Lapp, Am. Inst. of Phys., NY, pp. 261- 264, (1986).

17.**G. J. Rosasco,** and **W. S. Hurst,** "Dispersion in the Electronic Contribution to the Third-order Nonlinear Susceptibility of H_2," J. Opt. Soc. Am. B, Oct. 1986.

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20.**J. F. Schooley,** "Thermometry" CRC Press, Inc., Boco Raton, Florida, 245 pp. (1986).

21.**Charles R. Tilford**, Editor, "Abstracts from a Workshop on Calibration of Residual Gas Analysers," Vacuum 35, 629 (1985).

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27. **J. A. Wise** and **R. J. Soulen, Jr.**, "Thermometer Calibration: A Model for State Calibration Laboratories," NBS Monograph 174, Jan. 1986.

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B. W. Mangum, "Triple-Point Temperature of Water (273.16 K) as the Reference Temperature for Resistance Ratios and Reference Functions of Platinum Resistance Thermometers in the New IPTS", to be published in the Comite Consultatif de Thermometrie, Sevres, France (1987).

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K. E. McCulloh, Charles R. Tilford, C. D. Ehrlich, F. G. Long, "Low Range Flowmeters for Use With Vacuum and Leak Standards," J. Vac. Sci. Technol, (1987).

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Robert J. Soulen, D. Van Vechten, "The Impedance of Radio-Frequency Biased Resistive SQUIDS," Physical Review or Journal of Low Temperature Physics, (1986).

J. A. Wise, "National Bureau of Standards Calibration Service for Liquid-in-Glass Thermometers," documentation (1986).

S. D. Wood and **C. R. Tilford**, "The National Bureau of Standards High Vacuum Standard and its Use," documentation (1986).

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Temperature and Pressure Division (522)

V. E. Bean, Chairman, AIRAPT (International Association for the Advancement of High Pressure Science and Technology) Task Group on the International Practical Pressure Scale.

V. E. Bean, Member, BIPM (International Bureau of Weights and Measures) Consultative Committee for Mass and Related Quantities, Working Group on Medium Pressure.

V. E. Bean, Member, BIPM (International Bureau of Weights and Measures) Consultative Committee for Mass and Related Quantities, Working Group on High Pressure.

G. W. Burns, Member, ANSI (American National Standards Institute) SP-1, Committee on Temperature Measurement Thermocouples.

G. W. Burns, Member, ASTM (American Society for Testing and Materials) E-20 Committee on Temperature Measurement; Member, Subcommittee E-20.04, Thermocouples.

G. W. Burns, Member, ISA (Instrument Society of America) SP-1, Committee on Temperature Measurement (Thermocouples).

C. D. Ehrlich, Member, ASTM (American Society for Testing and Materials) E-7, Committee on Nondestructive Testing; Member, Subcommittee E7.08, Leak Detection Testing.

C. D. Ehrlich, participation and attendance on the American Vacuum Society Calibrated Leak Standards Committee.

A. R. Fillippelli, Member, Committee for Recommended Practice for Calibration of Residual Gas Analyzers.

G. T. Furukawa, Member, ASTM (American Society for Testing and Materials) E-20, Temperature Measurement Committee; Subcommittee E-20.03, Resistance Thermometers; Subcommittee E-20.04, Thermocouples; Secretary, Subcommittee E-20.06, New Thermometers; Member, Subcommittee E-20.07, Fundamentals in Thermometry; and Subcommittee E-20.94, Publications.

W. S. Hurst, Member, ANSI (American National Standards Institute) MC088, Committee on Calibration of Instruments, Subcommittee SC.03, Temperature.

R. W. Hyland, Board of Directors, Vacuum Technology Division of the American Vacuum Society.

B. W. Mangum, Member, NCCLS (National Committee for Clinical Laboratory Standards) C002, Area Committee on Clinical Chemistry; Subcommittee SC.01, Enzyme Assay Condition, (?) Working Group WG.01, Temperature Measurement and Control; and Member, NCCLS C010, Area Committee on Instrumentation; Secretary, Subcommittee SC.01, Temperature.

B. W. Mangum, Vice Chairman, ASTM E-20, American Society for Testing and Materials, Temperature Measurement Committee; Member, Subcommittee E-20.03, Resistance Thermometers; Chairman, Subcommittee E-20.06, New Thermometers; Member, Subcommittee E-20.07, Fundamentals in Thermometry; Subcommittee E-20.08, Medical Thermometry, Working Group WG.02, Fever Thermometers; Working Group WG.02A, Electronic Fever Thermometers; Working Group WG.02B, Mercury-In-Glass Fever Thermometers; Working Group WG.02C, Disposable Fever Thermometers; Working Group WG.03, Continuous Clinical Temperature Monitoring Systems; Working Group WG.04, Clinical Laboratory Temperature Measurement; and Member, Subcommittee E-20.90, Executive Subcommittee.

B. W. Mangum, Member, OIML PS12, International Organization of Legal Metrology, Measurement of Temperature and Calorific Energy Committee, RS4, Electrical Thermistor Thermometers.

J. F. Schooley, Chairman, ANSI (American National Standards Institute) MC088, Committee on Calibration of Instruments.

J. F. Schooley, Delegate, 15th Meeting of International Committee on Weights and Measures (CIPM), Consultative Committee on Thermometry (CCT); and Delegate, Subcommittee WG3, Replacement of IPTS-68.

J. F. Schooley, Delegate, OIML PS12, International Organization of Legal Metrology Committee on Measurement of Temperature and Calorific Energy.

J. F. Schooley, Editorial Board, Metrologia.

J. F. Schooley, R. J. Soulen, Co-editors, **S. C.** Ramboz, assistant editor, Organizing Committee for 1986 Applied Superconductivity Conference, Baltimore, MD.

R. J. Soulen, JR., Member NCSL (National Conference of Standards Laboratories.

R. J. Soulen, Jr., Member, ASTM (American Society for Testing and Materials) E-20, Temperature Measurement Committee.

R. J. Soulen, Jr., Member, ASTM (American Society for Testing and Materials) B001, Committee Electrical Conductors, Subcommittee SC.08, Superconductors.

R. J. Soulen, Jr., Member, International Committee on Weights and Measures (CIPM), Consultative Committee on Thermometry (CCT), WG4.

C. R. Tilford, Member, ASTM E021, American Society for Testing and Materials Space Simulation and Applications of Space Technology Committee, Subcommittee SC.04, Space Simulation Test Methods, Working Group WG.01, Revision of Standards E296-70 and E297-70.

C. R. Tilford, Chairman, BIPM C002, International Bureau of Weights and Measures Consultative Committee on Mass and Related Quantities, Working Group WG.02, Working Group on Low Pressures.

C. R. Tilford, Member, RTCA SC150, Radio Technical Commission for Aeronautics, Special Committee for Minimum Performance Standards for (Aircraft) Vertical Separation Above Flight Level 290.

J. A. Wise, Secretary, ASTM E-20, American Society for Testing and Materials Committee on Temperature Measurement; Member, Subcommittee E-20.05, Liquid-in-Glass Thermometers and Hydrometers; Member, Subcommittee E-20.08, Medical Thermometry; Subcommittee E-20.90, Executive Subcommittee; and Member, Subcommittee E@20.91, Editorial and Nomenclature.

S. D. Wood, Chairman, of the American Vacuum Society Subcommittee on the Use of the Spinning rotor Gage as a Transfer Standard.

Courses Taught - Division 522

Platinum Resistance Thermometry Seminar March 17 - 21, 1986
Oct. 21 - 25, 1986

This seminar consists of integrated instruction in Platinum Resistance Thermometry, Liquid-in-Glass Thermometry, Thermocouple Thermometry, and Thermistor Thermometry to be given over a five day period. Material to be covered includes the International Practical Temperature Scale of 1968; its use in the laboratory; thermometers and instrumentation, including automatic data acquisition; the treatment of calibration data; and innovations in thermometry. Time will be split between lecture sessions and hands-on measurements in the laboratory. The seminar is especially intended for calibration laboratory personnel and others who wish to undertake precision temperature measurements. Applicants should possess undergraduate training in physics or engineering and should have some laboratory experience in metrology.

Spinning Rotor Gage Workshop - Jan. 27 - 29, 1986
Jan. 29 - 31, 1986

This two and one-half day lecture and laboratory course is directed towards users desiring to calibrate high vacuum gages using spinning rotor or viscosity gages as transfer standards. The half day lecture covers basic elements of vacuum measurements, design of vacuum calibration systems, characteristics of hot filament ionization gages, and theory and operating characteristics of spinning rotor gages. The balance of the course is spent in the NBS vacuum standards laboratory learning to use the spinning rotor gage and performing a calibration of an ionization gage. The laboratory work is performed in small groups and structured to allow ample time to address problems of individual interest.

LENGTH AND MASS DIVISION

SUMMARY OF ACTIVITIES

FISCAL YEAR 1986

I. Overview

The Length and Mass Division (LMD) has the responsibility to: maintain the U.S. primary standards for length, mass, and density; provide the first level of transfer to secondary standards; and improve the standards and measurement instrumentation through basic and applied research. As of October, 1985, the Division has responsibility for the NBS mass calibration service.

Many activities occur in support of these responsibilities. Comparisons of the U.S. standards are made with the International Bureau of Weights and Measures (BIPM) and with other national laboratories to ensure international compatibility. A close working relationship is maintained with the divisions in the National Engineering Laboratory which provide length and force calibration services to the public. This cooperation not only concerns the first level of transfer of dimensional quantities but also includes the transfer of measurement techniques and instruments, such as the portable laser length standard, the submersible balance, and the load cell mass comparator, which were developed in the LMD. Cooperative projects with outside institutions, such as state metrology laboratories, universities, and private corporations, ensure that our activities are relevant to the problems of the measurement community. The Division is frequently requested to provide information and assistance to public and private organizations which need state-of-the-art length and mass measurements and cannot obtain adequate support from the private sector.

Length activities this year involved the determination of the Rydberg constant to a higher level of accuracy than had been previously achieved, collaboration with the Electricity Division on length metrology related to the redetermination of the NBS ohm by means of the reactivated NBS calculable capacitor in an effort to have sufficient information to adopt a value for a working standard of resistance based on the quantized Hall effect, and continuing development of the laser controlled kilogram comparator.

Activities in the mass program focussed on: development of servo-controlled kilogram balances for primary mass comparisons; development of retro-fitted servo-systems and automated weight changers for commercial balances used in the calibration program; continuation of an international round-robin to measure solid density artifacts; implementation of improved quality controls for mass calibrations; participation in a new measurement of the gas constant; and circulation of the new transportable mass measurement package to state and industrial metrology laboratories.

The atomic theory projects in the Division were significantly reduced this year. John Cooper is now collaborating with scientists in the Center for Radiation Research on experimental photoabsorption spectroscopic measurements in metallic vapors.

The DOD is continuing to sponsor a research activity aimed at the development of stable capacitance standards. Robert Cutkosky of the Length and Mass Division is providing the design and guidance for the technical work, which is being carried out by Mr. Lai H. Lee of the Electricity Division.

II. Technical Activities

1. Length Measurements and Standards

The length activities this year included the usual responsibilities of realizing and disseminating the length standard to industrial and scientific laboratories and also included the continuation of projects to extend the applications of high precision length measurements.

A. NBS Portable Laser Length Standard

The NBS laser length standard continues to be the instrument which generates the most interest for national and international laboratories which are in the process of acquiring the capability of realizing the unit of length to support science and industry. Activities this year involved its use in the measurement of fundamental constants and in extending the range of length measurements into the atomic domain. Howard Layer visited the Korean Standards Research Institute on the occasion of its tenth anniversary and participated in the scientific symposium which followed the ceremony. Formal contacts have also been made with Finland and Israel for the transfer of the laser length standard technology and will involve additional technical cooperation in the coming year.

ACCOMPLISHMENTS: The NBS portable laser length standard is currently being used in two new measurements of the ohm by means of the calculable capacitor: one in the Van Swinden Laboratory in Delft, the Netherlands, and the other in the NBS Electricity Division. These measurements are part of the continuing international effort by the electrical standards community to establish the quantized Hall effect as the primary standard of resistance. A meeting of the CCE was held at the end of the summer of 1986 to compare the results of the participating national laboratories. Howard Layer installed a laser system consisting of two lasers, an iodine stabilized laser reference and the cavity mode stabilized working laser, and the electronics necessary to calibrate the working laser. In addition, he has assisted

John Shields in disassembling, cleaning, making and replacing parts, and adjusting the calculable capacitor in an effort to upgrade its performance.

The Length and Mass Division is continuing to provide length measurement support for the gamma-p measurement in the Electricity Division and the silicon lattice measurement in the Quantum Metrology Group.

The collaboration with Dr. William Lichten of Yale University on the measurement of the Rydberg constant by using crossed atomic and optical beams has continued to make progress and has resulted in a value which has a precision of several parts in 10^{10}. This result is consistent with previous measurements and appears to be at the limit of accuracy which can be achieved with visible radiation.

PLANS FOR FY87: The work of providing access to the length standard through the iodine stabilized laser will continue at approximately the same level as in FY86 with the exception that the level of activity on the calculable capacitor measurements will be reduced in the beginning of FY87. Considerations are being given to a Rydberg constant measurement which would operate in the infrared and would be potentially capable of improving on the visible measurement by perhaps as much as an order of magnitude.

B. Servo-system for the NBS Scanning Tunneling Microscope

In the course of developing a capacitance motor and a highly stabilized electronic driver for the electrostatically servoed mass comparator, a collaboration between the Radiation Physics Division and the Length and Mass Division resulted in the construction and operation of a scanning tunnelling microscope (STM). This instrument, in which a sharp tungsten emitter is held within a few atomic diameters from a conducting surface by a high stability servo system, has many applications within the NBS and particularly the Length and Mass Division. It is a superior non-contacting probe and it provides a means of constructing a alternate configuration for the metal-insulator-metal (MIM) diode which has been used so successfully at NBS Boulder for comparing laser frequencies.

ACCOMPLISHMENTS: The major development of the servo system for the scanning tunneling microscope has been completed and is in operation in the Radiation Physics Division of the Center for Radiation Research. This microscope presently has a vertical resolution of a few Angstroms and it appears it will be capable of atomic resolution in both vertical and horizontal directions as soon as the new vacuum instrument is operational. The development of very high-stability high-voltage amplifiers was initially stimulated by the extreme sensitivity requirements of the STM. The latest model has a 2000 volt output and a drift which approaches 1/10 ppm over a 15 minute period.

This performance now exceeds the requirements of the STM but will be crucial for servoing the kilogram comparator.

With the completion of his collaboration on the servo-system for the STM, Howard Layer will redirect his efforts toward completion of the electrostatically-servoed kilogram comparator.

PLANS FOR FY87: Our contribution to the development of the STM has been completed and substantial further collaboration is not anticipated. However, several applications of this technology are of importance to the Length and Mass Division and these include its use as a non-contacting probe for length measurements and as a base for controlling the antenna substrate distance of a MIM diode. The stable high voltage amplifier will be used in the mass comparator program.

2. Mass Measurements and Standards

A. Servo-controlled Primary Kilogram Comparators

Two parallel projects are underway to develop completely new types of automated mass comparators. Both use the same basic structural design: cast aluminum base plates, symmetrical cast beam, etc. They differ in that one will use laser sensing of the beam position, an electrostatic servo-motor to restore the beam, and knife-edge pivots while the other will use a simple electromagnetic beam servo-system and commercial flexure pivots. Additional modifications have been made on the Voland balance which is now being used to calibrate working standards for the calibration laboratory.

ACCOMPLISHMENTS: The Voland balance, which last was retrofitted with a servo-control last year, has been further modified to improve the hydraulic weight changer and thermal environment. In addition, the data acquisition was fully automated.

In last year's report, it was noted that the standard deviation of the Voland balance, despite expectations, did not improve under servo control. Reasons for this were investigated and, as a result of minor adjustments, the long-term standard deviation has improved from 4 µg to 1.3 µg. The new number is now based on over 70 degrees of freedom. It is interesting note that the present standard deviation of the 1 kg Voland is now some 2 1/2 times lower than that of the NBS-2 balance as it performed at NBS before shipment to the BIPM.

All of the major components, except for the electrostatic beam restoring motor, have been completed and assembled for the new laser servoed knife-edge balance. A capacitance motor has been chosen for this balance because it does not require the use of magnetic materials even though a magnetic system would be advantageous from many other points of view. A very highly stabilized, low noise, high voltage electronic driver for the capacitance motor has been developed and successfully tested on the Scanning Tunneling Microscope. The capacitance motor is now under development.

A new project was initiated this year by Schoonover and Cutkosky to construct a automated kilogram comparator with flexure pivots, an electromagnetic servo system, and the same cast beam and structural components designed for the knife-edge balance discussed above. This project is divided into the following four steps:

1) Servo a beam with flexure pivots and demonstrate the required sensitivity.
2) Demonstrate precision by repeated weighings of a 1 kg weight.
3) If precision is adequate, develop a weight changing mechanism for intercomparing six 1 kg masses.
4) Investigate vacuum weighing.

The first step and the construction for the second step have been completed. Tests of the precision are now underway.

PLANS FOR FY87: Development and testing of the new kilogram comparators will continue.

B. Quality Control System for Mass Calibrations

The goal of this project is to ensure that the mass calibrations performed by NBS are compatible with the international system of mass measurements. The first step in this process -- the recalibration of the U.S. national prototype kilograms, K20 and K4, and two stainless steel kilograms at BIPM -- has now been completed and documented. Work is now underway to calibrate an group of stainless steel check standards and working standards for the calibration service. A new set of quality control procedures will be developed and implemented in the calibration laboratory to monitor the working standards.

ACCOMPLISHMENTS: The results of the BIPM recalibration have been analyzed and published. The major conclusions from that work can be briefly summarized in the following comments. The Pt-Ir standards must be cleaned in exactly the same manner as that used by BIPM in order to achieve comparable results. When the cleaning is properly done, repeated mass measurements agree to within 5 micrograms. After cleaning, the U.S. national prototype K20 was found to be only 1 microgram below its 1948 value -- a difference that is well within experimental uncertainties. The cleaning process removed approximately 20 micrograms. Repeated calibrations of the two stainless steel weights, both at NBS and BIPM, indicate a repeatability better than 30 micrograms. The majority of the non-reproducibility seems to be due to the difficulties associated with the air buoyancy correction.

The six stainless steel kilograms which will be used as check standards and working standards in the calibration service are now being monitored for stability. Their densities have been determined to high accuracy by hydrostatic weighing against our silicon transfer standards. Their masses have been measured against the stainless steel standards which were calibrated by the BIPM.

As soon as we reestablish the tie between the NBS platinum iridium and stainless steel kilograms, we will be in a position to introduce improved quality controls to our routine calibrations. We anticipate that the tie to the SI unit as maintained at the BIPM can be reestablished with an uncertainty of about 0.020 mg/kg. We believe that, by establishing a hierarchy of stainless steel standards, we will be able to maintain the NBS unit to better than 0.010 mg/kg for periods of years between comparisons of platinum iridium and stainless steel kilograms. We expect the essential features of the new quality controls to be in place by mid-year 1987.

PLANS FOR FY87: We will continue to monitor the stability of the new stainless steel standards and recalibrate N1 and N2, the present working standards of the calibration service, to carefully document any differences between the recalibrated and presently assigned mass values.

C. Laboratory Automation for the Calibration Program

There is a growing need in the NBS mass calibration laboratory and in the outside mass metrology community for automated mass comparators which perform as well as or preferably better than the mechanical balances now in common use. Modern electronic balances lack the combination of range and, most importantly, the precision required in the NBS mass calibration program. This deficiency has been overcome with the development of beam servo system that has been installed on existing high-precision mechanical balances.

The goals of this project are to automate the data acquisition of the balance observations and then to examine the possibility of automating the total calibration process.

ACCOMPLISHMENTS: A successful electromagnetic beam servo system has been developed and installed on the Voland kilogram comparator and on a Mettler model H315 balance used to calibrate the kilograms for the portable mass measurement package.

The servo system has enabled us to examine several ways to avoid the systematic errors that are known to be caused by thermal effects that arise from the presence of the balance operator and thermal gradients between the weights and the balance chamber. One approach has been to replace the operator with a mechanical weight changer. A second approach is to use a servoed thermal soaking plate which forces thermal equilibrium between the weights to be calibrated and the air in the balance chamber. Both approaches have been successfully tested and can be adapted to some of the mechanical balances used in the mass calibration program.

The remotely operated mechanical weight changers developed earlier for the Mettler balance were manually operated systems with limited applications. A new fully automatic robotic arm which is capable of loading the balance with weights in various combinations from a preloaded matrix has now been constructed.

The special robotic arm has been constructed and programmed to automatically load and unload a commercial electronic balance according to a readily modified schedule. The present system will store about 200 weights at a time on a flat aluminum plate that will be temperature regulated. Up to seven weights can be placed on the balance at a time as called for by the schedule, so that the usual weighing designs can be accommodated. The program places the weights so that the center of mass of the set is centered on the balance pan. The arm and plate have been designed so that they can be contained within a dust free, constant temperature enclosure. The enclosure will be designed and tested next year.

The robotic arm is actuated by four stepper motors controlled by a stepper motor driver which was designed with this project in mind, but which is expected to be of general utility. The driver will handle up to six stepper motors, features individually programmable velocities and accelerations for each motor, accommodates up to 12 limit switches for terminating the motor movements according to programmable masks, and drives each motor in a quarter-step mode to reduce the resonance effects usually associated with stepper motors. The driver is itself controlled from a personal computer through an IEEE 488-bus connection.

PLANS FOR FY87: Research and testing will continue on all of these automated components until adequate performance has been demonstrated. They will then be adapted to the mechanical balances in the calibration program.

D. Density of Solids

Working Group 5 of the Consultative Committee for Mass and Related Quantities (CCM) has organized an international round robin of solid density intercomparisons. NBS is serving as the pilot laboratory for these measurements.

ACCOMPLISHMENTS: The round robin has begun. NBS has made initial measurements of the artifacts and shipped them to the next participating laboratory. The artifacts include two stainless steel kilograms and two 800 g silicon crystals.

FUTURE PLANS: NBS will remeasure the density artifacts at the end of the seven-laboratory round robin. As the pilot laboratory, we will also analyze the data obtained by all participating laboratories and write the preliminary report.

E. Portable Mass Measurement Package

This project, sponsored in part by the NBS Office of Weights and Measures, is developing a transportable mass measurement package to assist State and industrial metrology laboratories in assigning mass values to kilograms, particularly those which have unusual shapes and densities and require significant air buoyancy corrections. Most laboratories have adequate balances but some lack the necessary auxiliary equipment and experience to make accurate air buoyancy corrections. This package will help to overcome these deficiencies. The package includes:

1. Calibrated kilogram masses of various geometries and densities,
2. Fractional mass standards for trimming mass differences at various altitudes,
3. Computer hardware and software for standardized data reduction and statistical control,
4. Air density instrumentation to measure temperature, barometric pressure, and relative humidity, and
5. Automatic data acquisition system for those laboratories equipped to use it.

ACCOMPLISHMENTS: The complete package has now been assembled and calibrated. It has been shipped to the California State Metrology Laboratory to begin a round robin which will include several other state and industrial laboratories.

PLANS FOR FY87: The Division will monitor the results of the round robin and make any further modifications that are required. One of the most important long-term objectives of this project is the training that participants will receive by using the package. Many participants will be exposed for the first time to state-of-the-art weighing techniques and laboratory automation. It may be desirable later to develop a formal training seminar based on the instrumentation and techniques used in this package. A further objective is to extend the mass calibration capability of the package from the 1 kilogram level down to 1 mg.

F. New Measurement of the Gas Constant

One of our staff (Davis) participated in a redetermination of the ideal gas constant, R. The experiment was conceived and lead by M. Moldover of the Thermophysics Division. Our task was to determine the interior volume of a 3 liter sphere by weighing the amount of mercury needed to fill it. We aimed for a precision of better than 1 ppm and a total uncertainty which would be dominated by the accuracy of the mercury density, which was determined in the 1960's by Cook at NPL. We believe we have succeeded in these objectives.

It is expected that the experiment will be repeated in the future. A second technique for measuring interior volume, using microwave resonances, may eventually play a role in the redetermination of the density of mercury and other liquids and gases.

PUBLICATIONS

R. S. Davis, "Documentation of the NBS Mass Calibration Services," (Internal Document).

T. J. Quinn, C. C. Speake, and R. S. Davis, "A 1 kg Comparator Using Flexure-strip Suspensions; Preliminary Results." Accepted by Metrologia.

H. P. Layer, "Design and Construction of the Iodine Stabilized Laser," Advances in Experimental Physics, 1986.

H. P. Layer, "Scanning Tunneling Microscopy Applied to Optical Surfaces," Optics Letters, September, 1986.

P. Zhao, W. Lichten, H. P. Layer, and J. C. Bergquist, "Remeasurement of the Rydberg Constant." In Press.

R. M. Schoonover, "Mass Comparator for In-Situ Calibration of Large Mass Standards," Bulletin OIML n° 100, page 13, September 1985.

R. M. Schoonover and J. E. Taylor, "Some Recent Developments at NBS in Mass Measurements," submitted to IEEE, 1986.

INVITED TALKS

R. S. Davis, "The Kilogram," symposium on the International System of Units at NBS, November 6, 1985.

H. P. Layer, "Applications of Stabilized Lasers," presented in Middlefield, Connecticut at the Zygo Corporation, November 1985.

H. P. Layer, "The Meter," symposium on the International System of Units at NBS, February 14, 1986.

H. P. Layer, "Role of Lasers to Length Measurement," presented in Seoul, Korea at the Korea Standards Research Institute, May 1986.

H. P. Layer, "Application of Lasers to Length Measurement," presented in Raleigh, North Carolina at the Region 3 meeting of the National Conference of Standards Laboratories, September 1986.

R. M. Schoonover and J. E. Taylor, "Some Recent Developments at NBS in Mass Measurements," presented at the IEEE Instrumentation and Measurement Technology Conference in Boulder, CO, March 25-27, 1986.

R. M. Schoonover, "Standards Lab Practice," presented at George Washington University, April 17, 1986.

R. M. Schoonover, "Standards Lab Practice," presented at George Washington University, October 20, 1986.

TIME AND FREQUENCY DIVISION
FISCAL YEAR 1986

I. INTRODUCTION

The Time and Frequency Division located in Boulder, Colorado is responsible for the U.S. standards of time and frequency. There is a secondary responsibility for the realization of the meter, since, by international agreement, the standard of length is now based on the frequency standard with the speed of light accepted as a constant. The division played a lead role in the measurement of the speed of light and has worked on the realization of the meter as well. However, primary responsibility for maintaining the standard of length and disseminating it resides in the Length and Mass Division.

The most important product of the division's work is the service provided to science, industry, and other government agencies. Standards operation, research on new standards, and development of methods of measurement all closely support the services of the division. The extension in accuracy and range of standards, measurement methods and broadcast signals should receive sufficient emphasis to keep NBS prepared to satisfy the demands for improved services. Basic research related to standards is performed to provide a sound technical basis for future standards and services. Advisory service to Government agencies and the development of devices to serve the special needs of Government are important NBS roles which increase the efficiency of government by applying the special expertise of NBS to significant Government problems. The expertise needed to provide this advice to other agencies is derived from involvement in both basic research and goal-oriented research and development.

A number of recent developments and general trends in the field are noted before entering into a discussion of the work of the different groups in the division. The discussion of these developments/trends in section II of this report is accompanied by actions which the division deems as appropriate responses to changes in the field. Following this, the work of the division which is divided among seven groups is presented in the following order.

- o Time and Frequency Services (Section III)
- o Time Scale and Time and Frequency Coordination (Section IV)
- o Phase Noise and Hydrogen Masers (Section V)
- o Atomic Beam Standards (Section VI)
- o Ion Storage (Section VII)
- o Optical Frequency Metrology and Devices (Section VIII)
- o Geophysical Measurements (Section IX)

In order to more clearly show the program emphasis, this report is presented along the lines of the division organization. The staff working in each area is listed at the beginning of each section. There is considerable overlap between the work of several of the groups, so certain tasks may appear within the discussion for 2 or more groups.

Each section of the report begins with a short description of the general program and objectives of the group. This is followed by a list of specific FY 1986 accomplishments and the plans for FY 1987. In an effort to relate the division's work to the division's mission, a set of objectives have been used. Any one of the objectives which are listed below may appear in the description of the work of several groups since there is heavy overlap and collaboration between a number of the groups.

OBJECTIVES

- o Generate NBS time scales, UTC(NBS) and TA(NBS)
- o Broadcast time and frequency signals from radio stations WWV, WWVH and WWVB and the GOES satellites.
- o Provide seminars, calibrations and measurement assurance on a fully reimbursable basis.
- o Maintain international coordination of time scales and frequency standards using the Global Positioning System
- o Develop advanced methods for time transfer using communication satellites.
- o Provide reference frequencies from the microwave to the visible region of the spectrum.
- o Establish the units of the International System for the "second" and the "meter".
- o Make fundamental improvements in atomic spectroscopy for future application to primary frequency standards.
- o Develop metrology for precise time, frequency and length measurements.
- o Perform basic studies in program areas related to future time and frequency standards.
- o Advise and work with other governmental agencies and industry to ensure efficient use of time and frequency metrology in their programs.
- o Measure far infrared frequencies of atoms and molecules (especially transient species) for radio astronomy and upper atmospheric science.

II. RECENT DEVELOPMENTS/TRENDS

Time Transfer

Satellite time transfer has clearly become the method of choice for international time coordination and NBS has played a key role in this through development of the GPS Common-View Method. This technique provides time-transfer accuracy on the order of 10 nanoseconds and provides for comparison of primary frequency standards at a level of accuracy which is limited by the primary standards themselves. Thus, satellites now provide the means to fully use the accuracy and stability of these standards and there are several applications (e.g., NASA Deep Space Network and studies of the Millisecond Pulsar) which are already taking advantage of these gains. Two-way time transfer using commercial communication satellites should provide for time transfer at an accuracy of better than 1 nanosecond although this method requires broadcast to the satellite from each site with the attendant costs of operating a full earth station. While the GPS system (which operates in the receive-only mode) will be used for some years to come, the two-way method may replace it in the future as accuracy demands increase and NBS should be prepared for that eventuality. The ability to effectively transfer time and frequency at these levels will most likely result in more applications which can effectively use this performance and one should expect to see pressures develop for still higher performance.

Primary Frequency Standards

Radiatively-cooled, trapped ions have been considered by many to be the system of choice for future standards. Recent trapped-ion research has bolstered this view in the form of a first demonstration of a Beryllium standard operating at an accuracy commensurate with that of NBS-6, our current standard, and the development of a 'commercial' ion standard. Slowed neutral beams, on the other hand, are in an embryonic stage and no one has yet proposed a specific scheme for using them to produce a frequency standard much less demonstrating anything in the laboratory. Nonetheless, recent progress in radiative cooling and focussing of neutral atomic beams now presents the potential opportunity for the development of an advanced frequency standard operating at a performance level which is intermediate between that of the optically-pumped technology of NBS-7 and the longer-term, but higher-accuracy performance expected for trapped ions. The real appeal of a slowed, neutral-beam standard is that it might permit one to realize the current definition of the second (based on cesium) at a higher level of accuracy, since conventional cesium standards are now nearing limits imposed by Doppler shifts.

An oft neglected consideration in projecting future development of frequency standards is the performance of the oscillator which excites the clock transition. In general, one assumes that increased observation time for the clock transistion (providing a higher Q resonance) will improve the performance of a frequency standard. But, remember that atomic frequency standards are usually passive devices which must be driven with a slave oscillator and this oscillator must have sufficient short-term stability to take advantage of increased interrogation time. For microwave standards at 1 part in 10^{15} at 1 day, an active hydrogen maser (cost $500K) would most likely be needed. At much higher accuracies one would require stability beyond the current state of the art. Perhaps the emerging cryogenic masers would provide the needed stability, but these are sure to be more cumbersome than conventional active masers, at least for the next decade. Thus, in the microwave region, trapped-ion and neutral-beam standards might be limited by the performance of the slave oscillator.

The limitation imposed by the local oscillator in the microwave region may not apply if the clock transition is in the infrared or visible portion of the spectrum, because lasers with excellent short-term stability have been demonstrated. Unfortunately, none of these very highly stabilized lasers operate at appropriate atomic-clock transitions, but it appears that such stablity can be achieved (with a lot of work) at the required frequency. During the last year, the NBS Ion Group has made significant progress toward an optical frequency standard and it seems likely that they will demonstrate a prototype of such a device in the next few years. Again, the real task is to develop a radiation source of sufficiently narrow linewidth (about 1 Hz). While an optical frequency standard could be used directly in the optical region, it poses another challenge if it is to be used as a reference for microwave and lower frequencies. This challenge, of course, is that of accurately relating an optical frequency to a microwave frequency. The Division does have expertise in this area, but all would agree that this is a difficult thing to do routinely. Thus, it would seem prudent to focus some effort on this problem in anticipation of the development of an optical frequency standard. A side benefit to such effort would be the opportunity to improve upon our realization of the meter.

Time Scale

The imminent improvements in primary frequency standards place additional requirements on the NBS time scale. The current time scale, acting as a flywheel, varies in frequency on the order of 1 part in 10^{13} per year setting the current requirement for time-scale calibration by NBS-6 at once per year. At an accuracy level of 1 part in 10^{14}, calibration would have to occur about once each month. In order to assure reliability in dissemination of time and frequency signals, time-scale performance should be improved to increase the period between calibrations. Efforts should continue to upgrade both the hardware (e.g., add passive hydrogen masers to the ensemble) and the reliability of the ensemble. Research on time-scale algorithms should also continue, since this can also contribute to long-term stability.

Broadcast Services

The benefits of satellite time transfer were discussed at the beginning of this section and it should be obvious that satellite broadcasts would improve significantly upon ground-based broadcasts. NBS does operate a satellite broadcast service through the GOES weather satellites, but that broadcast is limited in accuracy to 100 microseconds by the broadcast bandwidth and the inaccuracies of the knowledge of the positions of the satellites. Communication satellites provide a potential vehicle for the realization of a very simple broadcast service with accuracy in the range of 100 nanoseconds to 1 microsecond. Recent interactions with the electrical power industry suggest the need for 1 microsecond synchronization and that industry plans to support study at NBS of such a broadcast service. The National Research Council in Canada is also studying this issue and NBS will coordinate its efforts with them, since a single broadcast service might well serve both countries. Recently, the Division has entered into discussions with the telecommunication industry on similar issues and their timing requirements seem comparable to those of the power industry, although the telecommunications industry has additional concerns about characterization of a broad range of timing equipment. With deregulation of this industry, issues surrounding synchronization at the interfaces between different operating companies have started to surface and it appears that NBS might help to resolve some of these. The synchronization problems of these two major industries are significant and their solution might be considered to provide real productivity improvements with significant cost savings and/or improvements in performance. Continued, even heightened, interactions with these industries should clearly be pursued, since work in this area would provide the very highest level of leverage for limited NBS resources.

Measurement of Phase Noise

The aerospace industry is now starting to see procurements for space hardware with specifications for components of very low phase noise. Phase-noise measurements have been well developed at a few specific frequencies for characterization of frequency standards, but little work has been done on the methodology of such measurements across important regions of the electromagnetic spectrum. The Division has just entered into a small, but long-term contractual arrangement with the Department of Defense to develop and demonstrate phase-noise measurement systems in important spectral regions. This effort will be coordinated with the work in Division 723 on broadband thermal noise standards. Phase noise is in no way a fundamental quantity, but experience has shown that it is difficult to measure and many mistakes can be made. Thus, a common methodology is needed if specifications are to be met in a reasonable fashion.

III. TIME AND FREQUENCY SERVICES

The Time and Frequency Services Group has the primary focus of direct industry and other agency support. The division broadcast services, the new Frequency Measurement Service, and the Time and Frequency Bulletin all fall within their responsibility. In addition to these on-going services the group is working on four other projects: synchronization of clocks using two-way satellite time transfer, development of time transfer techniques appropriate to a tactical (military) communication environment and space-borne communications nodes, and a broad study of timing methods useful to the electric power industry. The group's work is described in more detail below.

Staff: D. W. Hanson, Project Leader
D. A. Howe
J. L. Jespersen
G. Kamas
M. A. Lombardi
R. E. Beehler (Broadcast Manager)

WWV, WWVB, Ft. Collins	WWVH, Hawaii
J. E. Folley (Part-time)	A. Fabro (Part-time)
J. M. Maxton	E. F. Farrow
J. B. Milton, Chief Eng.	M. Ferguson (Part-time)
C. S. Snider	N. Hironaka
A. R. Trevarton	C. L. Trembath, Chief Eng.

In order to have useful standards of time, frequency, and length it is essential to provide convenient access to these standards. This is accomplished primarily via the radio broadcasts of stations WWV, WWVH, and WWVB and a time code broadcast by the GOES satellites. NBS also provides telephone time-of-day services, publications of time and frequency values of other radio stations as received at NBS, portable clock comparisons and calibrations. Seminars concerning time and frequency metrology are regularly scheduled to educate new entrants to the field.

The division's services are important in many applications involving commercial, government, and scientific activities. These include:

Navigation

Celestial navigators need time to determine their precise location. An error of 2 seconds could cause a ship to miss its destination by about one kilometer. Thus military and commercial shipping and small boat owners depend in a life and death sense on the availability of the signals from WWV and WWVH.

More sophisticated electronic navigation systems such as LORAN-C and the Global Positioning System (GPS) must maintain time much more accurately. An error of only 3 microseconds could produce the same one kilometer error for the navigator.

Systems Control and Synchronization

The electric power industry uses both frequency and time information in the management of generation and distribution of electric power. Frequency measurement has been fundamental to the industry for many years and is satisfied by signals from WWVB and GOES. Time is becoming increasingly important in the recording of fast occurring events (faults), system control, measurement of power flow, avoiding outages caused by exceeding stability limits, and for fault location on long transmission lines.

Radio and TV stations need accurate frequency to broadcast signals at exactly their assigned frequencies. They need accurate time to set station clocks so they can join the network at the right instant.

The aviation/aerospace industry needs accurate time for aircraft traffic control systems and for synchronization at satellite and missile tracking stations.

The telecommunications industry needs time accurate to one microsecond and better to synchronize communication's nodes spread over wide geographical areas.

Data Acquisition

The FAA records accurate time on its audio tapes along with the air-to-ground communications from airplanes. Having an accurate record of when particular events happened can be an important factor in determining the cause of a plane crash or equipment malfunction.

Geophysicists/seismologists studying lightning, earthquakes, weather, and other geophysical disturbances need time to enable them to obtain data synchronously and automatically over wide geographical areas. They use it for labeling geophysical events. Other scientists use time for controlling the duration of physical and chemical processes.

Astronomers use time for observing astronomical events, such as lunar occultations, eclipses, and pulsars.

Science and Metrology

Manufacturers need time and frequency to calibrate counters, frequency meters and test equipment.

Accurate spectra of molecules are needed to measure atmospheric concentrations.

Laser frequency measurements provide accurate calibration frequencies for spectroscopists and for radio astronomy as well as the means for realization of the meter.

OBJECTIVE: Broadcast time and frequency signals from radio stations WWV, WWVH and WWVB and the GOES satellites.

NBS offers several around-the-clock time and frequency dissemination services to the general public. In 1923, radio station WWV was established by NBS and has been operated since that time. A sister station, WWVH was established in 1948, on the Hawaiian Island of Maui, and relocated to Kauai in 1971. In 1956, WWVB began low frequency broadcasts. WWV's signal is also offered by a telephone service, not toll-free, by dialing (303) 499-7111. A similar service from WWVH is available by dialing (808) 335-4363 in Hawaii.

Broadcasts from WWV and WWVH can be received on conventional shortwave receivers nearly anywhere in the world. Broadcast frequencies include 2.5, 5, 10, and 15 megahertz for both stations and 20 megahertz from WWV only. Accuracies within one millisecond can be obtained from these broadcasts if one corrects for the station's distance from the receiver. These services also provide standard frequencies, a BCD time code, astronomical time corrections, and certain public service announcements from other government agencies. The telephone service offers to individuals without receivers, the capability of obtaining NBS time and audio frequency signals. The caller can receive a time signal accurate to 30 milliseconds or better, about the maximum delay in cross-country telephone lines. WWVB offers a direct path signal of greater accuracy than WWV or WWVH, but a special 60-kilohertz low frequency receiver is required. WWVB's signal includes a binary coded system, needing special decoding equipment. The WWVB broadcast covers the continental US as well as most of the North American continent. These broadcast services are coordinated with similar operations in other countries through active participation in the international CCIR organization.

NBS time and frequency signals covering about 40 percent of the earth have been relayed via GOES geostationary satellites since 1975. The GOES broadcast covers North and South America as well as major portions of the Pacific and Atlantic including parts of Europe. More than 10 years of experience has shown that such a system provides continuous time and frequency reception with more dependable propagation characteristics than HF and LF broadcasts. The satellite position broadcast with the time code permits automatic correction for variations in path delay resulting in a time accuracy of 100 microseconds.

FY 1986 Plans

Plan - Complete a major survey of the users of the NBS time and frequency dissemination services and document the results.

Accomplishment - The questionnaire was designed, reviewed extensively and submitted to OMB for approval which was granted in September, 1986. The survey should be out to users by December, 1986 and competion is scheduled for June of 1987. Software for tabulation and analysis of the responses is under development.

Plan - Upgrade WWVH data acquisition system for more convenient data transfer operations to NBS/Boulder.

Accomplishment - A PC-based, data-acquisition system was designed and installed at WWVH and the staff at the station was trained in its operation. Data monitored at WWVH is now routinely transferred to NBS in Boulder.

Plan - Transfer operational GTDS satellite orbit determination program and related operations from Boulder Cyber 750 to appropriate components of the new NBS Cyber 840/855/205 computer system. Investigate alternative links to new NOAA/Suitland computer facility.

Accomplishment - The GTDS program and the related software was successfully converted to run on either the Boulder Cyber 840 or the Gaithersburg Cyber 855. A link to the Suitland computer must await future launches of new GOES satellites.

Plan - Develop an upgraded operational software package of GOES procedures that combines separate programs into a menu-driven, fully integrated program. Update related documentation accordingly.

> Accomplishment - The GOES procedures software, GOPROC was completed, evaluated and is now used for normal operations. An improved second-generation program is under development. The major GOES documentation project was completed in September, 1986 with approval by the review committee. These 2 accomplishments provide an excellent basis for continuity of operation of the GOES service.

Plan - Maintain reliable operations from WWV, WWVB, WWVH, and the GOES satellites.

> Accomplishment - Service interruptions were held at very low levels. Downtimes were: WWV - 0.1%, WWVB - 0.02%, WWVH - 0.02% and GOES - less than 0.05%. All broadcasts were maintained within published specifications.

FY 1987 Plans

Complete survey of WWV, WWVB, WWVH and GOES users and document results.

Develop and implement staffing plans at Fort Collins and Hawaii that respond to anticipated retirements of both Chief Engineers.

Conduct tests of electronic voice synthesis system for improved broadcast announcements.

Develop second-generation, more automated software for GOES time code operations.

Develop and implement an automatic tuning system for the standby WWVB antenna.

OBJECTIVE: Provide seminars, calibrations and frequency measurement assurance on a fully reimbursable basis.

Frequency Measurement Service

This new frequency measurement service is highly automated, modest in cost, and provides traceability to NBS at a level of one part in 10^{12}, although even applications which do not require this level of performance can be readily supported. The service is based on common-view reception of low frequency signals from stations such as WWVB or Loran-C. The NBS service consists of assisting the user to set up a low frequency receiver and data logger system which is the most appropriate for his needs and his location. A typical system contains a receiver, microcomputer, disc units and printer-plotter. The user's responsibility is to provide a dedicated phone line and modem so that his data can be compared with data recorded at NBS, thus providing assurance that the measurements are valid. The user also receives a bulletin which reports the performance of many of the accurate signal sources. To assist the user in getting the most out of this system NBS provides specific training using the actual equipment.

Time and Frequency Bulletin

The Division has continued the distribution of its Time and Frequency Bulletin to over 500 users of NBS services. The preparation and mailing of this bulletin has been constantly improved to reduce costs and to increase its usefulness. The bulletin has been expanded to support our new calibration services and will continue to be improved.

Seminars

The Division seminars provide industry, calibration labs and the military with information and training on the use of frequency standards. One seminar was offered in 1985 and it was well attended. This will be continued as long as the demand is there. A special effort is made to have the seminar support the introduction of new services and to be of particular interest to the nations's calibration laboratories.

FY 1986 Plans

Plan - Continue operation of Frequency Measurement Service. Provide information on service through published articles. Develop training on disk for system users.

Accomplishment - Subscribers to the Frequency Measurement Service now total nearly 40. Automated training routines have been written and are near implementation.

Plan - As demand dictates, provide a comprehensive Time and Frequency seminar on a fully reimbursable basis.

Accomplishment - The Time and Frequency seminar held in August of 1986 was fully subscribed. The seminar was characterized by strong participation on the part of the attendees.

FY 1987 Plans

Continue operation of the Frequency Measurement Service. Implement the automated training program so as to minimize staff hours spent on the service.

Provide a comprehensive Time and Frequency seminar (reimbursable). Investigate the possibility of conducting the seminar off site so as to provide the opportunity for more effective informal contact between the attendees and the staff of the Time and Frequency Division.

OBJECTIVE: Develop advanced methods for time transfer using communication satellites.

The use of communications satellites for time transfer at all levels of performance appears to be widely accepted in light of the success of several efforts during the last few years. Much of this is also due to a number of favorable changes in the available technology, economics, and demand. At the higher levels of performance, work reported by Japan and unpublished tests involving NBS, USNO, and COMSAT Laboratories have demonstrated one-half nanosecond time comparison precisions using two-way time exchanges through a communications satellite. Additional laboratory tests have indicated that 20 picosecond comparisons are possible using the same techniques with higher transmission power levels. The tests were encouraging and resulted in an informal agreement between NBS, USNO and the NRC in Canada to work together to develop a permanent network to serve these three laboratories. All of the necessary equipment has been acquired and tests will begin next year.

The use of communication satellites for the delivery of time and frequency information on a subscription basis also appears feasible with the application of technology known as spread spectrum. The integration of this technology with careful baseband design (representation of the time and frequency information) could yield a viable (and fully reimbursable) delivery system serving important industrial and government needs in a very economical and reliable fashion. Preliminary system examination by calculation and consultation with satellite industry engineers and scientists have confirmed feasibility. Potential industrial consumers of such a service have strongly urged NBS to further develop these concepts.

FY 1986 Plans

Plan - Complete two-way time transfer system and, using the system, begin coordination with the US Naval Observatory (USNO) and the National Research Council (NRC) in Canada.

Accomplishment - A complete ground station for two-way time transfer was built and tested. The system is now fully FCC approved (licensed). Coordination between NBS, NRC and USNO has been delayed since USNO has just started to install an earth station at their Washington, D.C. facility.

FY 1987 Plans

Initiate development, with assistance from INTELSAT, of a satellite-based network for nanosecond time comparisons between all major timing laboratories in North America and Europe. Provide to each laboratory the technical and regulatory information necessary to participate in the network operation.

Begin operation of the two-way, time-transfer system on a limited basis with a few laboratories.

OBJECTIVE: Advise and work with other governmental agencies and industry to incorporate advanced time and frequency metrology into their programs.

FY 1986 Plans

Plan - Pending other agency funding, conduct studies on the synchronization of space-borne communication nodes.

Accomplishment - The study has been funded and is now scheduled for completion on April 30, 1987.

Plan - Complete study of a one-microsecond reimbursable time service. Pending additional funding, continue work on this topic in the direction indicated by the study conclusions.

Accomplishment - The study was completed in February, 1986 and a comprehensive report was delivered to the sponsor. A recomendation to study satellite tracking problems was included with the report and the sponsor anticipates that funding will be provided for that. The program was presented to top NBS management who concurred with continued study of this service. Coordination of NBS efforts in this area with those of NRC in Canada was initiated through correspondence and a trip to Ottawa. A single service might well serve both countries.

FY 1987 Plans

Complete study of the synchronization of space-borne communications nodes.

Pending funding, implement a satellite tracking network and experimentally determine how best to generate the satellite ephemeris required to support a 0.1 microsecond time and frequency broadcast service.

IV. TIME SCALE AND TIME AND FREQUENCY COORDINATION

This group has the responsibility for the operation and further development of the NBS time scales and for coordination of these time scales with other standards laboratories and the Bureau International de L'Heure (BIH). These time scales are, of course, a key responsibility since they not only provide the basis for all services, but also serve as the stable reference against which much of the division gauges its' research. The group has developed a coordination scheme based on common view of the Global Positioning System (GPS) satellites which has become the de facto coordination approach for the world.

Staff: D. W. Allan, Project Leader
D. D. Davis
J. E. Gray
H. E. Machlan
T. K. Peppler
M. A. Weiss (Part-time)
J. Levine (1/2 time)
J. Honhart (Guest Worker)
P. Lin (Guest Worker)

OBJECTIVE: Generate NBS time scales, UTC(NBS) and TA(NBS)

NBS atomic time is generated from an ensemble of approximately twelve commercial and one laboratory cesium beam frequency standard and two laboratory hydrogen masers. The time of all the clocks is automatically measured every two hours with a precision of a few picoseconds. The UTC(NBS) time scale is computed immediately following a measurement cycle using a weighted-average algorithm. The small dispersion of the clocks during the two hour interval between measurements makes it possible for NBS to provide UTC(NBS) to users with 1 ns precision at all times. Coordinating with the Bureau Internationale de L'Heure, UTC(NBS) is steered toward and kept within a microsecond of UTC.

At the end of each month, the TA(NBS) time scale is computed using a Kalman algorithm. This computation is optimum in the statistical sense for clocks having both white frequency noise and random walk frequency noise, a good model for the clocks in the NBS ensemble. The second of TA(NBS) is steered toward NBS's best estimate of the SI second based on yearly calibrations of the ensemble by NBS-6.

FY 1986 Plans

Plan - Complete modifications and improvements of emergency power backup systems and develop procedures for their routine testing to assure reliability.

Accomplishment - Emergency power backup systems are complete and have been tested extensively.

Plan - Study alternatives for acquisition of a backup computer for the time scale. Consider long-term needs for replacement of current computer.

Accomplishment - This study has not yet been completed. A second PDP 11/70 is being given to NBS by NRL and this will be integrated with the current system to improve reliability.

Plan - Pending outside funding, initiate development of a "best research clock" as a reference for study of the millisecond pulsar. This work would be collaborative with Arecibo Observatory, Princeton, Berkeley, etc.

Accomplishment - Preliminary software for this "best research clock" has been written and is now under test. Through collaboration with the above organizations (using GPS time transfer), the pulsar stability has been documented to be at the level of 1 part in 10^{14}.

Plan - Complete implementation of time-scale environmental monitoring systems. System will trip alarm to alert staff when environmental parameters go out of operating range.

Accomplishment - Most of the equipment for this monitoring is in place. Completion of this project must await completion of the remodeling of the clock room.

FY 1987 Plans

Finish remodeling of the clock room.

Implement new alignment procedure (developed by A. De Marchi) for commercial cesium standards in the time scale to improve long-term stability of the individual standards and thus of the time scale.

Install and test backup measurement system for the time scale.

Improve time-scale reference for the NBS Global Time Service.

OBJECTIVE: Maintain international coordination of time scales and frequency standards using the Global Positioning System.

A satellite-based, time-transfer system developed in the Time and Frequency Division between 1979 and 1982 is now operational. A number of receivers are operating at: PTB in Braunschweig, West Germany; OP in Paris, France; Goldstone, California; Madrid, Spain; Canberra, Australia; NRC in Ottawa, Canada; IEN in Torino, Italy; RRL in Tokyo, Japan; VSL in Delft, The Netherlands; NPL in England; CSIRO in Australia; TUG in Austria; USNO in Washington, D.C.; as well as NBS in Boulder, Colorado. A computer-based, automatic-data-collection network acquires the data from the receivers. This data is combined with the data from the NBS Atomic Time Scale so that the time of the remote clock is known with respect to UTC(NBS) to a precision better than 10 nanoseconds after one day of averaging.

JPL employs three receivers developed by NBS in the same mode to provide frequency calibrations between the sites of the NASA Deep Space Network at a few parts in 10^{14}. In fact, JPL funded part of the receiver development at NBS. The GPS receivers at most of the national timing centers now transfer their data via the common-view technique to the International Time Bureau in Paris. This new system has replaced Loran-C as the principal time and time-interval transfer link for the SI second and the International Atomic Time Scale (TAI).

FY 1986 Plans

Plan - Cooperate with BIH guest worker to transfer GPS coordination methods and tracking procedures to this international organization. This is, of course, contingent upon the visit of this guest worker.

> Acomplishment - W. Lewandowski from BIH spent one and a half weeks in Boulder to learn about the GPS common-view system and the tracking procedures. Following this visit, BIH took over responsibility for the tracking schedules, although NBS is still assisting with that process having developed a major software package for that purpose.

Plan - Publish paper summarizing procedures used in GPS time and frequency coordination.

> Accomplishment - The paper "Precision Time and Frequency Transfer by Weighting and Smoothing GPS Common-View Data" by Weiss and Allan which was submitted to the recent CPEM for inclusion in the proceedings (IEEE Transactions on Instrumentation and Measurement) covers these procedures.

FY 1987 Plans

Transfer the software for handling GPS common-view data to the BIH.

Study methods for improving the accuracy of time transfer using the common-view technique.

Assist the BIH in determination of absolute time transfer by providing a delay-calibrated receiver to be carried to each of the participating timing laboratories. Assist other national laboratories, as needed, with use of GPS common-view time transfer.

OBJECTIVE: Develop metrology for precise time, frequency and length measurements.

Techniques for Characterization and Measurement of Frequency and Frequency Stability

The need for frequency measurements ranges from sub-audio to the ultraviolet. NBS has been a world leader in developing and disseminating the measures of frequency stability, their practical implementation, and accuracy. For example articles in the Feb. 1966 issue of Proc. of IEEE and the 1971 IEEE I&M laid the foundation for specifying a practical way of defining frequency stability, which has become the de facto international standard in the field. The dual mixer concept of measuring time, frequency, and frequency stability makes it possible to easily measure the difference between state-of-the-art frequency standards even if they are nominally the same frequency. This concept was introduced in 1975 by NBS and NRC (Ottawa, Canada), and is used in the new NBS time scale measurement system. Now, picosecond-precision, time-difference measurements can be made automatically on virtually any number of state-of-the-art clocks. Work in 1975 illuminated the limitations on frequency multiplication due to the phase noise in the standard or the multiplier chain, explaining numerous previous failures at precision infrared synthesis. This new understanding of the multiplication process then stimulated considerable improvement in the phase noise of crystal oscillators and signal processing equipment. In the rf region, the lowest noise crystal oscillators, buffer amplifiers, isolation amplifiers, and frequency multipliers presently available are a direct outgrowth of prototype designs and analysis developed at NBS. These new low noise devices have numerous applications in precision metrology as well as in the development of new frequency standards such as the passive hydrogen maser, stored ions, and cesium.

Techniques for Characterizing Noise in Clocks

As part of the generation and dissemination of the SI second it is necessary to have an ensemble of clocks as a memory of the rate given by the primary frequency standard. This is accomplished by running a set of clocks based on commercial frequency standards which, in general, don't have the accuracy of the primary standard but have very good frequency stability. These clocks, when properly characterized, act as a good flywheel for the rate of NBS-6. The memory accuracy of the clock ensemble can be improved by either increasing the number of clocks or by wisely utilizing the clocks available. NBS has chosen to use a modest number of clocks with sufficient reliability, redundancy and variety (to avoid systematics from a particular manufacturer) from the available vendors making clocks, but then to characterize the clocks with enough care so that optimum time and frequency can be generated from the ensemble as memory of the rate given by the NBS primary frequency standard.

One of the current time scale algorithms had its philosophical basis in 1968 and has evolved into different programs with different computers. It became important to know how well this algorithm was approaching optimal performance given the set of clocks at hand. A cooperative program with the Statistical Engineering Group of the Center for Applied Math was developed and out of that work came some very important results. First, a method was developed, using Kalman filters, to model atomic clocks and obtain maximum likelihood estimates of the model parameters from data on the ensemble of clocks. Tests for the validity of the model and confidence intervals for the parameter estimates were made and shown to be statistically significant. Techniques were also developed on the statistical significance of frequency drift and yielded some important insights. In addition, a Kalman or recursive algorithm for estimating time from the ensemble of atomic clocks was developed. The algorithm allows for the addition or deletion of clocks and provides for automatic error detection and correction. This Kalman algorithm is now used to generate the time scale TA(NBS) and the previous algorithm mentioned is still used to generate UTC(NBS). With this effort also came the conclusion that the past algorithm was very near optimum in its performance and during the last year its stability was shown to be of the highest order as it was used as a reference in the characterization of the stability of the millisecond pulsar, PSR1937+21.

FY 1986 Plans

Plan - Continue study of correlations between clock performance and environmental parameters.

> Accomplishment - This study awaits completion of the environmental monitoring systems.

FY 1987 Plans

Put environmental parameters into the time-scale data base and correlate the time scale performance with them.

Assist others in the application of the time-series statistical methods to other areas of metrology.

OBJECTIVE: Provide seminars, calibrations and measurement assurance on a fully reimbursable basis.

Global Time Service

The division now offers a service, based upon an NBS designed receiver, which provides for extremely high precision time and frequency transfer to a users site. A receiver which is located at the users facility communicates its data automatically to an NBS computer which stores the raw data, determines which data elements are suitable for time transfer calculations and provides an optimally filtered value for the time and frequency of the user's clock with respect to the NBS Atomic Time Scales. The user is given an account on one of the NBS computers through which he may access the results of the NBS analysis. Tests between receivers in Colorado and Canada, Germany, France, Spain, Wyoming, Louisiana, Washington, DC and California have demonstrated time comparisons with a precision of a few nanoseconds using an averaging time of 13 minutes and frequency comparisons with a precision of 1 part in 10^{14} for averaging times of four days and longer.

Calibration of Atomic Standards

In conjunction with its new time scale algorithms NBS has developed a time and frequency measurement system which is unsurpassed in many of its capabilities. This new system has vastly improved the NBS capability for calibrating high performance clocks.

FY 1986 Plans

Plan - Finish remodeling of calibration facility (room 2047).

> Accomplishment - Remodeling of calibration room is now complete.

Plan - Shift staff responsibility for Global Time Service to more effectively distribute work load within the group.

Accomplishment - Dick Davis was assigned responsibility for operation of the Global Time Service following the completion of development work on the GPS receivers.

FY 1987 Plans

During planned tests of intentional degradation by DOD of the GPS signals, determine the effect of the degradation on the accuracy of common-view time transfer.

Improve the algorithm for estimation of the performance of remote clocks (accessed through GPS) to improve accuracy and stability assessments.

OBJECTIVE: Advise and work with other governmental agencies and industry to incorporate advanced time, frequency and length metrology into their programs.

FY 1986 Plans

Continue to advise Air Force Space Division on operation of Global Positioning System. Pending outside funding, develop time-scale system for GPS ground control.

Accomplishment - Helped to locate several problems with the GPS performance including the identification of biases between different satellites and diurnal variations in the system. Funding for the time-scale system was not received.

Plan - Pending JPL funding, develop methods for remote steering of a clock using GPS.

Accomplishment - Funding for this system was not received. However, the concept for remote steering was demonstrated through steering of a real output of the time scale by the ensemble average.

FY 1987 Plans

Provide assistance to GPS operations in the areas of improved steering of GPS time, development of cross-link ranging for the GPS satellites and determination of the sources of system biases.

V. PHASE NOISE AND HYDROGEN MASERS

In past years, the primary goal of this group has been the development of a passive hydrogen maser with good medium-term to long-term stability for DoD requirements and for use in the NBS clock ensemble. The project, which has been funded by the Navy, has been quite successful. Two masers are currently operating in the ensemble and they have been out-performing the commercial cesium standards by a wide margin. The maser technology has been transferred to industry through the Industrial Research Associate Program. The project has also addressed a number of issues which are of importance to the division. These include: line-center errors in high performance servo systems and phase noise in frequency multipliers and synthesizers.

More recently the program emphasis has shifted to phase-noise measurements where emerging technology is pushing the state of the art. The group has just made a long-term commitment to the Department of Defense to develop and demonstrate phase-noise measurement systems in the microwave and millimeter-wave regions of the spectrum. This work should result in improved measurement systems for NBS and lower-phase-noise microwave and millimeter-wave synthesis to support development of primary standards as well as frequency synthesis into the optical regions of the spectrum.

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S. R. Stein (Industrial Research Associate)

OBJECTIVE: Generate NBS time scales, UTC(NBS) and TA(NBS).

Active hydrogen masers have long been touted for their excellent short-term stability, but long-term stability has generally been poor. The NBS maser project has focussed on improving long-term stability in a passive maser which is relatively simple and small. The goal has been a system which will fit into a package equivalent to that of a commercial cesium standard.

The results obtained to date have been impressive. The best of these masers provides medium-to-long-term stability equivalent to that of a cesium ensemble of approximately 20 high performance tubes. The fundamental design advance has been the servo locking of the physical cavity resonance to the hydrogen reference. The system also locks the slave oscillator to the same atomic resonance. The obvious conclusion is that the long-term stability of active hydrogen masers has been severely degraded by cavity pulling effects and that variations in the wall shift are extremely small relative to the present accuracy of primary standards.

<u>FY 1986 Plans</u>

Plan - Add a third NBS passive hydrogen maser to the NBS ensemble.

<u>Accomplishment</u> - The electronics and vacuum system for this third maser have been completed and both an alumina cavity and saphire cavity (with Q factor 2.5 times greater than for alumina) are available for the system. The saphire cavity should yield a factor of 2 improvement in performance. Completion of this project was slowed by a reduction in Navy funding.

Plan - Pending available funding, purchase a commercial version of the passive hydrogen maser to improve reliability of the NBS ensemble.

Accomplishemnt - The commercial passive maser will not be avialable until FY 1987. The maser will be purchased only after adequate tests of its performance against the NBS time scale.

Plan - Study correlation between frequency noise in the passive masers and environmental parameters (e.g. humidity, pressure, and temperature).

Accomplishment - The temperature coefficient of the maser was reduced to less than 2×10^{-15}/°C. Measurements at NRL showed the frequency sensitivity to humidity and pressure to be less than 3×10^{-15} for a 50% change in humidity and 10% change in pressure with the limits imposed by the reference frequency.

Plan - Complete study of servo errors and begin transfer of servo technology to primary standard project.

Accomplishment - A talk on the servo error analysis was given at the Frequency Control Symposium and a paper on the subject was submitted to an IEEE journal. General discussions on servo errors with staff of the cesium standard project occur on a regular basis.

FY 1987 Plans

Complete the third passive hydrogen maser for the time scale and determine the actual effect of the higher Q cavity on the maser performance. Convert a second maser on the scale to getter pumping in order to improve its mean time betwen failure.

Continue to advise the staff of the cesium standard project on servo issues including actual circuit implementations.

Explore new phase modulator concept theoretically and initiate experimental study if appropriate.

Purchase a commercial version of the passive hydrogen maser to improve performance of the NBS ensemble.

OBJECTIVE: Provide seminars, calibrations and measurement assurance on a fully reimbursable basis.

Measurement of Phase Noise

The improved phase stability of components developed for the passive maser have enhanced the division capability to provide special calibrations of phase noise in oscillators, amplifiers, frequency multipliers and synthesizers from 5 MHz to 700 MHz. The new DOD contract for development of phase-noise metrology through the microwave and into the millimeter-wave region will permit increased automation of measurements. The goal is to eventually cover the region from 5 MHz to 60 GHz for oscillators, amplifiers, multipliers, dividers and synthesizers. The emphasis will be on the development of sound measurement methodology and transfer of this methodology to industry and government laboratories.

FY 1986 Plans

Plan - Extend capability for phase noise measurement to 18 GHz.

Accomplishment - A prototype phase-noise-measurement system for signals ranging from 1 to 18 GHz has been completed. The system features selectable measurement bandwidths out to 31 MHz. Previous NBS systems were limited to a bandwidth of 100 KHz. The bandwidth for the 5 MHz to 1 GHz system was also extended with 31 MHz bandwidth available in the higher frequency range.

Plan - Extend calibration capability for $\sigma_y(\tau)$ down to a one-second averaging period.

Accomplishment - This project was not performed due to lack of other agency funding.

FY 1987 Plans

Modify prototype phase-noise system to cover frequencies from 1 to 26 GHz with capability for computer control of gains, measurement bandwidths and characteristics of the phase-lock loop.

Complete phase-noise system to cover frequencies from 5 MHz to 1 GHz with capability for computer control of gains, measurement bandwidths and characteristics of the phase-lock loop.

Develop a low-noise reference signal at 10.6 GHz.

OBJECTIVE: Establish the units of the International System for the "second" and the "meter".

FY 1986 Plans

Plan - Renovate and "recalibrate" electronics for NBS-4 and NBS-6.

Accomplishment - Electronics for NBS-6 was completely renovated and recalibrated. Plans for reworking the electronics on NBS-4 have been deferred for lack of available staff.

Plan - Finish synthesis to x-band. Multiply x-band signal to 70 GHz and phase lock the two systems.

Accomplishment - A theoretical study of a simpler method for low-noise synthesis to x-band was started. The method looks sufficiently promising that work on an earlier concept was deferred until the new idea could be adequately examined.

FY 1987 Plans

Conduct experimental tests of new method for low-noise synthesis to x band with funding from the University of Washington and the Department of Defense.

OBJECTIVE: Advise and work with other governmental agencies and industry to incorporate advanced time and frequency metrology into their programs.

Hydrogen Maser Technology

The passive hydrogen maser developed at NBS with partial military funding has demonstrated exceptional frequency stability from a few seconds to a few weeks. Based on 2 months of data, the stability is 5×10^{-15} at 1 day and 2×10^{-15} at 8 days. At a level of resolution of $\pm 3 \times 10^{-16}$/day, the drift is unobservable. The time dispersion per day is a factor of 4 to 5 times better than the best available commercial cesium frequency standards.

Several Industrial Research Associates have worked with NBS for three years on this program. This cooperation continues and the first passive hydrogen maser to be constructed in this program is now in operation.

Quartz Crystal Resonators

Vibration sensitivity is presently one of the most severe difficulties encountered when using a frequency standard in non-laboratory environments. Although NBS no longer has an experimental quartz crystal research program, consulting support is being provided to the U.S. Army and its industrial contractors. A new method for temperature control of clocks which was developed in the hydrogen maser project would appear to offer promise for quartz resonators. Interactions with industry on this concept will continue through the year.

The division has provided support to the quartz industry's effort to develop standards permitting interchangeability of quartz oscillators. Two workshops on the subject were organized in Boulder and the result appears to be a rather simple measurement procedure based on impedance measurements using commercial coaxial standards as references. The method provides full traceability to National standards and forms the basis for solid U.S. leadership in the development of standards at the international level.

FY 1986 Plans

Plan - Continue collaboration with Industrial Research Associates on the passive hydrogen maser.

Accomplishment - Consultation and collaboration with the Industrial Research Associates and with the Naval Research Laboratory continued through the year. A number of talks were presented to government organizations and professional conferences on the passive hydrogen maser and on phase-noise measurements.

FY 1987 Plans

Continue collaboration with Industrial Research Associates and the Naval Research Laboratory on the passive hydrogen maser.

Expand industrial and government contacts in the area of phase-noise measurement and develop plans for dissemination of techniques for phase-noise measurement as they are developed.

VI. ATOMIC BEAM STANDARDS

The budget for this program continues at a level which is sufficient to operate the current standard, NBS-6, and to allow construction of NBS-7, the next generation primary frequency standard which will be based on optically pumped cesium. The objective is a standard which can be easily operated in a nearly continuous mode with semi-automatic assessment of systematic errors at an accuracy level of 1 part in 10^{14}. The project is built upon successful tests of the concept on field-size standards pumped by laser diodes.

Staff:
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J. Shirley (Guest Worker)
J. Yoder (Industrial Research Associate)

OBJECTIVE: Establish the units of the International System for the "second" and the "meter".

Operate NBS-6, the U.S. Primary Frequency Standard

Since 1968 NBS has designed and developed three new cesium devices: NBS-4, NBS-5, and NBS-6. NBS-4 has a medium-length cavity of 50 cm, and was built to test new ideas for improving the stability of cesium devices. This standard is one of the most stable cesium clocks in the world, achieving a stability of 7×10^{-15}. It should be noted here that no previous NBS cesium frequency standards directly drove a clock; instead, they were used periodically to calibrate the frequency of an ensemble of commercial cesium beam clocks that ran continuously. NBS-4, because of its excellent stability, has served as a working clock in the time-scale ensemble.

NBS-5 was built on the framework of NBS-3 and in turn served as the basis for NBS-6, completed in 1975. The refinements incorporated over the years include greatly improved components to provide narrower resonance lines (25 hertz), the ability to reverse the direction of the atomic beam (which allows errors due to asymmetries in the cavity to be diagnosed), and other features aiding analysis of performance. It can also undergo routine maintenance without being completely turned off. NBS-6 has an accuracy of 8×10^{-14}; more accurate but not quite as stable as NBS-4. Used together, these two standards generate the U.S. standard second. A clock ensemble is used to carry the second forward in real time so that it is continuously available.

FY 1986 Plans

Plan - Complete modifications and rework of NBS-6.

> Accomplishment - The modifications to the vacuum system and the electronics have been completed. Previous problems with bursts of gas entering the system through the sliding seals have been completely eliminated and the rework of the electronics appears to have resolved some instability problems. Together with the new model for Rabi pulling developed by De Marchi, these changes should eventually permit a narrowing of the error limits for this standard.

Plan - Complete evaluation of NBS-6 by Jan. 31, 1986. Use evaluation of NBS-6 to calibrate TA(NBS).

> Accomplishment - The evaluation was delayed by problems with the oven on the east end. The oven/detector assembly was removed and completely rebuilt and the system is now back in operation. The evaluation is now complete.

Plan - Continue study of the field-size standard with emphasis on development of design information for NBS-7.

> Accomplishment - Studies on the present tube (OPCS-2) have been taken to the limit set by problems with the magnetic field and windows (high scattered light levels). New window fabrication methods have been developed by our industrial collaborator and the next generation tube should be provided to NBS in the near future. Despite problems with this tube, significant gains have been made in optics design and laser performance.

Plan - Initiate upgrade and modification of NBS-4 to bring it up to its earlier performance level.

> Accomplishment - The modifications of the electronics on NBS-4 have been completed, but the tube has just run out of cesium. With limited staff available to recharge the system, some further delay in bringing it back into operation can be expected.

FY 1987 Plans

Shift responsibility for future evaluations of NBS-6 to 1 group. Past practice involved rotation of this responsibility.

Initiate an extended evaluation of NBS-6 using the De Marchi model to account for Rabi pulling. Determine whether this evaluation procedure allows for a reduction in the quoted uncertainty statement.

As staff time becomes available, recharge NBS-4 with cesium and bring it back into operation.

OBJECTIVE: Make fundamental improvements in atomic spectroscopy for future application to primary frequency standards.

Primary Cesium Standard Development

The known limitations to the accuracy of NBS-6 lie with the microwave cavity phase shifts, exacerbated by the dispersive nature of the state selection magnets. In addition, there are unknown shifts of the cesium clock frequency associated with systematic effects which cannot be readily studied in conventional systems. Replacing the magnets in a cesium standard with optical pumping and detection using laser diodes should allow the reduction of cavity phase shift uncertainties, and permit a better understanding of the limitations of cesium standards. A small laboratory version of the optically pumped cesium atomic beam frequency standard has been constructed and performance demonstrated at $\sigma_y(\tau) < 7 \times 10^{-12} \tau^{-1/2}$. Long-term data showing the "flicker" floor has not yet been obtained.

A larger test bed for the optically pumped standard has been designed and the major components are under construction. This test bed will serve as the basis for NBS-7. This system features a longitudinal C-field and a novel Ramsey cavity which minimizes errors caused by distributed cavity phase shift. The optical pumping concept provides the means for minimizing errors due to end-to-end cavity phase shift.

FY 1986 Plans

Plan - Complete design of a frequency standard (test bed) based on optically pumped cesium, and initiate construction of the system.

Accomplishment - The design of this system has followed a thorough study of accuracy-limiting systematic errors. Rabi-pulling effects, distributed cavity phase shift, Majorana transitions, field homogeniety and the ac-Stark shift have all been carefully considered in this design. All major components of the physics package are now being fabricated.

FY 1987 Plans

Initiate development of advanced elctronic servosystem to achieve 10^{-6} splitting of the cesium resonance.

Develop practical laser systems for optical state selection and detection.

Complete construction of the test bed for NBS-7 and demonstrate preliminary operation (no error assessment).

Initiate experimental studies of light shift, cavity phase shift and Majorana transitions.

Initiate development of computer-controlled system for automated evaluation and operation of the standard.

OBJECTIVE: Advise and work with other governmental agencies and industry to incorporate advanced time and frequency metrology into their programs.

Cesium Beam Technology

Recent advances in cesium beam technology which have come from Division studies of optically pumped cesium clocks could improve the performance of commercial devices which are used in military applications. For example, this research could improve both the long-term stability and the reproducibility after turn-on of satellite based cesium clocks. These improvements involve the use of laser diodes, cesium heat pipe ovens, optical pumping, and fluorescence detection of atoms.

Much of this work is performed under contract for other governmental agencies. In addition, the Division has formed an Industrial Research Agreement with a manufacturer of cesium clock. This agreement permits the transfer of NBS research results to the private sector, and also brings guest scientists from industry to the NBS laboratories.

FY 1986 Plans

Plan - Fabricate modified recirculating (heat-pipe) cesium oven and compare its' performance with the model.

Accomplishment - Project delayed to meet higher priority objectives.

Plan - Continue collaboration with an Industrial Research Associate on the development of an optically pumped cesium standard.

Accomplishment - Work on the field-size, optically-pumped standard constitutes a major portion of our collaborative IRA work. This tube has been used to study the physics of the interaction between the laser beams and the atomic beam with emphasis on noise properties. It has also provided the basis for test of methods for laser-diode stabilization and line narrowing. In the latter area, a method for adequately controlling the laser-diode output was discovered and is now under further development.

FY 1987 Plans

Under DOD sponsorship, continue to work with industry to assist in the development of field-size frequency standards based on optical-pumping concepts. The work is to include design of beam tubes, fluorescence optics and laser-diode systems.

Complete design and tests of modified recirculating (heat-pipe) cesium oven.

Collaborate with De Marchi in completing tests of Rabi-pulling model on commercial cesium standards and transfer information on this work to industry and relevant government laboratories.

VII. ION STORAGE

The long term plans for primary frequency standards for the division involve an eventual shift to ion storage and radiative cooling. For the present the effort of this group is being directed toward development of the physics of the concepts. The group has already demonstrated a Be^+ ion clock which operates at a performance level equal to that of NBS-6, the present NBS primary standard. While the focus of this work is ion standards, the techniques are also applied to other problems of fundamental interest.

Staff:

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OBJECTIVE: Make fundamental improvements in atomic spectroscopy for future application to primary frequency standards.

Atomic Clock Based on Stored Ions

As a step towards realizing a primary frequency standard based on stored ions, the Division has made a clock based on a ground state hyperfine transition in $^9Be^+$. The combined uncertainties in all systematic frequency shifts (such as those due to Doppler effects) are at the same level as those of the present U.S. primary time standard, NBS-6 which has an uncertainty of about one part in 10^{13}.

In these experiments, a few hundred $^9Be^+$ ions were confined in a Penning trap and laser cooled to temperatures less than 1 K. An oscillator was locked to a magnetic field independent hyperfine transition (~ 300 MHz) using an optical pumping, double resonance technique. Measured stabilities were about equal to a commercial cesium clock. The hyperfine transition was driven for 20 s on each cycle which produced a linewidth of 0.025 Hz. During this time, the laser was shut off to avoid light shifts; this also allowed the ions to heat slightly from background gas collisions causing a second order Doppler shift of about 4×10^{-13}. Other systematic effects are below this level. Frequency stability and accuracy performance can be improved in the future by using an ion with a higher hyperfine frequency. For this reason, mercury ions with hyperfine transitions at around 30 GHz are now being studied. The heating problem is discussed below.

Farther in the future, it appears that the most accurate clocks will be based on optical transitions in atoms or molecules. The main reason for this conjecture is that the Q's for such transitions can be extremely high ($Q \geq 10^{-15}$). With this in mind, the two-photon S→D transition in Hg^+ has been studied. The transition was observed for the first time in a miniature rf trap. The present linewidth is limited by the laser bandwidth, but this transition has a fundamental Q of about 0.5×10^{15} (radiatively limited).

Ion-Cloud/Trapped-Ion Studies

Studies are made of ion dynamics and the relation of these dynamics to trap design. It appears that the principle limitation to accuracy of a frequency standard based on ions stored in a Penning trap will be the uncertainty in the second-order-Doppler (time-dilation) frequency shift due to the rotation of the ion cloud. This rotation is a non-thermal effect and is independent of the internal temperature of the cloud. Therefore detailed studies of ion-cloud temperature, density and rotation are being made using a two-laser, optical-optical double resonance technique.

A new concept for a frequency standard based on "sympathetic cooling" is being studied theoretically and experimentally. In sympathetic cooling, one ion species is cooled by Coulomb coupling with another ion species which is laser cooled. This was proposed and demonstrated (on the Mg^+ isotopes) a few years ago at NBS and has now been studied in more detail using Hg^+ and Be^+. The advantage is that the "clock" ions can be continuously cooled, but ac Stark shifts from the cooling radiation can be made negligibly small. This should result in substantially narrower linewidths (less than 1 millihertz) and reduction of errors due to the second-order Doppler shift.

FY 1986 Plans

Plan - Continue investigation of laser cooling of Hg^+ in rf traps. Study mechanisms which limit the linewidth of the two-photon transition in Hg^+ and develop methods for reducing this linewidth.

Accomplishment - Direct cooling of small numbers of Hg^+ ions has been accomplished. Cooling of more than about 10 ions is prevented by rf heating; this is consistent with experiments at other laboratories. The S→D transition has been driven via quadrupole excitation. In very accurate spectroscopy, this is desirable because the two-photon transition will have a systematic offset due to the a.c. Stark effect. This shift is absent for the single photon excitation. The quadrupole transition has been detected with 100% efficiency. Previously, in our optical-pumping, double-resonance experiments, quantum multiplications ($\geq 10^6$) have allowed detection efficiencies of about 30%. By collecting more scattered light in the single-ion Hg^+ experiments, 100% detection efficiency has been achieved. This has allowed observation of the quantum jumps between S and D levels. This work will be published in Phys. Rev. Letters.

Plan - Complete fabrication of array detector and use it to observe single Hg^+ ions.

Accomplishment - All electronics for this device have been completed, but the photocathode/image intensifier fabricated outside NBS did not work. This has caused a 6-month delay.

Plan - Conduct experimental studies of sympathetic cooling. Correlate results with computer solutions and study alternatives for using the concept as a basis for a primary frequency standard.

Accomplishment - By directly cooling Be^+, sympathetic cooling of Hg^+ ions stored in the same trap has been accomplished. Detailed studies of ion temperature, spatial distributions and (absence of) shear have been performed. For example, the spatial distribution of ions compares favorably with theoretical calculations. One interesting feature of this work is the centrifugal separation (due to "magnetron" rotation of the ion species. This work has been reported in Phys. Rev. Lett. 57, 70(1986).

FY 1987 Plans

Primary emphasis will be placed on narrowing the laser linewidth for the S→D quadrupole transition in single Hg^+ ions. This not only has a direct bearing on the optical frequency standard, but will allow us to study the motional sideband structure in this optical transition. This will allow more accurate measurements of ion temperature and allow study of limitations of ion cooling and the effects of imperfections in the traps. A possible goal is the attainment of ions confined in the zero-point state of the confining well.

Sympathetic cooling will be employed in a new experimental apparatus for Be^+ and Mg^+ ions. Initial tests of a $^{25}Mg^+$ rf frequency standard (similar to the $^9Be^+$ frequency standard) will be made. The new trap design (for the superconducting magnet) emphasizes axial symmetry in order to avoid the spurious heating observed in the previous $^9Be^+$ clock experiment.

Careful theoretical analysis of limits to high-resolution spectroscopy and frequency standards will be undertaken and written up.

OBJECTIVE: Perform basic studies in program areas related to future time and frequency standards.

As an outgrowth of studies on ion clouds stored in Penning traps for possible frequency standard application, several closely related basic studies have been undertaken.

Search for Spatial Anisotropy

Frequency standards, including those based on atomic or nuclear (Mossbauer) transitions, have traditionally played an important role in testing gravitational theories. One example is measurements of the gravitational red shift. In addition, the very high resolution attained in trapped ion spectroscopy enables other sensitive tests of the Einstein Equivalence Principle (EEP). All metric theories of gravity (including General Relativity) are founded on the EEP, according to which, any nongravitational physics experiment done in a local freely falling frame near a strongly gravitating mass will have the same outcome when done in a freely falling frame far away from all such masses. Also included in the EEP is local Lorentz invariance which states that the outcome of the experiment is independent of the velocity of the freely falling frame. In particular, two different atomic clocks (i.e., clocks based on transitions in two different kinds of atoms) located at the same point in space-time will have relative rates which are independent of (1) the velocity of the freely falling lab, and (2) the position and mass of strongly gravitating bodies. As a test of the EEP the frequency of the $^9Be^+$ "clock" transition (M_J = 1/2, M_I = -3/2) → (M_J = 1/2, M_I = -1/2) has been compared to the frequency of a passive hydrogen maser to see if a correlation can be found with orientation in space. Two gravitational interactions have been proposed which violate the EEP and shift the $^9Be^+$ "clock" transition relative to the hydrogen transition. Our experiments have searched for sidereal variations of the $^9Be^+$ "clock" transitions relative to the hydrogen transition. These experiments have achieved resolution better than 0.1 mHz and see no such variation. These results decrease previous experimental limits by a factor of 300 and in the future we expect to gain a further increase of two orders of magnitude in resolution.

Non-Neutral Plasmas

In the language of plasma physics, the ion clouds in a Penning or rf trap comprise a one component, non-neutral ion plasma. In a small plasma of laser cooled $^9Be^+$ ions stored in a Penning trap we have observed behavior which is indicative of the liquid state. In this case the Coulomb coupling constant Γ was as high as 10. Calculations predict that at $\Gamma \approx 2$, the pair correlation function should begin to show oscillations characteristic of a liquid, and at much larger values of Γ ($\Gamma \approx 170$) crystallization may take place. In our experiment a second laser was used to probe the ion plasma and measure the temperature of the ions from the Doppler broadening of the optical probe transition. The ion number density was determined by measuring the (ExB) cloud rotation frequency. Because the trap electric field and magnetic field were known, the space charge electric field was extracted from the cloud rotation frequency and used to determine the ion number density. Ion number densities of $2 \times 10^7/cm^3$ and temperatures of < 100 mK produced values of $\Gamma \approx 10$. Values of Γ large enough to observe a liquid-solid phase transition should be accessible in future versions of this experiment. If the theoretical cooling and density limits can be obtained, values of Γ as large as 15,000 are perhaps possible for Be^+ ions. Because experimental information on three-dimensional, strongly coupled plasmas is almost non-existent, these experiments can provide some useful tests of the theoretical calculations. The development of a clear understanding of ion-cloud dynamics is fundamental to the estimation of systematic errors in frequency standards arising from motions of the ions.

FY 1986 Plans

Plan - Complete fabrication of a highly symmetric (axially) ion trap and use it to conduct a study of the magnetic susceptibility perturbations to hyperfine structure in $^9Be^+$ or $^{25}Mg^+$.

> Accomplishment - The trap has been completed and is being installed in the superconducting magnet. It is not yet in operation, but first results are expected before the end of the calendar year.

Plan - Using the trap described above, improve sensitivity of system for studying anisotropy of space.

> Accomplishment - These further studies of spatial anisotropy have been shelved. By measuring nuclear spin-flip transitions in neutral atoms, Professor Forton's group (U. Washington) has improved on our reported sensitivity by nearly a factor of 10^3. We should achieve comparable sensitivity, but probably not next year.

Plan - Continue study of phase transitions in $^9Be^+$ plasmas using three-dimensional cooling. Initiate design of system for study of low-angle (Bragg) scattering in these plasmas.

> Accomplishment - Coupling constants, Γ, of approximately 100 have now been achieved (about 10 times higher than our previous work). The basic design of the Bragg-scattering experiment is finished, but the experiment awaits completion of a new trap for the superconducting magnet.

Plan - Study statistics of fluorescence from a single ion.

> Accomplishment - Observations have been made of quantum jump phenomenon on single Hg^+ ions and photon antibunching (first observation for a "rate" process) with 100% efficiency (also a first). This work has been accepted for publication in Phys. Rev. Letters.

Plan - Study stimulated Raman technique for measuring plasma temperature.

> Accomplishment - This project was started, but was then shelved due to the early departure of a postdoc.

FY 1987 Plans

Perform more careful and complete studies of Hg^+ single-ion fluorescence statistics. Investigate possibilities for observation of 1) single-ion absorption, 2) motional sidebands in optical spectra, 3) cooling to zeroth quantum level and 4) cooling in the sideband cooling limit.

Study Single-ion fluorescence statistics of Mg^+. Experiments with this ion can be more accurately compared with theory. Examine the possibilities for observation of stimulated Raman transitions on single Mg^+ ions.

Initiate experimental study of Mg^+ nuclear diamagnetism, that is, magnetic-field-induced, nuclear-shape distortions. This previously unobserved effect can show up as a small perturbation to the Breit-Rabi formula and could produce a small systematic error in frequency standards.

Study Bragg scattering of laser radiation from a strongly coupled ion plasma. This can be done in the new trap being installed in the superconducting magnet. The only missing element is the imaging photon counting tube which should arrive soon.

VIII. OPTICAL FREQUENCY METROLOGY AND DEVICES

This group retains the expertise and facilities which were used in earlier measurements of the speed of light and the subsequent work which led to the redefinition of the meter in terms of the second. More recently, this frequency synthesis has proven to be extremely useful as a basis for spectroscopic standards in the infrared and far infrared. Of particular note is the generation of tunable far infrared radiation (TuFIR) using either second or third order mixing. The radiation generated completely spans that part of the spectrum. The group continues to improve devices and concepts for frequency synthesis. This will prove to be especially valuable should the stored ion work move to an optical frequency.

Staff:
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E. C. C. Vasconcellos (Guest Worker)
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OBJECTIVE: Provide reference frequencies from the microwave to the visible region of the spectrum.

Spectroscopic Frequency References (Measured with Respect to the Cesium Standard)

The pioneering work done by the laser frequency synthesis group in extending direct frequency measurements from the microwave to the visible portion of the electromagnetic spectrum is now being used to measure the frequencies of atomic and molecular transitions which are of importance to spectroscopists, astronomers, and atmospheric scientists. Before the advent of heterodyne optical spectroscopy (in which the frequency is measured with respect to cesium) the wavelengths of spectral features were measured. These measurements were hundreds of times less accurate than the new direct frequency measurements. The knowledge of the frequencies of selected species allows the spectroscopist, astronomer or atmospheric scientist to carefully calibrate spectrometers and receivers to the appropriate frequencies (or wavelengths).

The generation of reference frequencies with requisite accuracy involves accurate heterodyne frequency measurements and the reliable fitting and analysis of the spectral data. Coordinated activity at NBS (between the Time and Frequency Division in Boulder and the Molecular Spectroscopy Division in Gaithersburg) involves selection of suitable molecular calibration candidates, measurement of their frequencies, and the analysis, and dissemination of the results in the form of reference frequency tables.

To meet current needs absorption frequency calibration standards must be readily obtained and easily handled with at least one calibration point every few gigahertz. The reference lines must be well resolved and free of accuracy-limiting fine structure each to an accuracy of one part in 10^8.

The far infrared (0.1 to 5 THz, 3 mm to 60 μm)

The frequencies of several hundred optically pumped lasers have been measured and are used by laboratory spectroscopists to measure absorption features. Laser Magnetic Resonance (LMR) spectroscopy has been developed into one of the world's most sensitive techniques for observing and measuring frequencies of molecules. Laser magnetic resonance spectroscopy uses these known frequencies to predict the frequencies of free radicals used by astronomers and upper atmospheric researchers. The new technique of tunable far infrared spectroscopy (Tufir), developed by NBS, promises a much more general technique for measuring frequencies in this region. Further mention of this concept is made later in this section.

The CO_2 laser which is stabilized to CO_2 itself furnishes the main frequency grid for all of our measurements and is widely used for reference purposes.

The Infrared Region (25 to 200 THz, 1.5 to 12 μm)

The frequencies of hundreds of lines of OCS, DBr, CO, N_2O, and NO now furnish reference grids for this region. The methane line used to stabilized the He-Ne laser is especially noteworthy. It serves as a particularly accurate reference for both metrology and spectroscopy. Work on a number of the other molecules has been funded for a number of years by NASA in support of the Clean Air Act Amendments of 1977. Accurate spectroscopic measurements of molecules which are important in upper atmospheric chemistry provide the basis for heterodyne studies of the upper atmosphere. This work is thus helpful in resolving questions about pollution issues (e.g. acid rain).

Carbonyl Sulfide, 815-2140 cm^{-1}

Tables of OCS absorption lines have been provided for use as frequency calibration standards in the following regions of the infrared: 815-892 cm^{-1}, 1008-1092 cm^{-1}, 1649-1738 cm^{-1}, 1850-1921 cm^{-1} and 2013-2140 cm^{-1}. The absorption line frequencies and approximate intensities are calculated from spectroscopic constants which have been determined by fitting selected data from the literature. This data includes NBS heterodyne frequency measurements for all except the 2013-2140 cm^{-1} region. The uncertainties of most of the recommended frequency standards are on the order of 1 to 10 MHz. Hot band transitions and transitions for some of the less abundant isotopic species are included in the tables in order to provide patterns for the unambiguous identification of the lines as well as to provide additional calibration standards in some cases. The calibrations atlas contains over 6600 entries. Subsequent work on the 12^00-00^00 band provided a new table covering 1866-1919 cm^{-1}.

Deuterium Bromide, 1-0 band (Tunable Diode Laser)

Heterodyne frequency measurements have been made on selected deuterium bromide 1-0 band transitions ranging from 1630 to 1985 cm^{-1}. New DBr constants have been determined and a table of frequencies, believed to be accurate to 3 MHz, is available.

Nitrous and Nitric Acids (Tunable Diode Laser)

Heterodyne frequency measurements reported earlier included measurements at 5.3 μm, 9.0 μm and 7.7μm. An additional major experiment at 7.7 μm has been completed and these new measurements have been used with the previous work to provide a detailed calibration atlas in the 1196 to 1355 cm^{-1} region. This atlas conatins over 1650 entries in this region. Other tables derived from the 7.7 μm work include tables in the 1816-1930 cm^{-1}, 2135-2268 cm^{-1}, and 2490-2605 cm^{-1} regions. Subsequent to this study, work at 10 μm on the 10^00-02^00 band of N_2O has led to a table from 990 to 1090 cm^{-1} by direct measurements and tables from 1120 to 1220 cm^{-1} and 2408 to 2508 cm^{-1} appear in the latest paper as derived tables. Work has also been published on the nitric oxide fundamental band (1741-1980 cm^{-1}). This molecule may be used for calibration purposes and is also of intrinsic interest for atmospheric science.

Carbon Monoxide (2-0), 4120-4350 cm^{-1}

The 2-0 ro-vibronic band of $^{12}C^{16}O$ has been studied extensively by Fourier Transform Spectroscopy techniques and has become a widely accepted calibration standard. A color center laser spectrometer has permitted use of an alternate technique not only to confirm these results, but also to lead to an improved set of molecular constants. A new frequency calibration table with some entries differing by as much as 15 MHz from Fourier Transform technique results has been published.

Nitrous Oxide (Color-Center Laser)

The absolute frequencies of 39 lines in the 00^02-00^00, 20^01-00^00, and 12^01-00^00 bands of N_2O in the 4300 - 4800 cm^{-1} range have been measured by heterodyne frequency techniques. The lines were each measured in Doppler-limited absorption with a color-center laser as a tunable probe of the N_2O and two stabilized CO_2 lasers as reference frequencies. New ro-vibrational constants have been fitted to these measurements. Tables of calculated transition frequencies are given with estimated absolute uncertainties as small as 10^{-4} cm^{-1}.

Visible Region

Measurements in the visible region are described in the next section.

FY 1986 Plans

Plan - Compete measurements on N_2O bands in the 7.7 μm region. Initiate measurements on N_2O at 10 μm.

Accomplishment - Heterodyne frequency measurements on N_2O in the 7.7 μm region have been completed and the paper submitted to Atoms, Molecules and Clusters. A 1650 entry calibration atlas covering the range 1196 to 1355 cm^{-1} based on the two 7.7 μm papers is now available on request. Heterodyne frequency measurements have also been made on N_2O in the 10 μm region and a paper is just ready for submission.

Plan - Use N_2O calibration frequencies for tunable-diode-laser spectroscopic studies of HNO_3 at 7.7 μm.

Accomplishment - The calibration atlas mentioned in the previous accomplishment was used in a tunable-diode-laser study of HNO_3 in our laboratory (this study complements Maki's Fourier-transform-spectrometer study and provides higher resolution than his system permits). Maki has fitted the results to better than 18 MHz for some 600 lines and is currently completing a paper on this topic.

Plan - Measure the OCS band at 5 μm.

Accomplishment - Heterodyne frequency measurements on the nitric oxide fundamental band (1741-1980 cm^{-1}) have been completed and the paper published in J. Mol. Spectroscopy. Measurements on the 1200-0000 band of OCS have been completed. These heterodyne frequency measurements also required the use of a CO laser as a transfer oscillator. The paper, which was published in the Int'l J. Ir and MM Waves, contains a calibration table covering the 1866 to 1919 cm^{-1} range.

FY 1987 Plans

Complete heterodyne frequency measurements on the asymmetric rotor, nitrogen dioxide. These measurements will permit self calibration of NO_2 in a Fourier-transform-spectroscopic study.

Make heterodyne frequency measurements of hot-band features of OCS which may be used with the Ritz combination principle to provide a calibration table in the 2900 cm^{-1} region.

Make heterodyne frequency measurements on high-J rotational transitions of HF for use with TuFIR measurements to determine the best possible constants for HF. Current values at 10 μm have uncertainties of 200 MHz.

Make heterodyne frequency measurements on the weak N_2O band at 1635 cm^{-1}, the 10^00-01^10 transitions. Calibration tables in the 1500-1700 cm^{-1} region are currently not available.

OBJECTIVE: Establish the units of the International System for the "second" and the "meter".

Provide Frequency Measurements of Lasers Suitable for Realizing the New Definition of the Meter

In 1982 the Comité Consultatif pour la Definition du Metre (CCDM) proposed a new definition for the meter, namely that: "The meter is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second." In October of 1983 the General Conference of Weights and Measures approved this change which is based to a large extent on both pioneering work and exacting measurements made by NBS. With this definition the meter can be realized from the wavelength of any laser which is stabilized to a narrow atomic or molecular absorption for which the frequency is known. The wavelength λ is determined from the relation $\lambda = c/\nu$, where c is the fixed value of the speed of light and ν is the measured frequency of the laser. Thus, the realization of the meter will require the measurement of the absolute frequency of suitable spectral lines in the visible spectral region. To this end, the Division has performed two highly accurate frequency measurements of hyperfine transitions in molecular iodine used for laser stabilization. One is in the yellow spectral region, and the other, red.

The absolute frequency of a dye laser stabilized on the o hyperfine component of the $^{127}I_2$ 17-1 P(62) transition at 520 THz (576 nm) in iodine was measured with respect to the CH_4 stabilized 88 THZ (576 nm). A 26 THz CO_2 laser, a color center laser at 130 THz, and a He-Ne laser at 260 THz, were used as transfer oscillators. The measured I_2 frequency was 520 206 808.547 MHz with a total uncertainty of 1.6 parts in 10^{10}.

The absolute frequency of the 473 THz He-Ne laser (633 nm), stabilized on the i hyperfine component of the $^{127}I_2$ 11-5 R(127) transition, was measured by comparing its frequency with a known frequency synthesized by summing the radiation from three lasers in a He-Ne plasma. The three lasers were an 88 THz CH_4 stabilized He-Ne laser (3.39 μm), a 125 THz color center laser (2.39 μm) with its frequency referenced to the $R_{II}(26)$ $^{13}C^{18}O_2$ laser, and a 260 THz He-Ne laser (1.15 μm) referenced to an I_2 stabilized dye laser at 520 THz (576 nm). The measured frequency is 473 612 214.789 MHz for the i hyperfine component with a total uncertainty of 1.6 parts in 10^{10}.

These frequencies, when used to realize the new meter, represent a 25-fold improvement over the Krypton length standard.

OBJECTIVE: Develop metrology for precise time, frequency and length measurements.

Techniques for Characterization and Measurement of Frequency and Frequency Stability.

Frequency metrology from the far infrared to the visible has been greatly stimulated by the work at NBS. The early work on W-Ni point contact metal-insulator-metal (MIM) diodes, carried out simultaneously and independently by MIT and NBS, laid the groundwork for precision frequency synthesis in this spectral laser region.

An extremely important outgrowth of this work was the first frequency measurement of the 3.39 micron line of CH_4 followed by the wavelength measurement of the same line. The product of the frequency and wavelength produced a value for the speed of light nearly 100 times more accurate than the previously accepted value. This work coupled with recent frequency measurements of visible spectral lines has led to the replacement of the Krypton lamp as the length standard and the assignment of an exact value for the speed of light.

Recent work on the MIM diode has expanded the frequency difference range over which measurements can be made by a factor of 100 (in the visible). This is expected to greatly simplify frequency metrology because of the reduction in the number of frequency markers to reference lines necessary to fully cover this spectral region.

Techniques for Laser Frequency Synthesis

Frequency synthesis is usually achieved in some non-linear device which adds, subtracts and multiplies the frequencies of the radiations incident on it. In the Time and Frequency Division we have used W-Ni metal-insulator-metal (MIM) point contact diodes as detectors, harmonic generators, and mixers of coherent radiation from the microwave to the visible region of the electromagnetic spectrum. The MIM diode plays a major roll in the Laser Frequency Synthesis Chain which connects the cesium clock to the visible I_2-stabilized lasers and hence provides the realization of the meter from the new definition.

The MIM diode has been used for the past 15 years and the mechanical and electrical engineering improvements have been steady. Recent use of conical coupling along with off-axis parabolic focusing mirrors has led to an exciting new technique of generating tunable far infrared radiation.

Tunable coherent radiation can be generated in the uv, visible and near infrared regions of the electromagnetic spectrum with the use of tunable lasers and non-linear optics. Only recently have tunable sources been available in the far infrared and these did not allow complete coverage since the technique involved the addition of microwave sidebands to several of the stronger far infrared lasers. Division scientists have now succeeded in generating tunable cw far-infrared radiation via CO_2 difference frequency mixing in a tungsten-nickel, (MIM) diode. Previously, the MIM diode had been used mainly to make direct frequency measurements from 0.3 to 200 THz.

Six tenths of a microwatt of tunable, cw far infrared radiation has been generated by mixing 180 mW of radiation from each of two CO_2 lasers in a MIM diode. The difference frequency was radiated from the MIM diode, and was detected in a calibrated germanium bolometer. The use of a waveguide CO_2 laser with its greater frequency tunability as one of the lasers used to generate the difference frequency promises a complete coverage of tunable cw radiation in the entire far infrared band from 100 to 6000 GHz with the additional advantages of simplicity and high accuracy. Using this technique, it has been possible to readily detect the J=5←J=4 transition of CO (576 GHz) and the J=1←J=0 transition of HF (1.23 THz). Just recently the HCl spectrum from 0.5 to 5.5 THz has been measured and this simple molecule now provides for an excellent calibration standard in that frequency range.

<u>FY 1986 Plans</u>

Plan - Bring second TuFIR spectrometer (using third-order FIR generation) into operation

> <u>Accomplishment</u> - The second TuFIR spectrometer was completed with support from the Chemical Manufactureres Association.

Plan - Increase TuFIR sensitivity through use of a ^3He bolometer and a cooled grating prefilter.

> <u>Accomplishment</u> - The required increase in sensitivity (a factor of 30) in the region from 30 cm^{-1} to 120 cm^{-1} was achieved using a Ga doped Ge detector. With this success, the original plan has now been defferred until needed.

Plan - Study properties of diodes for second-order and third-order mixing. Search for diodes with improved mixing properties

> <u>Accomplishment</u> - A tungsten-cobalt diode was found to be most efficient for third-order mixing, but is not particularly reliable. That is, 1 in 10 of these diodes works whereas almost every diode fabricated from tungsten and nickel is successful. The tungsten-nickel combination still appears to be best for second-order mixing.

<u>FY 1987 Plans</u>

Formulate plans for the development of a frequency synthesis chain coupling a microwave frequency to the optical transition to the metastable $^2D_{5/2}$ state in Hg^+ in support of the development of an optical frequency standard based on that transition.

Continue the study of diode base materials and coatings for the tungsten whiskers in an effort to develop more efficient and more stable mixers.

Finish work on the helium-cooled pre-filter detector.

Initiate measurements of the spectral purity (phase noise) of the low-end components for a multiplier chain in collaboration with Fred Walls.

OBJECTIVE: Measure far infrared frequencies of atoms and molecules (especially transient species) for radio astronomy and upper atmospheric science.

High resolution spectroscopic measurements in the far infrared have been advanced significantly through development (at NBS) of two measurement techniques. These techniques are used to make unique laboratory measurements, previously inaccessible, which have bearing on difficult atmospheric and astronomical studies.

Laser Magnetic Resonance (LMR) spectroscopy has been developed into an ultrasensitive technique (i.e., several orders of magnitude more sensitive than microwave spectroscopy) for observing and measuring reactions involving molecules. LMR techniques are singularly effective in measuring parameters necessary to model the effects of pollutants (e.g., fluorocarbons, nitric oxide, etc.) in the atmosphere.

Subsequently LMR was used to make the first laboratory observation of the CH_2 spectra. The CH_2 radical is an important building block for all organic molecules and is present as a free radical intermediary in many chemical reactions. Measurements of CH, CD_2 and CD were completed and the spectra of GeH_3, GeH, SiH, and Si were identified.

The new techniques of Tunable Far Infrared (TuFIR) spectroscopy promises to enhance the LMR technique by measuring some of the same free radicals at zero field. Zero field measurements will have a greater accuracy. The technique, an outgrowth of NBS frequency synthesis work involving MIM diodes, also allows the measurement of all far infrared active molecules, not just paramagnetic ones. Measurements of OH frequencies have been completed. Tables of far infrared transition frequencies for the molecule are now available.

FY 1986 Plans

Plan - Using TuFIR methods, search for spectra of molecular ions.

Accomplishment - Molecular ions observed to date include HCO^+, H_2D^+, OH^- and ArH^+.

Plan - Perform OH line-broadening measurements for use in upper atmospheric studies.

Accomplishment - Completed measurements of the room-temperature, low-pressure broadening coefficient for OH and HCl with O_2 and N_2 as broadening gases.

1987 Plans

Search for the ions HeH^+, ArO^+ and OH^+.

Measure the temperature dependance of the broadening coefficient for OH and HCl. Measure the broadening of HF produced by O_2 and N_2.

Search for other molecules (frequency measurements and molecular constants) such as H_2O, H_2O_2, HO_2, HOCl and O_3.

IX. GEOPHYSICAL MEASUREMENTS

This is a small program conducted in JILA by Time and Frequency Division staff. One of the projects involves construction and demonstra- tion of an apparatus for measuring intermediate baselines (25 km to 50 km) with an uncertainty of 1/2 cm or less. The multiple-wavelength technique that is used is closely related to satellite navigation and timing problems which also require a complete accounting for atmospheric dispersion. A second project involves use of an array of tilt detectors to study properties of the earth's mantle and core-mantle boundary. A third program which is just starting, is a feasibility study for using GPS timing signals for very accurate geodesy.

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- V. Sadofsky (Guest Wroker - USSR)
- N. Sampas (Res. Assistant - CU)

OBJECTIVE: Develop metrology for precise time, frequency and length measurements.

Distance Measurement Techniques

The need to accurately determine the lengths of baselines on the surface of the earth arises in many different contexts, ranging from the calibration of tracks used for rocket tests to estimation of the relative motions of large geographical regions in seismically active zones. This work is particularly timely, since the use of timing techniques for such distance measurement is expected to grow and a key roadblock to improved resolution involves the dispersion of the atmosphere.

Geodesy from the GPS Satellites

Using signal time of flight from GPS satellites and radiometric corrections for atmospheric and ionospheric dispersion, it apears that very accurate geodetic measurements can be accomplished. A major program in this area, funded by NSF, involves collaboration between a number of univerisities to demonstrate this concept. This NBS group has assumed responsibility for hardware and software developments involving the GPS satellites.

FY 1986 Plans

Plan - Complete field and laboratory evaluation of the three-wavelength geodimeter system.

Accomplishment - Laboratory tests of the system have been completed. The first field measurements over a 25 Km baseline are also finished and the short-term (2-day) resolution was found to be 0.2 mm at this distance. The telemetry and data acquisition systems are nearly complete.

Plan - Establish feasibility for using GPS satellites to make measurements of baselines hundreds of kilometers in length with a fractional uncertainty of 1 in 10^6 or less through extensive measurements in Iceland.

Accomplishment - The Iceland campaign was completed using TI4100 receivers. About 300 tapes of data were recorded.

1987 Plans

Continue field tests of the three-wavelength geodimeter system. Perform measurements along calibrated baselines and determine the long-term stability of the calibration constants of the system.

Initiate analysis of GPS/Iceland data to extract network baselines.

OBJECTIVE: Evaluate the utility of nano-radian level tilt measurements in studying earth structure.

FY 1986 Plans

Plan - Complete comparison between theory and experiment on the model of the Yellowstone Caldera.

Accomplishment - The experimental work and data analysis have been completed. Models for the system are almost finished. A Ph.D. thesis (Meertens) will be written on this work (December 1986).

1987 Plans

Test usefulness of the tiltmeter as a short-period, surface-wave seismometer to improve resolution in tests of the model.

NOTICE OF TALKS

K.M. Evenson, "Frequency Spectroscopy: The Last Measurement of the Speed of Light: And the New Meter", The Sculoa Normale, Pisa, Italy, September 20, 1985.

K.M. Evenson, "Tunable Far-Infrared Spectroscopy," The High Resolution Spectroscopy Meeting, Riccioni, Italy, September 25, 1985.

K.M. Evenson, "Tunable Far-Infrared Spectroscopy," University of Alaska, Fairbanks, AL, November 14, 1985.

K.M. Evenson, "New Spectroscopy: The Speed of Light, and the Redefinition of the Meter," University of Vancouver, Vancouver, Canada, November 19, 1985.

K.M. Evenson, "The Last Measurement of the Speed of Light: The Redefinition of the Meter", The Annual Meeting of Alexander von Humbolt, Bonn, Germany, June 23, 1986.

Wayne M. Itano, "High Resolution Laser Spectroscopy of Mercury Ions," National Bureau of Standards, Gaithersburg, MD, November 12, 1985.

John Bollinger, "Generation of Liquid and Solid Ion Plasmas," National Bureau of Standards, Gaithersburg, MD, November 13, 1985.

Randy Hulet, "Laser Cooling of a Single HgII Ion," CLEO/IQEC, San Francisco, CA, June 12, 1986.

Randy Hulet, "Progress Towards the Observation of Quantum Jumps of a Single Ion," American Physic Society Annual Meeting, Eugene, Oregon, June 18, 1986.

David J. Wineland, "Laser Cooled Trapped Ions," University of Nebraska, Lincoln, Nebraska, April 24, 1986.

K.M. Evenson, "Tunable Far-Infrared Spectroscopy," International Conference of High Resolution Spectroscopy, Liblice, Czechoslovakia, September 8-12, 1986.

K.M. Evenson, "Tunable Far-Infared Laser Spectroscopy," 11th International Conference on Submillimeter and IR Waves, Pisa, Italy, October, 21, 1986.

R.E. Beehler, "Available Time Services," Western Area Power Administration, Loveland, CO, November 5, 1985.

D.W. Hanson, "Looking Ahead," Western Area Power Administration, Loveland, CO, November 6, 1985.

D.A. Howe, "Preliminary Report of the BPA Sponsored Research on Providing an One Microsecond Time Service to the Power Industry," Western Area Power Administration, Loveland, CO, November 6, 1985.

D.W. Allan, "GPS Error Analysis," Aerospace GPS Meeting, El Segundo, CA, October, 28, 1985.

D.W. Allan, "Status of Work at NBS: International Time and Frequency Coordination; Optical Pumped Cesium Research; GPS and Passive Hydrogen Maser Performance," Air Force Space Division GPS Meeting, Colorado Springs, CO, October 23, 1985.

D.W. Allan, "GPS Clocks Characterization and System Performance," Data Analysis/Working Group (DAWG), Santa Barbara, CA, November 11, 1985.

D.W. Allan, "Characterization, Optimum Estimation, and Time Prediction for Precision Clocks," 17th Annual Precise Time and Time Interval (PTTI) Meeting, Washington, DC, December 3, 1985.

D.W. Allan, "NBS Time and Frequency MAP Program" and "Clock Characterization Tutorial," Measurement Science Conference Panel Meeting, Orange County, CA, January 23, 1986.

D.W. Allan, "Hydrogen Maser Performance Characteristics," Air Force Space Division Meeting, Los Angeles, CA, January 14, 1986.

D.W. Allan, "A Brief Review of the History and Theory of Statistical Analysis Techniques Developed in Time and Frequency and Their General Applicability to Metrology," NBS, Center for Basic Standards, Gaithersburg, MD, February 11, 1986.

D.W. Allan, "The Meaning of the Mean Value and Its Uncertainty When the Standard Deviation is Undefined, and An Application of Time and Frequency Statistical Technique to Standard," Center for Basic Standards, Gaithersburg, MD, February 12, 1986.

D.W. Allan, "Should the Classical Variance be Used in SI Metrology," NBS, Boudler, CO, March 4, 1986.

D.W. Allan, "Steering of GPS Time" and "Clock Characterization and Systematic Problem in GPS," Falcon Air Force Station, Colorado Springs, CO, March 12, 1986.

D.W. Allan, "Should the Classical Variance be Used in SI Metrology," NBS, Boulder, Colorado, March 14, 1986.

D.W. Allan, "The NBS Atomic Clock and Some Applicaitons," University of Colorado, Boulder, CO, March 18, 1986.

D.W. Allan, "Should the Classical Variance be Used as a Basic Measure in SI Standards Metrology?," CPEM '86 Conference, Gaitehrsburg, MD, Juen 25, 1986.

M.A. Weiss, "An NBS Calibration Service Providing Time and Frequency at a Remote Site by Weighting and Smoothing of GPS Common View Data," COEM '86 Conference, Gaithersburg, MD, Juen 25, 1986.

F.L. Walls, "Characteristics and Performance of Miniature NBS Hydrogen Masers, CPEM '86 Conference, Gaithersburg, MD, June 25, 1986.

J. Levine, "Earth Based and Satellite-Based Distance Measuring, Symposium for Innovation in Measuremetn Science, Geneva, NY, August 8, 1986.

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A. DeMarchi and R.E. Drullinger, "Long Term Behavior of Cavity Phase Difference in NBS-6," submitted to Metrologia.

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L.R. Brewer, J.D. Prestage, J.J. Bollinger, W.M. Itano, and D.J. Wineland, "A High Γ Strongly Coupled Non-Neutral Ion Plasma," submitted to Strongly Coupled Plasma Physics (NATO ASI Series).

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SEMINARS ORGANIZED

NBS Time and Frequency Seminar, August 12-14, 1986, Boulder, Colorado.

Workshop on Traceability of Quartz Measurements to U.S. Standards, January 15-16, 1986, National Bureau of Standards, Boulder, Colorado.

Second Workshop on Traceability of Quartz Measurements to U.S. Standards, August 22, 1986, National Bureau of Standards, Boulder, Colorado.

Workshop on Fundamental Measurements on Optically Prepared Atoms, September 29-30, 1986, National Bureau of Standards, Gaithersburg, MD.

SPECIAL REPORTS

D.W. Hanson and D.A. Howe, "Industrial Time Service Study," NBSIR 86-3042, February, 1986.

PARTICIPATION AND LEADERSHIP

D. W. Allan, Study Group VII, International Radio Consultative Committee (CCIR).

D. W. Allan, IEEE IM TC-3 Frequency and Time.

D. W. Allan, NASA Team Member for Shuttle Timing Experiment.

D. W. Allan, URSI Commission A

R. E. Beehler, CCIR Study Group 7; International Chairman of Interim Working Party 7/4 on "Improved Time Coordination and Dissemination Using Satellites".

K. M. Evenson, URSI Commission D.

D. W. Hanson, Member Technical Advisory Committee for TDRSS, NASA Satellite Program.

D. A. Jennings, Member CCDM

J. L. Jespersen, Chairman IRIG Timing Committee.

G. Kamas, Measurement Assurance Subcommittee, National Conference of Standards Laboratories.

J. Levine, Chairman, Electronic Shops

J. Levine, Computing Allocation Committee, Colorado University

J. Levine, National Academy of Sciences, Committee on Geodesy

J. Levine, Board of Review of Science Institute

J. Levine, NBS Computer Users Committee

D. B. Sullivan, URSI Commission A

D. J. Wineland, Committee for NBS Precision Measurements Grants

D. J. Wineland, Program Committee of the Division of Electron and Atomic Physics, American Physical Society

QUANTUM PHYSICS DIVISION

SUMMARY OF ACTIVITIES

FISCAL YEAR 1986

OVERVIEW

The Joint Institute for Laboratory Astrophysics[1] (JILA) has had another productive year under the able leadership of its Chairman, Carl Lineberger.

- The NSF block grant to the University of Colorado for research in atomic and molecular physics at JILA has been renewed for another 4.5 years with a substantial (for these times) increase in funding. Included in this grant is support for university graduate students and postdoctoral research associates working with members of the Quantum Physics Division.

- The project to expand JILA's research facilities is progressing well. The ground breaking for the addition to the JILA building took place on October 20, and construction is expected to take about 12 months. The building will provide an additional 16,000 square feet of desperately needed office and laboratory space. NSF is provding a $500K toward the construction costs, and a further grant is being sought from the Department of Education.

- Steve Leone received the Arthur S. Flemming Award, presented by the Jaycees of Washington, D.C. to honor outstanding young men and women in the Federal Government.

- Two senior scientists in the Quantum Physics Division have officially retired from their NBS positions this year. Steve Smith continues to maintain his vigorous research program as a JILA Fellow Adjoint; Sydney Geltman will also remain in JILA as a Professor Adjoint in the Physics Department.

- JILA has greatly benefited from the visit of Dan Kelleher, who has spent the past year here working on theoretical problems in plasma spectroscopy as the NBS/JILA Exchange Fellow from the Center for Radiation Research.

- The Fellows of JILA are particulary pleased to welcome Norman Ramsey as a Visiting Fellow for 1986-1987. He plans to spend the year consulting and working with a number of different Fellows.

- Pat McInerny received the Department of Commerce Bronze Medal for his contributions to the overall effectiveness of JILA, where he has served for 15 years both as Administrative Officer for NBS and as Executive Officer for the University of Colorado.

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[1] Quantum Physics is the division through which NBS participates in the Joint Institute for Laboratory Astrophysics, a cooperative enterprise between NBS and the University of Colorado. More background on the Institute is included in the last section of this report.

o During the past year, Quantum Physics Division scientists have:

- Made a breakthrough in observations of squeezed light showing two-fold (and greater) noise reductions relative to the quantum vacuum level (in collaboration with M. J. Kimble, University of Texas, Austin).

- Demonstrated that a 50 kg relativity satellite included as part of a future Mercury Orbiter Mission could monitor the Earth-Mercury distance with about 6 cm acuracy.

- Finished the last of six absolute gravimeters developed in cooperation with two national and five international programs.

- Showed that the equation of state recently developed for moderately dense plasmas is the first to reproduce the ionization of helium in the Sun's interior (in collaboration with D. Mihalas, NCAR).

- Demonstrated empirically that the magnetic field strengths in the photospheres of stars cooler than the Sun are governed by the equality of magnetic and local gas pressure.

- Made major strides in the development of a powerful computer program for the accurate calculation of cross sections for electron-impact induced vibrational excitation of molecules.

- Made the first quantitative measurements and models of electron, fast ion and fast atom behavior in uniform electric field discharges in N_2, Ar and D_2 at very high electric field to gas density ratios.

- Measured for the first time the spin and orbital angular momentum dependence of inelastic excitation of atoms.

- Found evidence for the need to reasses our concept of the structure of hydrogen bonding complexes.

- Obtained the bond strength of Ga on silicon (100) surfaces by a new laser probe method, important to the growth of GaAs semiconductors on silicon substrates.

FUNDAMENTAL AND PRECISE MEASUREMENTS

Laser Stabilization and Stopped Atoms - J. L. Hall

The application of stable laser techniques to fundamental spectroscopic problems requires the availability of stable - but widely tunable - cw dye lasers. The apriori incompatibility of high stability with wide tunability (not to mention with the rapidly-flowing intracavity free dye stream) has greatly prolonged the development of such lasers. Industry is also interested in these problems. At present there are something like 550 commercially produced, actively-stabilized, cw dye laser systems in service worldwide, all based on a fundamental stabilization technique published and developed by Hall's group. With linewidths of about 1 or 2 MHz, these commercial lasers are in part responsible for the explosion of tunable-laser spectroscopic techniques over the past five years. Dramatically higher levels of dye laser frequency stability have now been demonstrated in Hall's laboratories, variously 50 kHz, 1 kHz and 200 Hz. A high power dye laser has even been phase-locked to a stable low-power He-Ne source. Now that sufficient transducer bandwidth can be obtained to suppress intrinsic laser instability using feedback techniques, the next major challenge is to develop refined methods of tuning/guiding/offsetting the laser's frequency and of controlling it to an appropriate reference in order to enhance the mid- and long-term stability. Hall's group has now developed an interferometric scan technique for wide scans ($\Delta\nu/\nu \leq 10\%$) and moderate accuracy (< 1 MHz). The accurate tuning problem has been addressed for modest scans (± 3.5 GHz) by the development here of a broadband traveling wave electro-optic phase modulator (based on a miniature $LiTaO_3$ crystal), which produces a tunable optical sideband with the full sub-Hz accuracy of the rf source and with the full 34% efficiency available in the phase modulation process. Using this system, augmented by computer control, Hall has recently studied isotope shifts and hyperfine structure in Hg with an accuracy in the 20 kHz range, limited principally by the 24 MHz natural linewidth of the transition.

Another interesting application of the tunable sideband technique is the conversion of an atomic beam to a static gas sample at millikelvin equivalent temperature. The velocity deceleration of the atomic beam is provided by the directed momentum transfer from the laser to the counter-running atomic beam, about 30,000 absorption/random-emission events being required to suppress the initial thermal velocity and stop a beam of sodium atoms dead in their tracks. During this process, the changing velocity-induced Doppler shift sweeps through about 100 resolvable natural linewidths. The availability of the inertia-free sideband frequency sweeping capability (using a swept frequency oscillator to feed the broadband electro-optic modulator) has been fundamentally useful in this work, enormously simplifying the interpretation of these atom-cooling experiments. Hall's group has obtained a three-dimensional residual velocity distribution of 3 m/s RMS, equivalent to a kinetic temperature of about 8 mK, which is in quantitative agreement with the fundamental limit imposed by the natural linewidth. Hall is now preparing to follow this stage with a period of post-cooling, pumping a 20-fold weaker line (which happens to be in the uv for Na). This work will open qualitatively new regimes of "atomic beam" physics, including gravity-effects as a first-order consideration, atom bouncing, and atom aggregation with "atom mirrors" formed by pulsed, reversing curved wavefronts. One of the most exciting prospects for spectroscopy implicit in this work is the availability of long perturbation-free coherent interaction times, certainly 10's to 100's of milliseconds. Hall's computer simulations suggest that an average atom may spend a few 10's of seconds in this bounce trap. Thus, a high density buildup factor may be expected given the typical 2 ms "recharging" cycle repetition rate. Strong optical cooperative effects (super radiant emission and soliton modes) are expected, while high density collisional effects (such as Bose condensation) may possibly be accessible with a suitably chosen atomic system and/or still stronger cooling. The immediate payoff of this stable laser and cold-atom technology will be for the laser stabilization problem itself - to provide a super-narrow (in view of the increased interaction time) transition for the laser frequency reference. The first "ultra-resolution" experiment will be an attempt to observe Ramsey-type interference fringes at the Na hyperfine frequency due to free-flying cooled atoms that interact first on their upward flight and second in their free-fall stage. (There will be questions about the trajectories and interaction-time distribution, so it seems wiser for the first experiment to study hyperfine rather than optical coherences.) When the interaction techniques are well-evolved, the transition of choice will be a two-photon transition in Ag that has a one second resonance lifetime.

As an adjunct to this work, Hall and his group are pressing the limits of laser stabilization to a passive material optical reference cavity. Lowering the noise and drift rate of such a locked source will allow slower servo loops in guiding on to an atomic resonance. The lower bandwidth there will thus lead to lower frequency noise of the system. In addition, the cavity locking techniques are interesting in their own right because of possible application in inertial guidance (passive laser-driven ring resonator gyroscopes), local oscillator stabilization for space satellite communication, and as the optical reference source for gravity wave detectors based on interferometry. The dye laser experiments up to now have used servo bandwidths of a few (≤ 5) MHz. If the frequency servo bandwidths can be pushed into the 30-40 MHz domain, it will be possible to lock the exciting - and now widely available - single frequency solid state laser diode to produce kilohertz linewidths or perhaps less. Hall's preliminary experiments in this direction are very promising. On the other side, driving toward the ultimate stability/lock accuracy limit with conventional gas laser sources is also very exciting. While the increase in space and improved environmental control planned for the new JILA addition will certainly help the laser stability experiments described above, these cavity stabilization experiments will require drastic improvements in environmental stability if they are to begin to reach their full potential. In the meantime, the scientists in Hall's group are investing considerable effort and occasional cleverness in overcoming the thermal changes, acoustic noise level, floor-borne vibrational noise level, 60 Hz magnetic fields, elevator-induced changes in the Earth's magnetic field, tilting of the laboratory floor driven by wind forces on the JILA tower, etc. At present they have generated and measured beat stability of two independent lasers well below the 100 millihertz level, which would correspond to laser linewidths of the same value if the cavity used for the locking were equivalently stable. By means of heterodyne techniques with a laser stabilized on an I_2 reference line, we found that the previous reference cavity was profoundly influenced by temperature rates of change, barometric changes, and floor-tilt effects. A new cavity support/isolation structure has dramatically helped such problems, as has a Peltier cooler-based thermal controller located inside the vibration/acoustic/thermal isolation box ("Quiet house"). Temperature variations of $\pm$ 2.5 mK are now obtained, which are further attenuated and filtered by the thermal controller on the reference cavity structure. The presently observed 100 Hz amplitude at 24-hours period will allow $\approx$ 500-fold improvement on the Kennedy-Thorndike experiment, which checks that the velocity-dependent transformation of time and length are equivalent. A long-term, almost noise-free drift of + 2.08 Hz/sec ($\approx$ 200 kHz/day) is observed due to an aging of the Zerodur interferometer spacer bar (see Figure 1). This value is in agreement with the known aging rate of Zerodur gauge blocks ($\approx 1 \times 10^{-7}$/yr), which decays to ($\approx 1 \times 10^{-9}$/yr) after a few years. Since this is a constant drift, it is of little concern. However, to work effectively in the millihertz domain of interest for laser gyros, and ultimately for laser cooled ion spectroscopy, a laboratory with isolated piers reaching bedrock is essential. Modern control systems for temperature and electric service will also be required in these labs.

At various stages in these developments, techniques have been in hand to allow precision measurements of high physical interest. Representative experiments include the measurement of the relativistic Doppler shift, observation of Ramsey fringes, an improved test of the isotropy of space, measurement of Rydberg atom levels using a traveling-carriage Lambdameter, development of optical sideband techniques for high precision and ultra-sensitive spectroscopy, measurements of state-dependent hyperfine coupling in HF, observation of Rydberg energy level shifts due to thermal radiation, and the stopped atom work described above. In addition to the 100-plus publications, the program has developed five patents - three issued, one pending, and one under evaluation.

A description of the JILA stable laser program would be seriously incomplete without mention of the collaborative experiments undertaken jointly with other labs. One previous collaboration with S. Chu and A. P. Mills of Bell Labs led to precise measurement of the 1S-2S transition frequency of triplet positronium. Hall's contributions to this

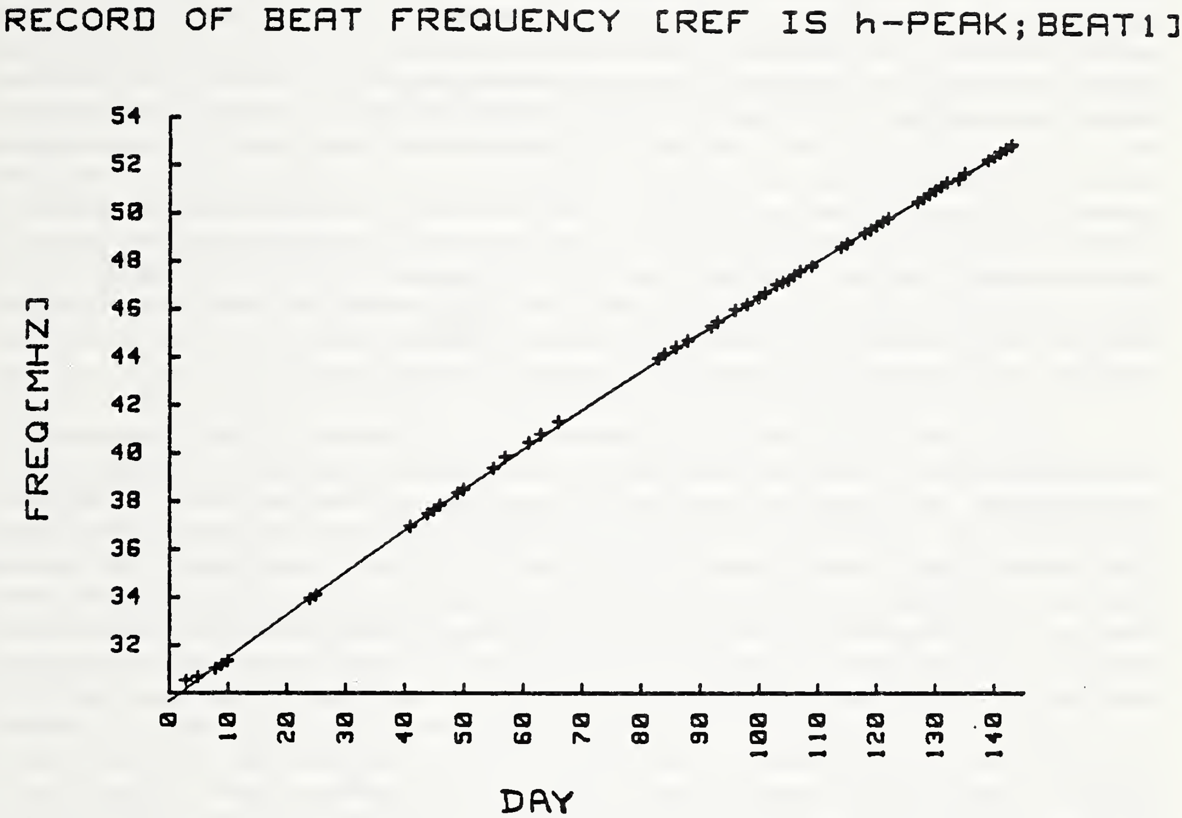


Figure 1. Long-term stability of cavity-stabilized laser frequency. Reference cavity consists of 30 cm long by 15 cm diameter Zerodur spacer with optically-contacted ultra-low loss mirrors ("gyro quality"), which is suspended in vacuum by a pair of thin stainless-steel ribbons. Temperature controller has 10 microkelvin noise level for 1 s averages. System is located in JILA "Quiet House", whose temperature is controlled to ± 5 millikelvins unless the University switches off the air conditioning chilled water supply. Laser stabilized to this cavity is heterodyned with an atomic physics standard laser stabilized to an I_2 component at 633 nm. The beat frequency shows an almost noise-free uniform drift of 2.08 Hz/s due to ageing of the Zerodur spacer. This value corresponds to $\approx 1.4 \times 10^{-7}$/yr contraction of the zero thermal expansion coefficient material and is in good agreement with measurements made at the Physikalisch-Technische Bundesanstalt. Their measurements show this creep rate reducing to below 10^{-9}/yr after a few years. Over a one day time frame the drift is about 200 kHz, but is so uniform that any 24-hour component is below 200 Hz pk-pk. This limit already represents a 500-fold improvement on the Kennedy-Thorndike experiment which shows the equivalence of the velocity-dependent square-root factor in the transformation of time and length. The < 0.1 Hz linewidth of this stabilized laser promises major progress in the ultrahigh resolution spectroscopy of trapped ions and/or slow atoms.

positronium experiment were mainly in frequency stabilization and wavelength metrology. Much the same ingredients are present in the JILA-Stanford collaboration (Professor T. W. Hänsch) on the precision measurements in hydrogen. Hydrogen transitions are being measured at Stanford relative to reference transitions - for example in Te_2 - that will ultimately be measured with extreme accuracy at JILA using advanced interferometric techniques now under development. Another by-product of this cooperation with Stanford is the development of a novel and universal laser stabilization technique. The method can work with the output of any cw laser since the active transducer is located outside the laser cavity. The technique uses both an electro-optic phase modulator and an acousto-optic frequency shifter. In addition to frequency correction, the system provides optical isolation against optical feedback to the laser source and can be configured to provide effective intensity control as well. There is strong commercial interest in this device, and a patent application has been filed jointly with Stanford.

In collaboration with Professor H. J. Kimble of the University of Texas (Austin), Hall has made the first measurements and demonstration experiments in which a practical, significant level of "squeezing" has been obtained. Rather than the 7% effect reported by the initial Bell Labs team, they have shown a factor of 2.0 or 2.5 effect. While the full metrological implication of these results may only become clear over a half-decade timescale, it is already obvious that dramatically enhanced measurement sensitivity will be available for important national objectives such as earth-based searches for gravitational radiation. The squeezing experiments are limited by a number of remediable effects at present. One of the most significant is the use of $LiNbO_3$ crystal as the nonlinear medium - it suffers from light-induced damage - rather than the more attractive $BaNaNbO_3$. This material is unfortunately no longer produced in this country. Hall was able to get a small sample from the Shanghai Institute of Ceramics. This crystal was used inside the laser resonator to produce the green second harmonic light that served as his pump source for the degenerate parametric oscillator that produces the "squeezed darkness". He is optimistic about getting a sample of beta-$BaBO_3$, a new Chinese crystal with still more favorable characteristics, in view of his recent personal contact and visits with leading Chinese crystal growth labs.

<u>Laser Gravitational-Wave Observations in Space</u> - P. L. Bender and J. E. Faller

Funding to the University of Colorado has been obtained under the NASA Innovative Research Program to support continued work on studies of possible laser gravitational wave observations in space. The basic concept for the experiment has been described in earlier annual reports. It requires placing three spacecraft in Earth-like orbits around the Sun, with separations between the spacecraft of about one million kilometers. By choosing the orbit parameters properly, the baselines from the center spacecraft to the other two can be made to stay roughly perpendicular and equal in length to about 0.1% over periods of a number of years. Beams from a laser in the center spacecraft can be used to phase-lock separate lasers in the other two spacecraft, and the returned signals from these lasers can be heterodyne detected against the central laser. In this way, any differential changes in the lengths of the two baselines due to gravitational waves can be detected. The distance measurements are actually between carefully isolated and free-floating test masses inside the three spacecraft, in order to minimize apparent signals due to spurious accelerations.

As discussed last year, studies of expected gravitational wave signals due to binary star systems have been carried out by D. Hils, R. F. Webbink (JILA Visiting Fellow) and Bender. A draft paper on the results has been written, and will be submitted for publication. To summarize briefly, it appears that the power spectral density of signals due to different types of binary star systems will be above the instrumental sensitivity for frequencies from very roughly 10^{-6} Hz to 10^{-1} Hz. Since about 10^{8} binaries in our galaxy contribute to the signals, it will not be possible to resolve individual sources unless they are unusually close by. Exceptions are double neutron star binaries and close white dwarf binaries with frequencies near 10^{-2} Hz, for which the number in the galaxy is fairly small. The reality of the gravitational wave signals can be checked by observing the change in signal strength as the plane of the galaxy goes through one of the nulls in the antenna pattern, which correspond to the plane bisecting the two baselines and the perpendicular plane. Information on the location of resolvable sources can be obtained in the same way.

In view of the results on binary sources, some additional consideration has been given to other possible basic designs for a gravitational wave antenna in space. One possibility is to put the three spacecraft about 90 degrees apart in geosynchronous orbit. This would give 60,000 km baselines and increase the sensitivity for frequencies above about 0.1 Hz, where the gravitational wavelength becomes shorter than a few million kilometers. However, the expected signal strength for sources of gravitational wave pulses at cosmological distances, such as collisions of very massive black holes, would still not be strong enough to detect except for objects of roughly 10^{4} solar masses or larger. Whether such shorter baselines are desireable may depend on the plausible frequency of collisions involving somewhat less massive black holes at non-cosmological distances. Even if roughly 60,000 km baselines were chosen, putting the three spacecraft in solar orbit rather than geosynchronous orbit might still be desireable in order to avoid changes in the baseline orientations with respect to the solar direction at the once per day frequency. Such orientation changes would make the instrument design more difficult and cause substantial thermal perturbations at harmonics of the diurnal frequency.

Another attractive possibility would be to use roughly 100 km baselines where perhaps 1,000 bounces of the light in two perpendicular Fabry-Perot interferometers could be achieved. This would give a major improvement in precision, but at the expense of much larger sensitivity to spurious accelerations of the test masses. Thus the performance at frequencies above roughly 10^{-13} Hz could be very much improved, but the performance at lower frequencies would be seriously degraded. Whether this approach is desireable will depend on further studies of gravitational wave sources and on the detection sensitivities near 1 Hz that may be achievable in future ground-based measurements. These questions will be explored further by R. T. Stebbins and D. Hils (University of Colorado), along with Bender and Faller.

<u>Mercury Orbiter Relativity Subsatellite</u> - P. L. Bender

M. A. Vincent and Bender have investigated the accuracy with which the orbit of a relativity subsatellite around Mercury could be determined from a number of roughly eight-hour periods of high-accuracy tracking data from the Earth. The purpose of this work is to support earlier investigations by N. Ashby, J. M. Wahr and Bender on how well gravitational theory could be tested in a Mercury Orbiter Mission if the center-of-mass distance between Earth and Mercury were determined within a given systematic error limit over a period of one to eight years. In order to convert the measured distance from the Earth to the subsatellite into the desired center-to-center distance, the component in the direction toward the Earth of the satellite position vector with respect to the center-of-mass of Mercury has to be determined.

The orbit calculations assumed that the relativity subsatellite would be in a high inclination orbit at roughly 2,500 km altitude. Initial results obtained a year ago indicated that an uncertainty of about 15 cm was achievable for the center-to-center distance. However, considerably more accurate results have now been obtained by considering only tracking periods when the solar radiation hitting the satellite is not eclipsed by Mercury. This minimizes the effect of uncertainty in the solar radiation pressure on the orbit. Doppler tracking data with 1×10^{-14} accuracy and range data with 3 cm accuracy were assumed for 40 carefully chosen 8-hour periods. The gravity-field coefficients for Mercury up through degree and order 10 were solved for, along with initial orbit elements for each of the 40 tracking periods. The main errors allowed for were radial and off-axis biases in the calculated solar radiation pressure on the satellite plus uncertainties in 48 gravity field spherical harmonic coefficients of degree 11 and 12. With only one range measurement per 8-hour period and Doppler measurements every 10 minutes, the rms range uncertainty was found to be 4.2 cm. Including allowances for uncertainties in the tracking station location, the Earth's rotation, and the atmospheric propagation correction, the total uncertainty in the Earth-Mercury distance would be about 6 cm.

Eötvös Experiment - J. E. Faller

The weak equivalence principle tested by the Eötvös experiment is the hypothesis that all test bodies fall with the same acceleration in the same gravitational field. This principle provides the experimental foundation on which the geometrization of space-time in Einstein's General Theory of Relativity is based. The central position of the principle in Einstein's and other metric theories of gravity emphasizes the importance of testing it to the best possible accuracy. Any failure of the universality of free-fall would necessitate a theoretical revolution.

Though in concept this principle is testable by dropping different masses and observing whether or not they fall at the same rate, torsion balances have been used since the experiments of Baron R. von Eötvös and his colleagues in the late 19th and early 20th centuries. Accordingly, since that time, experiments designed to test this equivalence of gravitational and inertial mass have been referred to as Eötvös experiments.

The approach to the experiment that Faller has adopted arises from the observation that in the traditional torsion pendulum, the fiber serves both to support the masses and to determine the torsion coefficient. In Faller's approach, the suspension is provided entirely by a liquid, and the restoring and centering functions of the fiber are achieved by an appropriate electrode array subject to adjustable voltages.

During the past year, P. Keyser and Faller temporarily focused their efforts (in part to assure that Keyser would finish his thesis in the University of Colorado's mandated time limit) on the smaller gradiometer floats (see next section).

GEOPHYSICAL MEASUREMENT METHODS

Gravity Gradiometer - J. E. Faller

Faller and Keyser are proceeding with the testing of two 0.25-meter diameter fluid-supported pendulum apparatus as gradiometers. This development - in addition to its importance for the Eötvös work - has applications to tunnel and intrusion detection as well as security for nuclear stockpiles. Commercial applications of these devices for sink holes, etc. are being explored. During the past year, Faller and Keyser have been testing these two floats under differing temperature control conditions, both near room temperature and at 4 °C. They have also run one of these floats as a "non-gradiometer" (using a cylindrically symmetric mass distribution) in an attempt to separate out gravitational (gradient) noise from instrumental noise. During this same period, their study of contamination and centering problems as they effect their large Eötvös float have successfully continued using several smaller floats (because of the quicker experimental turn around time between modifications). In addition, specific convective noise mechanisms have been identified, and modifications in the float geometry aimed at ameliorating these effects appear to be successful. One of the floats has now operated continuously for eight months; the others have served as modification test beds for new ideas.

During this past year, a rather dramatic (it appeared in all the popular press) target of opportunity appeared - the suggestion of a new "Fifth Force." As this suggestion is relevant to things Faller has been doing with Keyser, and T. Niebauer, and as it is, in principle, testable with relatively minor modifications to their various existing apparatus, they have to date devoted approximately three months of previously unprogrammed activity to it. Re-evaluating the original Eötvös and Renner data, they have shown in a "Comment" on Fischbach, et al.'s "Physical Review Letter" that the Eötvös-type experimental basis for the suggested new effect is quite a bit less compelling than the original letter would seem to imply. They are now ready to begin several experimental tests (one free-fall type and one fluid-float Eötvös type), which should serve to put meaningful contemporary experimental constraints on this and similar types of hypotheses.

In connection with a laboratory need to sense floor tilting at the sub-second-of-arc level, Faller and his eldest son have designed and tested a new and simple type of recording-level device. This new device has demonstrated sensitivity at the 20 milli-sec-of-arc level.

Absolute Gravimeter (g) - J. E. Faller

The absolute value of g continues to play a significant role in the determination of certain physical constants and standards. With the accuracies obtainable today, its measurement also has broad application to geophysics and geodesy. With these purposes in mind, Faller and T. Niebauer, together with J. Gschwind and A. Joll of the Defense Mapping Agency (both assigned to work in JILA) have just completed the construction of six new absolute gravimeters. These new instruments are based on the free-fall interferometric method: A freely falling mass that contains a corner cube serves as a mirror in one arm of a Michelson interferometer. The times at which selected interferometric fringes occur are used to calculate the acceleration of the mass by the Earth's gravity. A stabilized laser, used as a light source in the interferometer, provides the standard of length, while an atomic frequency standard provides the standard of time. A new dropping mechanism eliminates several sources of systematic errors, and a long period isolation device greatly decreases the instrument's sensitivity to ground vibrations.

In the summer of 1985, Faller participated in the Second International Comparison of Absolute Gravity Instruments held at the BIPM. During the past year, he has analyzed his results and determined a value for Serves Point A5. Intercomparing his results (by using relative measurements to transfer all of the absolute measurements to the same site) gives a value for the average of all measurements that differs from his transferred value by 1.2 μgal and from the average obtained by rejecting three "outlying" measurements by 0.3 μgal! A publication, "Results of the Second International Comparison of Absolute Gravimeters" (with Yu. Boulonger, USSR and E. Groten, West Germany) is in preparation.

The Canadian (Mines, Minerals and Resources, Ottawa), the West German (Institüt für Erdmessung, Hannover) and the NGS/DMA instruments appear to be working well. A suggested improvement made to the Hannover group regarding their super-spring alignment has resulted in a factor of 5(!) reduction in their measurement scatter. The Canadians have helpfully discovered a 1.0 to 1.5 μgal systematic effect in their laser wavelength. The "cooperation" is successful and a two-way street. The Finish and the Austrian instruments (the last two instruments) will be finished in November. In terms of populating the world with absolute gravimeters, this has been an extraordinarily successful year.

<u>Water Vapor Calibrator Development</u> - P. L. Bender

The accuracy of a number of geophysical and astronomical studies based on microwave distance measurements is limited mainly by uncertainty in the propagation correction due to water vapor in the atmosphere. Measurements of tectonic plate motions by Very Long Baseline Interferometry are among those affected, as will be the tectonic studies soon to be made with dual-frequency Global Positioning System receivers. Water vapor radiometers that measure radiated power in the 22 GHz water vapor emission line are likely to be used with increasing frequency to measure the integrated water vapor content along the line of sight to the sources of the microwave signals. However, the accuracy of these results is currently checked only against radiosonde data.

S. J. Walter and Bender have obtained funds from the Jet Propulsion Laboratory to develop a microwave-optical system to improve the accuracy of the correction to the microwave distance measurements due to the atmospheric water vapor. Since optical distance measurements are affected much less by water vapor, the difference between microwave and optical measurements to an aircraft at about 6,000 meters would serve to determine the microwave distance correction. Such an aircraft would be above about 95% of the atmospheric water vapor, and meteorological measurements at the aircraft would permit correction for the remaining water vapor. The resulting measurements of the total amount of water vapor integrated through the atmosphere would be compared with estimates from a dual frequency water vapor radiometer looking along the same line of sight. Such comparisons are expected to give a valuable calibration of the water vapor radiometers used in geophysical and astronomical applications. The comparisons of results also may aid in improving the algorithms used in analyzing the water vapor radiometer results.

The basic transmitter and receiver for the calibrator have been constructed and tested in the laboratory. A 35.25 GHz microwave carrier from a Gunn diode oscillator and a roughly 830 nm optical carrier from a laser diode are modulated at 1.5 GHz in the transmitter. The modulation signals are recovered in the receiver, amplified, filtered, down-shifted to 15 kHz, and then compared in phase. Phase-lock circuits to stabilize the frequencies of the Gunn diode oscillator in the transmitter and another one in the receiver are now being constructed. These circuits are needed before beginning outside tests of the transmitter and receiver. Work also is being started on the construction of an image motion compensator, which will automatically direct the light received in the aircraft in later tests onto the avalanche photo-diode detector, despite rapid and irregular tilts of the aircraft.

ASTROPHYSICAL MEASUREMENT

Atmospheric Parameters of Hot Stars - D. G. Hummer

In a continuing project to determine accurate values for the atmospheric parameters of hot stars, Hummer, D. Abbott and B. Bohannan, and Hummer's student S. Voels, all of JILA, have carried out a detailed analysis of the line spectra of six hot stars they observed at Kitt Peak National Observatory to very high photometric precision (S/N of order 300). The analysis is based on non-LTE stellar models that account for radiation scattered back into the star by its stellar wind, an effect shown by Hummer to be important for hot luminous stars. This so-called "wind blanketing" causes the value of the effective temperature inferred from stellar spectra to be significantly lower than would be found if the effect were ignored. The results for the star Zeta Puppis, which are now in press, appear to settle a long-standing uncertainty of about 40%; those for the five Orion stars are being prepared for publication.

An analysis of this kind gives accurate values of the effective temperature and surface gravity, and can be extended to yield the chemical composition. A program has been set up in collaboration with a group headed by R. Kudritzki, Director of the Institute for Astronomy and Astrophysics of the University of Munich, to determine as accurately as possible the stellar parameters of 20 to 30 stars in our Galaxy and in each of the Magellanic Clouds. In view of the widely different elemental abundances of these three galaxies, these data will provide the first observational tests of stellar evolution theory that can discriminate among alternative theories of mass loss and convective overshooting, which now constitute the main recognized sources of uncertainty in our understanding of stellar evolution. Hummer's group has obtained spectra for approximately 10 additional stars that have not yet been analyzed, and the Munich group has, in the past year, acquired spectra for about 15 stars in the southern hemisphere. Hummer and Abbott are at present computing stellar wind models to be used by the Munich group in the analysis of their spectra.

Hummer and Kudritzki have pointed out that by using the terminal velocity of a star's stellar wind, which can be measured from line profiles, in addition to the effective temperature and surface gravity, it is possible to infer the absolute luminosity, and hence the distance to the star. This development, which uses purely spectroscopic data and contains no calibration or empirical correlation, was made possible by refinements in Munich of the theory of radiatively-driven stellar winds originally developed at JILA. This method can be definitively tested in the next few years when distances to some "nearby" hot stars will be measured accurately by satellite observations using trigonometric methods. The spectroscopic method will be applicable to much more distant stars, for which the trigonometric methods fail.

Equation of State - D. G. Hummer

Hummer, in collaboration with D. Mihalas (NCAR, Univ. of Illinois) has been working for the past two years on the development of an improved equation of state for material with temperatures and densities in the range $3.5 \leq \log T \leq 7.0$ and $-12 \leq \log\rho \leq -2$. This work is part of the international "opacity project", of which Hummer is a co-founder and co-director. The approach is to minimize, with respect to all level populations, the free energy, which depends on, among other things, the internal partition function. The evaluation of the expression for the internal partition function for atomic systems has long been recognized as one of the primary unsolved problems of statistical physics. Hummer had previously shown that the value of this quantity is controlled in moderately dense plasmas by the Stark ionization of excited atomic states. He has recently refined his quantal treatment of this mechanism to include the effects of mixing of Stark states by the plasma micro-field as well as by collisions. In a complementary study of the effect of Stark ionization in the classical picture, Hummer found an exact solution to the saddle-point description of this phenomenon for arbitrary angular momentum. Both of the new developments indicate that the classical field strength at which a state changes character from bound to free is significantly larger than the value given by simple arguments used previously in evaluating the internal partition function.

A computer code has been written to carry out the free energy minimization for arbitrary temperature and density. Because Hummer and Mihalas have been able to obtain a completely analytic expression for the free energy and to calculate analytically all of the desired derivatives, the minimization with respect to all ion densities (about 200) can be performed rapidly, as can the evaluation of the thermodynamic quantities of interest, which can be expressed as various partial derivatives of the free energy. The code has been checked by evaluating the same derivatives numerically. A comparison of this equation of state and the various thermodynamic functions derived from it with other theoretical estimates and some experimental data is now underway, as is a comparison with quantities derived from an analysis of solar oscillations.

Collisional-radiative Recombination - D. G. Hummer

In an ongoing collaboration with P. J. Storey (University College London), Hummer has been involved in an improved and extended calculation of radiative recombination line intensities and total recombination rates accounting for the effects of electron collisions, which become crucial as the electron density increases. They have recently completed the calculations for H I and He II, giving the intensities for all transitions between states with upper and lower principal quantum numbers up to 50 and 29, respectively. This wide range is necessitated by the extended wavelength range expected for infra-red astronomy within the next few years. For H I the temperature and density ranges are $3 \leq \log T_e \leq 4.5$ and $2 \leq \log N_e \leq 10$, while for He II, they are $3.5 \leq \log T_e \leq 5$ and $2 \leq \log N_e \leq 13$. As each of these 201 cases requires two pages of tables, the paper presenting this material is being published with micro-fiche tables. The calculation of the corresponding results for the hydrogenic ions of C, N, and O is well underway, and should be completed by the end of 1986.

Because, as the ionic charge Z increases, the radiative rates increase strongly and the collisional rate coefficients decrease also quite rapidly, an important limiting case is that of zero density. This case, which depends on only one parameter, $T_e Z^{-2}$, can in principal be solved exactly by the so-called "cascade matrix" technique, although the calculations are extremely large. Hummer and Storey have written a code in which the problem is reduced to tractable dimensions by making full use of all possible physical selection rules, and by finding mappings that reduce the dimensionality of the matrices and eliminate most of the zero elements. This code has been used to obtain extremely accurate results for $n \leq 50$, which are invaluable for checking and extending the more general case with finite densities, as well as being useful in themselves for analyzing low-density objects such as planetary nebulae. However, because of the very slow convergence of the method for states with large values of the atomic angular momentum, states with $\ell > 15$ could not be treated with requisite accuracy. Work is underway to find an analytic asymptotic theory to improve the convergence of these difficult cases.

Hummer and L. Smith (Univ. of Wollengong, Australia) have used the He II results, as well as preliminary results for non-hydrogenic carbon ions computed earlier by Hummer and Storey, to determine the C/He ratio of 17 Wolf Rayet stars from spectra obtained by Smith for this purpose.

Modeling of Supernovae Atmospheres - D. G. Hummer

The accurate determination of distances to very remote galaxies is among the most important astronomical measurement problems, and is one of the primary goals of the Space Telescope. A solution to this problem would yield the Hubble constant and perhaps even the value of the deceleration parameter, both of crucial importance to modern cosmology. It seems logical to use the most luminous astronomical objects that are likely to be sufficiently well understood to achieve this goal. Supernovae appear to be prime candidates for this purpose, as they are very bright and are at present fairly well understood. One method that is free of the empirical calibrations that have plagued this area is to determine the (large) rate of expansion and the intrinsic flux from an analysis of line profiles. The angular diameter can then be obtained from the ratio of the intrinsic to observed flux. By using data from two or more observations well separated in time, the distance can be found from the ratio of the change in expansion velocity to the change in angular diameter. However, to extract this information from the observations it is necessary to have realistic models of supernova atmospheres. Hummer and Abbott, who have had many years of experience in solving radiative transfer problems in rapidly expanding spherical atmospheres, are well equipped to carry out this difficult task. A new student, C. Hackman, has recently started to work on this project.

Radiative Transfer in Multiple Shock Structures - D. G. Hummer

There is now considerable evidence that radiation-driven stellar winds contain a system of multiple shock fronts, with which stellar radiation must interact in driving the flow of gas. As radiation can be scattered upstream from a particular shock front to interact with an earlier one, a quantitative description of this common phenomenon can be quite complicated. Hummer, Abbott and a new student, Yueming Xu, are working on a solution of the combined radiation transfer and gas dynamical equations that describe the flow of gas and radiation in this situation, using a combination of analytical and Monte-Carlo methods. This theory will be applicable to a wide variety of objects, including Wolf Rayet stars and supernova atmospheres.

Measurements of Magnetic Fields in Cool Dwarf Stars - J. L. Linsky

Linsky and his Ph.D. thesis student, S. Saar, are pursuing a major program to measure surface magnetic fields on stars cooler than the sun. They have already succeeded in making magnetic field measurements on stars much cooler than was heretofore possible; they have also developed an analysis technique to take into account for the first time the saturation of optically thick absorption lines.

Magnetic fields broaden spectral lines by the Zeeman effect. Attempts to measure such fields in cool stars using standard Zeeman analysis techniques with circular polarization optics have been unsuccessful, presumably because highly turbulent and oppositely directed fields cancel the circular polarization signal. To get around this problem, astronomers in the last few years have followed a different approach in which they measure the magnetic field by the increased broadening of unpolarized profiles of absorption lines with large Landé g factors (large Zeeman splitting) compared to lines with small Landé g factors.

Linsky and Saar have extended this work in two important ways. First they have developed a radiative transfer computer code that simulates the formation of spectral lines in a stellar atmosphere, including Zeeman broadening and saturation due to large opacity at line center. They have then used this code to derive stellar magnetic fields and surface coverage factors by comparing high quality observed line profiles with their computed profiles. Second they have acquired a large number of high spectral resolution and high signal-to-noise profiles from different observatories. For example, they obtained spectra of the cool flare star EQ Virginis using the Multimirror Telescope and of AD Leo using the Fourier Transfer Spectrometer (FTS) on the Kitt Peak 4 m telescope. They measured fields of 2500 ± 300 Gauss covering 80 ± 15% of the surface of EQ Virginis and 3800 ± 250 Gauss covering 73 ± 6% of the surface of AD Leo. These are the first field measurements for any dwarf flare stars. Linsky and Saar are presently analyzing additional observations from Kitt Peak and the Multimirror Telescope, which indicate fields on more than twenty additional stars.

These measurements of magnetic fields in cool flare stars confirm the hypothesis that magnetic fields are at the heart of solar-like phenomena by showing that stars with the most energetic phenomena, for example flares and enormous starspots, also have the strongest measured field strengths and filling factors. Two additional conclusions may be drawn from this measurement and the field parameters in somewhat warmer stars. The first is that the photospheric field strengths appear to increase towards the cooler dwarf stars such that the magnetic pressure ($B^2/8\pi$) in the photosphere equals the local gas pressure (see Figure 2). This implies that the field strength is determined by hydrodynamic processes in the photosphere and not by dynamo field creation processes in the stellar interior. The second conclusion is that stars with very energetic or widespread magnetic-related phenomena have fields that nearly cover the whole star. This large magnetic flux, the product of the field strength and fractional surface coverage, must indicate a large rate of field production in the stellar interior. Thus, high resolution spectroscopy can provide valuable information on the surface and interiors of stars even when they are viewed as point sources.

Planning for Future Space Observatories to Obtain Ultraviolet and X-Ray Astrophysical Data - J. L. Linsky

Linsky is participating in the detailed planning of a number of astronomical missions. The most immediate mission is the Hubble Space Telescope to be launched in 1988/89. Linsky has been a co-investigator on the High Resolution Spectrograph (HRS) since 1978 and has participated in the major decisions that have led to the design and construction of this instrument. As a part of the commissioning and calibration

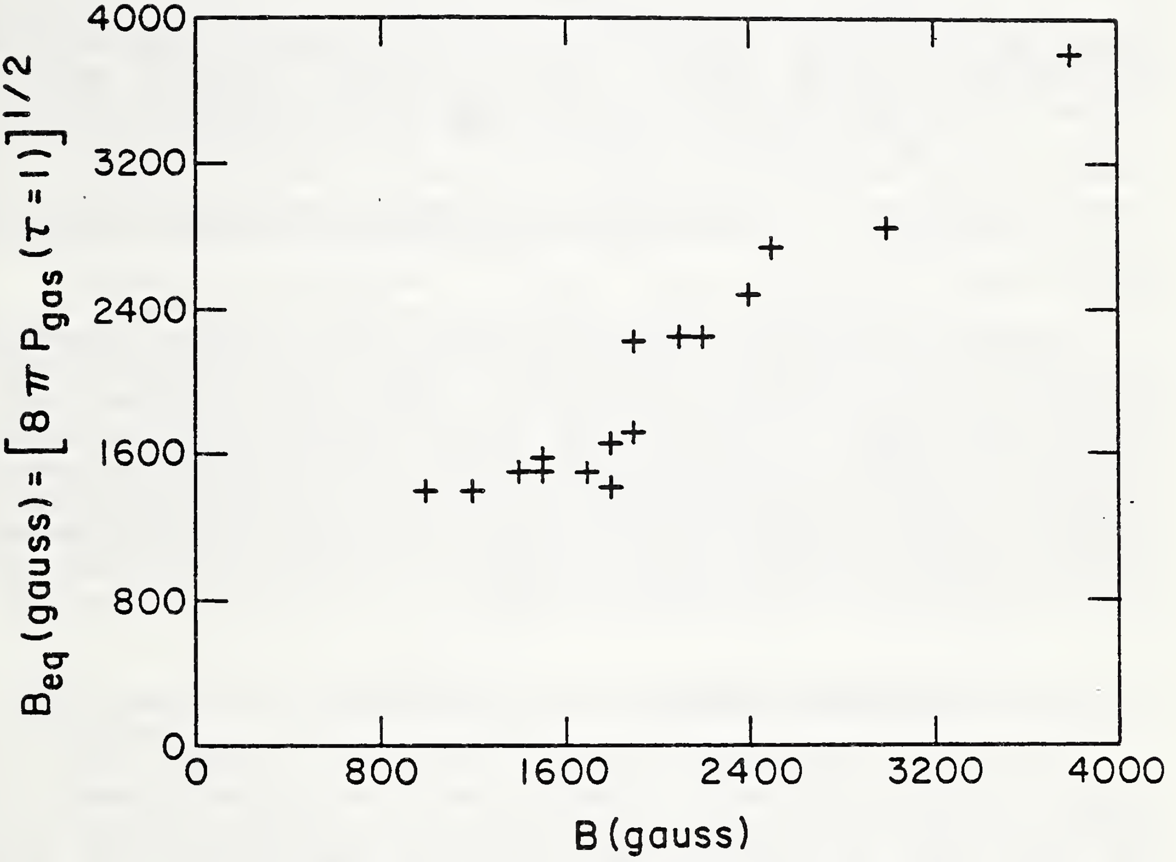


Figure 2. Correlation of the inferred equipartition magnetic fields (B_{eq}) with magnetic fields measured for 16 stars by Saar and Linsky. The equipartition magnetic field is that for a plasma in which the magnetic pressure equals the gas pressure in the stellar photosphere. Plasma physicists refer to this as a $\beta = 1$ plasma.

of the instrument after launch, the co-investigators will be making the first observations of stars with this instrument. The HRS will obtain spectra with resolution up to 10^5 covering the spectral region 110-320 nm. Linsky is also a co-investigator on the Space Telescope Imaging Spectrograph (STIS), which will replace the HRS five years after launch. This instrument, now being designed, will have high spectral resolution and high spatial imaging capability over the extended spectral range 110 - 1100 nm. Linsky will participate in the design of this instrument.

In 1985 Linsky was appointed an interdisciplinary scientist and member of the Science Working Group for the proposed Advanced X-Ray Astrophysical Facility (AXAF). This 1.2-m grazing incidence telescope is being planned to obtain high resolution X-ray spectra in the mid-1990's. During the next ten years or so, he will participate in the scientific and technical decisions to be made by the AXAF project. His specific interests are high-throughput spectroscopic observations of stars to measure stellar coronal temperatures, densities, and flow velocities.

During the last year Linsky collaborated with colleagues at several universities and the NASA Goddard Space Flight Center to write a proposal to NASA to study a far ultraviolet spectroscopic explorer satellite called LYMAN. This proposed satellite will contain a grazing incidence telescope and spectrograph to cover the 10 - 200 nm spectral range at both low and high spectral resolution. This is a particularly important spectral range both instrumentally and scientifically because the 10 - 120 nm spectral region is unexplored except for the Sun, and the spectrograph is a challenging design.

<u>Microwave Measurements of Stars</u> - J. L. Linsky

Linsky and postdoctoral research associate, S. Drake, have completed a survey of microwave emission from 39 of the closest stars that are more luminous and cooler than the sun. This survey at 5 and 15 GHz was made using the National Radio Astronomy Observatory's Very Large Array (VLA). The purpose of the survey was to measure mass loss rates for a class of stars (giants and supergiants of spectral types G, K, and early M) for which there was little data heretofore. Microwave emission from these stars is thermal bremsstrahlung from the ionized component of the circumstellar gas that is leaving the star, a phenomena called "mass loss," which is of great interest in astrophysics. In their survey they detected six stars, five of which are wind sources, and one is a hot coronal source (Capella). For these five sources, the microwave spectral indices are consistent with optically thick emission from a stellar wind. The inferred mass loss rates for the ionized components of these winds indicate that the gas is partially ionized (one to five percent) and that the mass loss rates can be used to constrain different theories proposed to explain the acceleration of stellar winds. Drake and Linsky are now writing up their survey of microwave emission from close binary stars. These are all synchrotron sources and show an interesting dependence of microwave luminosity on period and thus on proximity and rotational velocity. They have also completed a microwave survey of binary systems containing white dwarf companions and with very strongly enhanced heavy metal abundances.

Linsky and another postdoctoral research associate, J. Bookbinder, have begun a large survey of microwave emission from the coronae of low mass flaring stars called M dwarfs. They have been granted 250 hours of observing time on the VLA to observe all known M dwarfs within five parsecs (16 light years) at 1.4, 5, and 14 GHz. The goals of this ambitious project are to understand the microwave emission mechanisms and coronal heating processes by studying an unbiased volume-limited sample of stars with differing masses, ages, and rotation rates.

Models for the Outer Atmosphere Layers of Stars - J. L. Linsky

Linsky and colleagues, C. Jordan (Oxford University) and A. Brown (JILA postdoctoral research associate), have completed work on a set of detailed models for the outer atmosphere of solar type stars. These models describe the amount of emitting material at each temperature level in the stellar atmosphere from 10^4 K to 10^7 K in layers called the chromosphere, transition region, and corona in analogy with similar layers in the Sun. These models were constructed to match ultraviolet emission line fluxes observed by the International Ultraviolet Explorer satellite and X-ray fluxes observed by the *Einstein* X-ray Observatory. The analysis procedure incorporates the most recent collisional excitation and radiative decay rates.

Doppler Imaging of Active Regions on the Surfaces of Stars - J. L. Linsky

Linsky and his Ph.D. thesis student, J. Neff, have begun a study of the surface structure of stars using a technique called Doppler imaging. This technique involves the analysis of high spectral resolution, high signal-to-noise (by astronomical standards) profiles of emission lines from rapidly rotating stars obtained at a large number of aspect angles (phases). As a star rotates, bright regions (called plages) on its surface first appear at one limb with a large blue shift, then move across the visible surface with increasing Doppler shift and then disappear over the receding limb with a red shift corresponding to the rotational velocity of the star. This new technique can be used to infer the existence of plages, their spatial location, size, and brightness contrast. The knowledge of surface inhomogeneity in the chromospheres of stars is essential for modelling their atmospheres. An example of the Doppler imaging technique is shown in Figure 3.

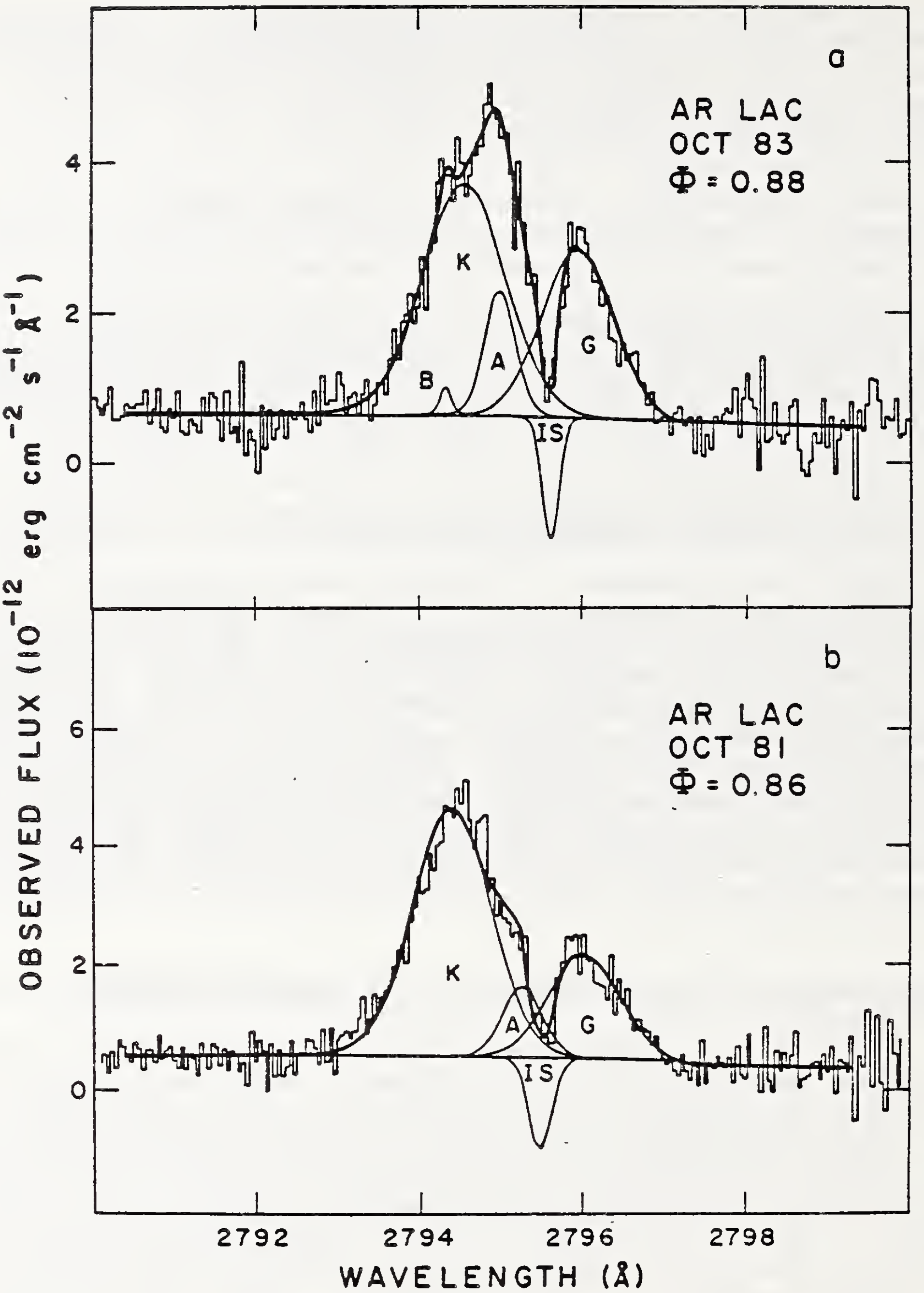


Figure 3. An example of Doppler imaging of the Mg II resonance line of the binary system AR Lacertae observed with the International Ultraviolet Explorer spacecraft. Profiles of these lines are fit by four or five least squares gaussians in such a way that the gaussian components are consistent with each other for observations obtained at a large number of aspect angles. The components refer to the cooler star (K) and hotter star (G) of the binary system, interstellar Mg II absorption (IS), and two plages (A and B) located at different positions on the cooler star. The two observations obtained at nearly the same aspect angle (phases 0.88 and 0.86) but two years apart in time show that the plages change in brightness and position with time.

Ultraviolet Spectral Diagnostics of Solar Flares - K. B. Gebbie

Geophysical responses to solar activity are dominated by enhanced electromagnetic and particle fluxes associated with solar flares. This highly energetic radiation can cause irregular, impulsive ionospheric disturbances that affect the intensity, frequency and phase of radio signals. Thus an ability to understand and predict flare events is crucial for maintaining and improving our communication systems.

Solar flares are typically very energetic events, the total energy emitted being of order 10^{32} ergs in about 15 minutes, half the energy in the form of electromagnetic radiation and half in accelerated particles. Yet the mechanisms by which this energy is stored and released are still largely unknown. Various theories attempting to explain these processes have been put forward, but the tests required to discriminate between them depend critically on measurements of temperature and density throughout the flare plasma, and reliable techniques for determining these parameters do not presently exist.

The structure and evolution of flares in the solar transition region ($10^4 \le T_e \le 10^5$) is much less well understood than in either the lower chromosphere or in the corona. It is in this region that the very intense EUV resonance lines of neutral and ionized helium have a crucial role not only in determining the physical conditions during many phases of the flare, but also as a diagnostic tool for studying these conditions.

Gebbie, in collaboration with J. G. Porter (NASA/Marshall Space Flight Center), and L. J. November (National Solar Observatory), has calculated helium resonance line intensities for a set of six flare models corresponding to different rates of heating and varying fluxes of soft x-rays. They have examined the differing ionization and excitation equilibria produced by these models, the processes that dominate the various cases, and the predicted helium line spectra. The line intensities and their ratios are compared with values derived from Skylab NRL spectroheliograms for a class M flare to determine (1) which of the models most nearly represents the density versus temperature structure and soft x-ray flux in the flaring solar transition region, and (2) the temperature and dominant mechanism of formation of the helium line spectrum during the flare. They find that throughout the range of conditions in the flare kernels the He II $L\alpha$ line is formed by collisional excitation from the ground state . The $L\alpha$ flux thus represents a local energy loss term. The main contribution to the line formation comes at temperatures from 6×10^4 K to 2×10^5 K. In the brightest and most heated of these flares, there is substantial collisional contribution to the formation of the higher He II Lyman lines up through at least $L\delta$. In bright regions of slightly less enhanced heating, the upper levels of the higher lines are populated mainly by photoionization to He III and subsequent recombination at temperatures near 2.5×10^4 K.

Rapid Ultraviolet Brightenings in Active Regions - K. B. Gebbie

J. Toomre and Gebbie, in collaboration with J. Porter (NASA/ Marshall Space Flight Center) are pursuing their discovery of rapid changes in the ultraviolet emission from bright sites in active regions, as a Guest Investigator Program on the repaired Solar Maximum Mission (SMM) satellite. Their analysis of C IV and Si IV line emission observed with high spatial and temporal resolution suggested that heating events of modest amplitude occur almost continually at many sites in active regions. Such heating events suggest that magnetic field reconnection in an active region is proceeding almost stochastically, with modest events occurring far more frequently than those with large amplitudes. This may be evidence in the transition region for the "magnetic burning" or "topological dissipation" advocated by Parker as a means of heating the corona.

Extensive sets of observations have now been obtained of five additional active regions. Analysis of this new data shows that the level of microactivity can vary considerably from one active region to another, and can vary with time in any given active region. These minor brightenings are far more prevalent in regions that are producing flares and subflares. Furthermore, there is both an increase in frequency of the brightenings and a pronounced shift to larger amplitudes during an interval of a few hours immediately before *and* after a flare or subflare.

ATOMIC AND MOLECULAR PHYSICS

Electron-Molecule Interactions - D. W. Norcross

The main thrust of this program is large scale computational studies of the scattering of electrons and positrons by molecules. The interaction can take several forms and can have a variety of products (e.g., rotational and vibrational excitation of the molecule, capture of the electron to form a molecular negative ion, and dissociation of the molecule into other atomic and molecular fragments). The effort is primarily developmental (i.e., inventing and extending numerical techniques for more rigorously representing the electron-molecule interaction, and for treating ever more complicated molecules and processes), but opportunities to produce useful data are not overlooked. Results will find application in studies of many practical and fundamental processes (e.g., laser modeling, physics of the interstellar medium) and in studies of chemical reaction dynamics (e.g., the flow of energy from electron kinetic energy to molecular dissociation via excitation of molecular nuclear motion).

Recent production work includes detailed calculations of cross sections for vibrationally elastic scattering of electrons by HF, CO and (linear) HCN; for ro-vibrational excitation of HF by electrons, and of CO by positrons; and calculations of the attachment energies of the three lowest negative ion states of HCl^- as a function of internuclear distance. HF and HCl are members of the larger group of hydrogen halides, constituents of several laser systems, and popular subjects of studies in chemical reaction dynamics. They are also among the simplest examples of highly polar molecules, interesting for the unique properties conferred, relative to nonpolar systems, by the long-range dipole potential. HCN is particularly fascinating for several reasons: It is a prototypical triatomic polar molecule with a simple, linear ground electronic state; it shares characteristics in electron scattering with nonpolar N_2 (a prominent Pi resonance) and polar HCl (a diffuse Sigma resonance); it exists in diffuse interstellar clouds and in CN laser systems; and it is a strong candidate for a critical constituent of a gaseous high-power electrical switch. CO is, of course, a very common molecule, both weakly polar and yet structurally very similar to nonpolar N_2.

Work continues to extend the scattering code to carry out full vibrational close-coupling (we have used the adiabatic-nuclei approximation to date, which fails near thresholds for vibrational excitation) with an exact treatment of exchange. It has been successfully tested with extensive vibrational coupling and a local model of exchange, and with exact exchange and limited coupling. An improved package for the calculation of asymptotic solutions of scattering equations is nearing completion, which will be instrumental in treating vibrational excitation with closed channels. This will also permit the first practical and realistic calculations for the binding energies of weakly bound and diffuse molecular negative ion states (the general rule), which cannot be handled using conventional molecular structure approaches.

The immediate target of these developments will be calculations of vibrational excitation of H_2, an extremely important and often studied benchmark molecule for which the best current theoretical and experimental results are in serious disagreement. Vibrational excitation of HF and HCl will be next attacked, in order to provide the first definitive near-threshold results, with work on vibrational excitation of CO to follow. The richest prize will be new results for the lowest bound states of HF^-, HCl^- and HCN^-, to be generated by the extended scattering code. This latter work will, it is hoped, be the first to uncover the full spectrum of the infinite number of bound states that can be trapped in the field of a polar molecule, and provide the first systematic connection between negative ion resonances and true bound states as a function of internuclear distance.

<u>Electron Impact Excitation of Atoms and Atomic Ions</u> - D. W. Norcross

Norcross' group is pursuing several fundamental and applied problems in the theory and computational physics of electron impact excitation. F. Parpia has completed a new attack on one of the most perplexing discrepancies in electron-ion collisions work - a difference of several times credible uncertainties between measurements (by Dunn's group) and calculations (by Norcross, coworkers, and others) for excitation of the resonance line in the simple "one-electron" lithium-like ion Be^+. Inclusion of effects due to polarization of, and correlation with, the atomic core made no significant change in either the cross section or the polarization of the resonance radiation, the latter being the much more easily and accurately measured quantity. J. Mitroy is taking the attack in another direction, that of a much more extensive basis set expansion (including the entire $n = 4$ complex of Be^+ states) of the system wave function than heretofore thought necessary. Preliminary calculations of energies for Be bound states and for the touchstone $2p^2\ ^1S$ resonance have led to much improved results, but the effect on the excitation cross section has yet to be determined.

This difficulty with Be^+, discovered only because of the high precision and absolute measurements by Dunn's group, adds to the growing body of evidence that electron-impact excitation of singly-charged ions may be much more difficult to calculate accurately than that for either neutral atoms or multiply-charged atomic ions. This hypothesis will be further explored in future work of a similar nature on the first ions of the Na and K isoelectronic sequences.

A. K. Pradhan has completed work on a comprehensive set of cross sections for excitation of five magnesium-like ions (S V, Ar VII, Ca IX, Cr XIII, and Ni XVII) for application to fusion diagnostics and plasma modeling. The results will be further analyzed to produce detailed rate coefficients for practical applications. Some progress has also been made on the next major project, excitation of boron-like ions, with preliminary atomic structure calculations. Pradhan continues, in collaboration with D. A. Harmin, to develop and apply an extension of quantum-defect theory of dielectronic recombination (DR) to include the influence of arbitrary electric fields. The first application of the new formalism and program for treating field effects in DR will be to the case of Mg^+ currently under study by Dunn's group.

F. de Paixao, a guest worker at the University of Colorado (CU) on a Fellowship from Brazil, largely completed an elaborate seven-state close-coupling calculation of electron scattering by the ground and excited states of sodium, looking towards analysis of a variety of experiments using mixtures of laser oriented atoms in excited states and spin polarized electron projectiles. Comparisons of the initial results with the measurements by Gallagher's group were very encouraging, confirming the essentially instantaneous onset of the 3p-3d cross section. Before his departure, the calculations were extended to produce results for more transitions (3s-4s, 3s-4p, 3p-4s), but work on obtaining angular distributions and detailed analysis around prominent resonance structures has been delayed while a new graduate student is brought up to speed.

Electron-Atom and Atom-Atom Collisions Processes - A. C. Gallagher

The electric breakdown and conduction of a gas and the radiation from the resultant plasma are of importance in lasers and area lighting, in switching and power generation, and in the diagnostics of man-made and astrophysical plasmas. The radiative and electrical properties of these hot gases depend on electron-atom and atom-atom collision processes, which couple the kinetic energies of the particles into radiative transitions and vice versa. During this year, Gallagher has collaborated with postdoctoral research associate, J. Kelly, and graduate students, X. Hahn, M. O'Callaghan, and G. Schinn, to study several kinds of collision processes that occur in these hot gases. As it is neither practical nor economical to investigate all specific species and processes of current or potential interest, these investigations are designed to obtain highly detailed diagnostics of a few specific processes, thereby guiding and testing basic understanding applicable to all similar processes. Specifically, Gallagher and his colleagues are carrying out the following experiments.

An experiment to measure fully differential electron excitation of Na atoms from the 3S to 3P state is now operational. This experiment uses a completely new approach, the detection of differential cross sections by Zeeman splitting and recoil Doppler shift, to allow measurements that are fully differential in M_ℓ, M_S, and θ. Excellent signal-to-noise and spectral resolution are now being achieved, and systematic effects are being evaluated to provide accurate threshold-region differential cross sections. These will test theories in the critical threshold region with orders of magnitude more detail than has previously been available.

Inelastic atom-atom collisions are also being measured differentially using the recoil Doppler shift. Here Na atoms are excited to the $3P_{3/2}$ state with a single velocity in the laser direction (v_z), and a small fraction of these atoms are inelastically transferred to the $3P_{1\backslash 2}$ state by collision with an inert gas atom. The v_z distribution of these post-collision atoms is then measured from the laser induced fluorescence (LIF) spectrum of the $3P_{1/2} \rightarrow 4D$ transition. The results of this gas-cell experiment involve a collisional velocity average that somewhat dilutes its diagnostic power, but new line-broadening information is also obtained.

In order to measure differential inelastic cross sections directly, crossed atomic beam apparatus has been constructed to remove the velocity averaging and allow direct measurement of differential (in angle) inelastic atom-atom collision cross sections and delineate precisely the theoretical understanding of the interactions and the energy transfer process. Initial experiments in the atomic beam apparatus will study collisions between equivalent and dissimilar alkali atoms in the excited state. This experiment is currently at the stage of producing reliable, high-density, and well-characterized atomic beams.

Another experiment measures total cross sections and stimulated radiation processes in Sr vapor. Here fluorescence transients following pulsed radiative excitation of Sr are being diagnosed to establish radiative and collisional pathways to many excited states, leading to a highly excited vapor and ionization.

Silane Neutral Chemistry - **A. C. Gallagher**

The quality and utility of hydrogenated amorphous silicon (a-Si:H) film photovoltaics has increased every year since their initial production in 1976. Efficiencies of 8% to 10% are now routinely achieved compared with crystal silicon cell efficiencies that are now about 18%. Because a-Si:H can be deposited inexpensively from a discharge as a thin layer on large areas, it is a leading contender for solar power generating systems, as well as large-area photoconductors. In spite of this impressive progress, major improvements in deposition rate, large-area reliability, stability, and efficiency are still believed to be feasible.

Since 1979, Gallagher and his group have been studying the discharge and surface processes that lead to the film production in order to assist this progress with improved understanding of the microscopic processes. During the last year, they have concentrated on understanding the surface chemistry in these discharges. Along with modeling of the surface reactions, based on observations of radicals in the discharges, they have studied the character of the growing a-Si:H surface layers by post-deposition sputtering. Here a film surface is grown in a silane discharge, then sputtered off with an Ar discharge, and the sputtered species are mass analyzed. This has shown, amongst other things, that the silicon-silicon bonding, with H_2 evolution, occurs in the top monolayer of the growing film.

Electron-Ion Collision Processes - **G. H. Dunn**

The consequential roles of electron-ion collisions in a variety of plasmas -- astrophysical, fusion, laser, etc. -- have been responsible in substantial measure for a keen interest in these kinds of collisions in the past two decades. Elastic scattering, excitation, ionization, and recombination are all conceptually simple processes that have been studied and considered in electron-atom collisions for more than seventy years. Yet these same processes in electron-ion collisions continue to challenge the creative efforts of many.

Technological breakthroughs leading to crossed beam experimental measurements on the various processes have led to impressive progress, and continued advances in technology are leading to progress in electron-ion collision studies. For example, the introduction of Electron Cylcotron Resonance (ERC) and Electron Beam Ion Sources (EBIS) has made it feasible to study a far broader range and variety of target ions; it is now possible to make colliding beam measurements with ions having charge $Q > 5$. Similarly, it is only in the past three years that the important process of dielectronic recombination has lent itself to cross section measurements.

For each of the collision processes there remain different needs and different problems. However, some common issues emerge from the work that has been done, pointing the way to some general features of work that should be done in the next few years. Indirect ionization mechanisms like excitation-autoionization, resonant-capture-double-autoionization, and resonant-capture-auto-double-ionization have been shown to become important for highly charged ions - especially for moderate and high Z ions. In some cases, these processes dominate over the direct ionization mechanism by an order of magnitude or more. Similarly, dielectronic resonances may enhance excitation cross sections by large factors. Dielectronic recombination itself has been shown to be a "tuneable" process that is changed and controlled by angular momentum mixing parameters in the environment.

Thus these processes - all of which involve autoionization phenomena - should be studied as a function of atomic number Z and ion charge Q. Since radiative lifetimes become comparable to autoionization lifetimes for $Q \approx 20$, the range $15 < Q < 25$ would seem to be a particularly attractive and important one to study. The lower limit of this range has just become technologically feasible; the remainder of the range will require continued creative effort. Another important challenge lies in the study of the basic electron-ion collision processes for heavy ions, where electron correlations and relativistic effects may be amplified.

JILA has been intimately involved in the progress in this area during the past two decades - both theoretically and in the laboratory. Further laboratory progress, however, now depends on development of effective new measurement methods. During the past year, Dunn has been involved in such development both directly in the laboratory and in the general community, evaluating possible new thrusts in terms of major new apparatus ($10M - $20M).

In the laboratory, construction is nearing completion on a merged electron-ion beam apparatus that will be used to detect scattered or ejected electrons from ion collisions with energy and angular dispersion and with the unprecedented collection efficiency necessary for colliding beams measurements. The method involves merged beams using trochoidal analyzers fore and aft of the merge region, position sensitive detectors, beam probes using a multi-channel plate - fluorescent screen - CCD combination, coincidence detection with other products, and ultra-high vacuum. The apparatus is built to be compatible with the ECR ion source at Oak Ridge National Laboratory (ORNL) and will be taken there for use with multi-charged ions after a "shakedown" period at JILA. It is not practical to build another source (about $750,000) at JILA. Much of the new apparatus has been tested - vacuum, magnet, probe parts - and final assembly is in progress.

This project has occupied C. Timmer, E. Wahlin, B. DePaola, K. Rinn and Dunn for much of the past year; the only new data actually obtained during this time was in collaboration with ORNL. Here our previous data indicated that the indirect ionization mechanism, dielectronic capture-auto-double ionization, was important in ionizing the lithium-like, O^{5+}. Work during the past year by Rinn and D. Gregory has definitely isolated the resonance involved, and gives the first unequivocal experimental evidence for this ionization mechanism.

Dunn has served on a committee during the past year to determine whether the U.S. should construct a major new facility for use in the study of multiply charged ions and their reactions. The facility would be an ion storage ring costing $10M - $20M and would be operated primarily for atomic physics including precision spectroscopy (R. Deslattes of NBS, e.g., would use this feature for QED tests), electron-ion collisions, ion-ion collisions, and ion-atom collisions, as well as other interesting physics such as ion condensation. The possibilities for electron-ion collision studies in the critical $15 < Q < 25$ range would obviously strongly impact the NBS programs in this area as well as the precision spectroscopy area.

Low Temperature Ion-Molecule Reactions - G. H. Dunn

Work continued by M. Schauer, S. Jefferts, and Dunn to implement the facility to study pure parahydrogen reactions with ions stored in a cooled hyperbolic Penning trap. Previous measurements used a 3:1 ortho/para-mix, and many of the low temperature processes will be sensitive to this. Thus they have been studying reactions at temperatures corresponding to about 0.8 meV, and the rotational spacing in H_2 is about 15 meV. Measurements during the past year using D_2, where the lowest rotational state is dominantly populated at low temperatures, showed a large difference from H_2. However, density of states and other issues cloud interpretation of this in terms of the energy differences only. Thus the apparatus change to use pure parahydrogen is proceeding. Negotiations were carried out with B. Moore at Berkeley to obtain pure orthohydrogen, and the apparatus changes may also make studies on the "species" possible.

Kinetics of Metastable H_2 - A. V. Phelps

Phelps and his colleagues are making measurements of collision processes responsible for the production and loss of molecular metastables in electrical discharges in H_2 and N_2. Such discharges are important in devices such as hydrogen thyratrons, negative ion sources, and high power gas lasers using N_2.

A. B. Wedding (CU) and Phelps have completed measurements of the collisional destruction of $H_2(c^3\Pi_u)$ metastables in representative rotational and vibrational levels. They find the probability of metastable destruction in collisions with ground state H_2 to be essentially unity for all levels of the metastable state. At present they are measuring the absolute metastable density in the discharges in order to determine the coefficients for the electron excitation of the metastables. The measurement uses a single mode dye laser to measure the absorption line profile in a striation free discharge for which the electric field strength is determined with floating probes. After completing these measurements, Wedding and Phelps will extend the techniques to the measurement of the rates of destruction of the higher metastable states of N_2, which are important in models of the stability of high power discharges, such as used in CO_2-N_2 lasers.

Collision Processes in Electrical Discharges at Very High E/n - A. V. Phelps

Phelps and colleagues are making experimental tests of models they have developed to describe the behavior of electrons, ions and fast atoms in gas discharges at very high electric field to gas density ratios, E/n.

B. M. Jelenković (CU) and Phelps have completed the first phase of experimental measurements of the behavior of electrons at extremely high E/n such as is found in some high voltage switches and in the cathode fall region of electrical discharges and as predicted to occur during charged particle beam propagation. Measurements are made of the spatial distribution of light output as the electrons and ions are accelerated through the gas under the action of a spatially uniform electric field. Comparison of experiment with the predictions of models of electron motion for the highest E/n and low gas densities shows the observed light output is much greater than predicted and has a different spatial dependence. Figure 4. shows examples of the measured spatial distribution of the absolute excitation coefficient for the 811 nm line emission from Ar. At the lowest E/n, the light output increases exponentially toward the anode as expected in the conventional electron avalanche. At the highest E/n, the emission is much larger and increases toward the cathode. It is proposed that this excitation is largely due to collisions of fast Ar (≈100 eV) atoms with ground state Ar. The fast atoms are produced in charge exchange collisions of Ar^+ with Ar.

D. A. Scott (CU on CSIRO fellowship) and Phelps have measured the time dependence of the light emission at gas densities below those required for steady-state discharges by using a pulsed laser illuminated photocathode to provide the initiating electrons. They find that at very high E/n most of the 811 nm emission occurs in the form of a slowly varying, wave-like transient consistent with excitation from ions and/or fast atoms rather than simultaneously throughout the gas as expected for

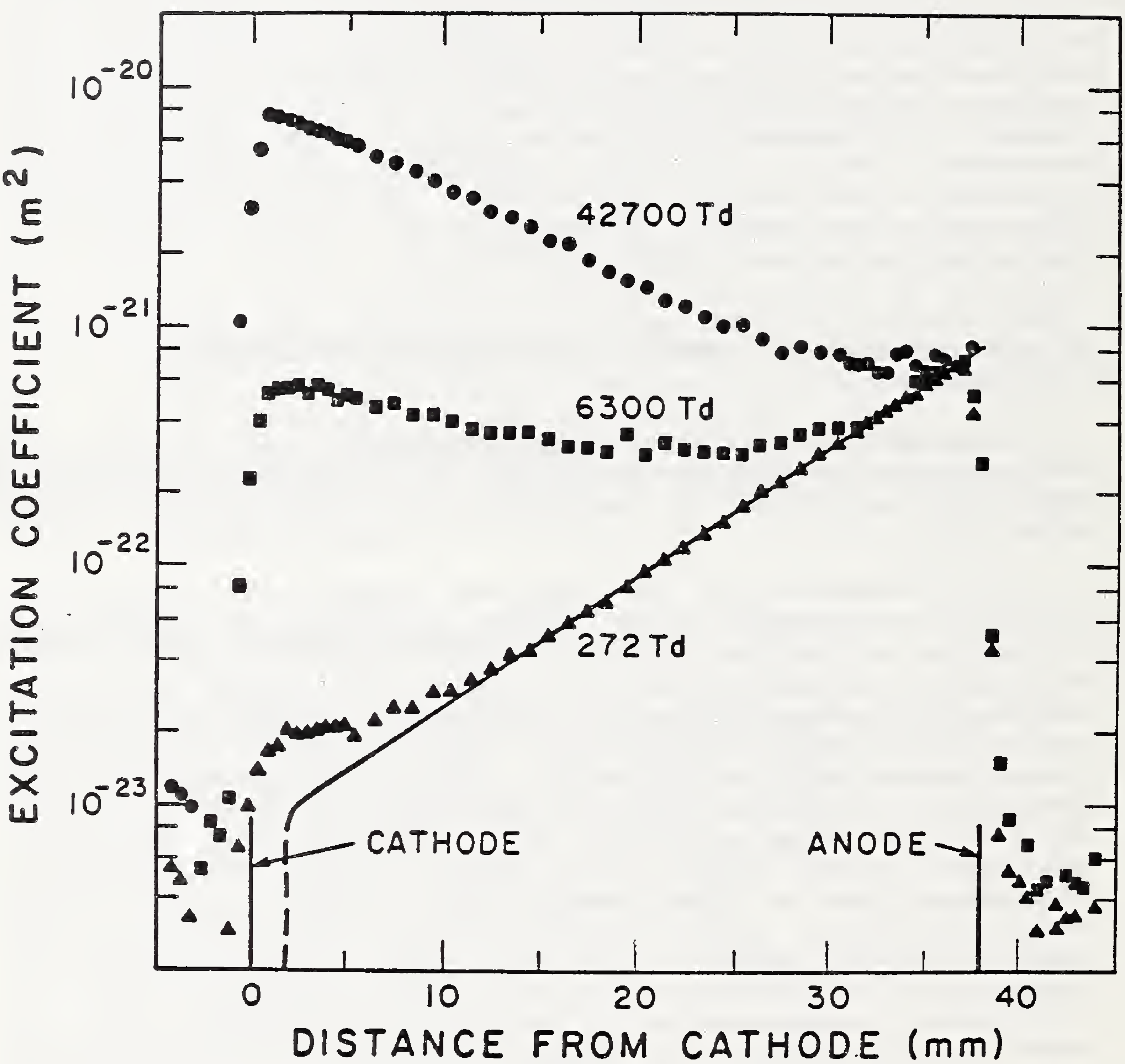


Figure 4. Spatial variation of excitation of 811 nm emission form Ar at moderate to very high electric field to gas density ratios E/n. Here 1 Td = 10^{-21} Vm^2. The dominant excitation mechanism changes from electron excitation at the lowest E/n to excitation by fast atoms and ions at the highest E/n.

electron excitation. Further work will be necessary to separate the effects of fast ion and fast atom excitation and to extend the technique to other gases.

In collaboration with L. C. Pitchford of GTE Laboratories Inc., Phelps has continued calculations of electron transport and reaction coefficients in gases at very high electric fields. Principal concern has been with the modeling of electron motion in the very high E/n experiment described above. Some effort is also being devoted to the problem of the proper calculation of large attachment coefficients in gases, such as the SF_6-N_2 mixtures considered in the collaboration with Gaithersburg.

Collaboration with NBS/Gaithersburg - A. V. Phelps

The six-month exchange visit of Phelps to NBS/Gaithersburg was completed toward the end of October, 1985. During the visit he worked in the Applied Electrical Measurements Group on the calculation of electron transport and reaction rate coefficients for mixtures of SF_6 with gases such an N_2, O_2, and Ne. This work was in support of an experimental program in the area of the chemical effects of corona discharges being carried out under R. J. Van Brunt for the Department of Energy. These calculations have been incorporated into the discharge chemistry models and have been reported at appropriate engineering meetings.

Modeling of Discharges of O_2-Iodine Lasers - A. V. Phelps

In return for funds from Air Force Wright Aeronautical Laboratories for the new pulsed laser being used in the H_2 metastable experiment, Phelps has initiated a project directed toward improving models of proposed electric discharge excited O_2-iodine lasers, with the hope of pointing the way to successful operation of this laser. A chemical kinetics code was obtained from R. L. Brown (Chemical Kinetics Division), adapted to problems of common interest by W. E. Anderson (Applied Electrical Measurements Group) while Phelps was at Gaithersburg, and installed at JILA. This code and Phelps' recently improved electron Boltzmann code are being used to model the limited experimental data (Russian) prior to making predictions of optimum operating conditions for the lasers. Initial calculations show serious disagreement with experiment.

JILA ATOMIC COLLISION CROSS SECTION DATA CENTER - Jean W. Gallagher

The JILA Data Center under the direction of J. Gallagher has carried on an active program to compile and evaluate data in the areas of electron and photon collisions with atoms, ions, and simple molecules. Several projects entailed collaboration with Data Center visitors who participated in the review and evaluation of data in their fields of expertise.

FY 1986 Accomplishments

- *Critical Survey of Data on the Spectroscopy and Kinetics of Ozone in the Upper Atmosphere.* J. I. Steinfeld, S. M. Adler-Golden, and J. W. Gallagher. JILA Data Center Report #31, October, 1986.

Spectroscopic data and reaction rate coefficients pertinent to ozone in the upper atmosphere are compiled and critically surveyed. These data are of use in modeling atmospheric infrared luminescence, measuring atmospheric ozone concentrations by remote sensing, and the design and interpretation of laboratory measurements.

- *Collision Cross Section (Atomic Collisions).* Jean W. Gallagher.

This article was prepared for the Academic Press Encyclopedia of Physical Science and Technology.

Work in Progress

During FY 1986 work continued on three major reviews:

- *Collisional Alignment and Orientation of Atomic Outer Shells. I. Direct Excitation by Electron and Ion Impact.* N. O. Andersen, J. W. Gallagher, and I. V. Hertel

Professors Hertel and Andersen each spent several weeks at the Data Center during the winter of 1986 working on this project. Collisional alignment and orientation of the target charge cloud are represented by four "natural parameters" in the fully coherent case exemplified by helium and by five such parameters in the incoherent cases with conservation of atomic reflection symmetry exemplified by atomic hydrogen and without conservation of atomic reflection symmetry exemplified by the rare gases. Comparative figures for excitation of helium (four different final states), atomic hydrogen, sodium, lithium, and rare gases were reviewed and refined. Additional data were added and a composite presentation of the material was planned. Figures for heavy-particle collisions with configurations similar to electron collisions were developed. A first draft of the manuscript for Physics Reports was completed.

- *Review of Electron Impact Optical Excitation Functions for Atoms and Atomic Ions.* D. W. O. Heddle.

Professor Heddle spent a month at the Data Center continuing work on this review. During this time effort concentrated on completing the evaluation of pertinent data. Additional work was done to determine recommended values for the excitation cross sections as functions of incident electron energy of the 4^1S and 4^1D levels of helium. These cross sections are fundamental in that they have been widely used in the normalization of cross sections for other targets. The values determined from our analysis are expected to be accurate to within 10%. Recommended values for the excitation function of the n ^1S (n = 3,5,6) and n ^1P (n = 2-6) states of helium were also determined.

Comparative figures for the highly structured electron impact excitation functions for mercury emission lines were prepared. Data for the threshold excitation of sodium were reviewed. Comparative figures for ionization and excitation of atoms and excitation of singly charged ions were prepared for the alkaline earths, zinc and cadmium. In some cases, optical excitation functions were polarization corrected and normalized using Bethe plots and known optical oscillator strengths.

On the basis of work done during this and previous summers, Professor Heddle will present an invited talk entitled "Optical Excitation Functions: What Can One Believe" at the Gaseous Electronics Conference in Madison, Wisconsin, in October, 1986. He will continue to work on the review at his home institution and plans to complete a first draft of the manuscript for *Reviews of Modern Physics* during the coming winter.

o *Absolute Cross Sections for Molecular Photoabsorption Above the Ionization Threshold, Partial Photoionization, and Ionic Photofragmentation Processes*. J. W. Gallagher, C. E. Brion, J. A. R. Samson, and P. W. Langhoff

The authors met at JILA in July, 1986, to review and finalize the manuscript and over 230 figures comparing photoabsorption cross sections, partial channel photoionization cross sections and asymmetry parameters, and dissociative photoionization cross sections for twenty one common small molecules. After adding recently published data and modifying details, the manuscript will be submitted to the Journal of Physical and Chemical Reference Data. A more extensive version, including tabular listings of the data, will be published as a JILA Data Center Report.

Other on-going projects include the following:

o *Collisions of Electrons with Atoms and Molecules, Atomic Data for Fusion, Vol. II*. A collaboration with Oak Ridge National Laboratory

Electron-impact excitation cross sections for atomic, molecular and ionic species present in fusion plasmas were collected in figures and tables and transmitted to ORNL. These data will be used as input to existing programs that generate reactions rates to be presented in the final report. Cross sections for other electron-impact processes will be compiled during FY 1987.

o *Near Threshold Electron-Molecule Collisions: Theory and Experiment.* Michael A. Morrison

Professor Morrison spent six weeks at the Data Center working on this review which is scheduled for publication in *Advances in Atomic and Molecular Physics*. The Data Center provided support, i.e., literature search, acquisition of pertinent articles, compilation of reference lists, capture of numerical data, and preparation of comparative figures.

o **The Atomic Collisions Data Base.**

In addition to the Data Center's bibliographic collection, approximately 1100 data records of cross sections for electron-impact excitation cross sections have been loaded into the Data Base. These are being used to prepare figures supporting the Center's review activities. Decisions by the computer facility used for the Data Base (NOAA Cyber 840) have required conversion from the IMF to the CDCS Data Base Management System. This conversion will require some revision of existing programs and structure, unloading and reloading the Data Base. Once this task is completed, on-line enquiry capability will be developed, and expansion of the numerical data base is planned.

o **New equipment**

Two IBM-PC/XT computers and a laser printer were acquired. Incorporation of these into existing procedures has improved the Data Center's efficiency; new uses are being explored and developed.

Work continues on incorporating the DEC Pro-380 into the data-capture system. Programs for entry of tabular material are complete.

FY 1987 Plans

In addition to continuing the projects described above, two new projects will be started. Work on a second part of the review on collisional alignment and orientation will begin. A collaboration with the Ion Kinetics Data Center in Gaithersburg on an evaluated compilation of ion-molecule reaction rates has been suggested and preliminary work, such as exploring how best to approach the project, the division of material, and the development and coordination of methods, will be done.

CHEMICAL PHYSICS

State-resolved Dynamics via Infrared Laser Absorption Spectroscopy - D. J. Nesbitt

Nesbitt is pursuing four areas of research into molecular structure and dynamics using ultra high sensitivity infrared absorption techniques: 1) Spectroscopy of weakly bound clusters in a supersonic molecular beam by direct absorption of a tunable difference frequency laser; 2) Gas-solid interactions by monitoring the nascent quantum state distributions of sublimation of simple molecular solids into a vacuum; 3) Intramolecular energy distribution in jet cooled hydrocarbon molecules; and 4) Laser flash photolysis studies of transient radicals via time resolved laser absorption.

C. Lovejoy and Nesbitt have already obtained high quality spectra of several van der Waals and hydrogen bonded molecules. Study of these prototypic, weakly bound species provides new information on the nature of bonding, collisional energy transfer in the gas phase, and the extremely important issue of the time scale for intramolecular vibrational relaxation. Their novel technique uses time resolved, direct infrared absorption of a high resolution tunable difference frequency laser in a slit supersonic expansion. The slit expansion device provides a two-order-of-magnitude enhancement in absorption path length, but still allows the extreme cooling, lack of spectral congestion and propensity for cluster formation characteristic of a supersonic jet. In addition, much like a stream of water through a slit aperture, hydrodynamic effects in the slit expansion geometry serve to collimate the velocities along the plane of the expansion. This results in dramatically reduced Doppler widths in an unskimmed molecular beam.

Using these techniques, Lovejoy and Nesbitt have obtained the first infrared spectra of ArHF in both the fundamental (ν_1) and combination band (ν_1+ν_2). They observed considerable shifts in the molecular geometry upon vibrational excitation. It is particulary interesting that although the excitation energy exceeds the van der Waals bond strength by forty fold, the narrow line widths of the spectra indicate vibrational predissociation lifetimes greater than 2.4 million vibrational periods. Two groups (Klemperer at Harvard and Saykally at Berkeley) are presently searching for the low frequency modes of ArHF based on the above spectra. Furthermore, they have succeeded in observing transitions to ν_1+2ν_3, i.e., a vibration with one quantum of HF stretch and two quanta in the weak van der Waals stretch. This represents the first characterization of all vibrational modes in a van der Waals complex. More recently, spectra of N_2HF and $HFCO_2$ complexes have been detected and analyzed, which highlight one fascinating feature that may prove endemic to larger polyatomic complexes: the low frequency vibrations can occur on time scales comparable to end-over-end rotations, and thus the two motions can be strongly dynamically coupled. Theoretical efforts to understand and analyze these couplings are underway.

M. Schuder and Nesbitt are investigating the quantum state dynamics of sublimation phenomena. Their approach relies on ultra sensitive detection of molecules that have freshly sublimated into a vacuum, before collisions can scramble the nascent quantum states. The sublimation process can be stimulated by gentle heating of the surface by a pulsed laser. Such information provides insight into the nature of solid gas interaction at the interface, as well as determining by detailed balancing the sticking coefficients for collisional deposition as a function of quantum state.

A. McIlroy and Nesbitt are exploiting the novel properties of slit jet expansion to study the dynamics of vibrationally excited, but ultra cold, hydrocarbons. A given vibration in a molecule, if excited, can eventually relax into a linear combination of many other vibrational modes via intramolecular relaxation pathways. Spectroscopically, the fingerprint of this intramolecular relaxation is line broadening or excess fine structure in the spectrum, which is completely obscured at room temperature. Studies in the cooled jet environment, however, elegantly avoid this difficulty and permit a detailed spectroscopic investigation of intramolecular dynamics in a collision-free regime.

A. Schiffman and Nesbitt are in the process of building a new experiment to study transient radicals by time and frequency resolved absorption spectra. A pulsed excimer laser will be used to cleave photolytically appropriate molecular precursors in a fast gas flow to generate highly reactive radical species. By use of a tunable IR laser probe collinear with the photolysis beam, weak transient absorbance signals from the radicals can be detected, signal averaged and analyzed for the desired kinetics. First efforts will be directed towards OH in order to characterize the infrared integrated absorption strengths of this atmospherically important radical.

<u>Energy Transfer</u> - S. R. Leone

The study of energy transfer processes is important for making high powered lasers more efficient, for accurately describing the collisional excitation processes and emission processes in the upper atmosphere and interstellar media, and for interpreting a wide variety of chemical reaction dynamics problems such as occur in combustion. In addition, energy transfer processes are one area for which accurate theoretical interpretation of the results is possible.

W. Bussert and Leone are studying electronic energy transfer processes in atomic calcium vapor as a function of the orbital "alignment" of the calcium excited state in the collision. Using linearly polarized laser light for the excitation and an atomic beam apparatus to define the relative velocity direction, they can align the p-orbital of the excited calcium either parallel or perpendicular to the collision direction. The rates of electronic energy transfer processes are then studied as a function of this alignment. In earlier work, dramatic dependences on the orbital alignment were observed with a variety of rare gas collision partners for the transfer from the Ca 5 $^1P_1$ state to the Ca 5 ^3P_J state. For He and Ne the perpendicular configuration is more efficient than the parallel alignment by 50% and 70% respectively, whereas for Xe the parallel alignment is more efficient by 25%. No preferential alignment effect occurs for Kr. The results are interpreted with reasonable success in terms of curve crossing models.

Recent incorporation of a pulsed source of the collision partner allows the process to be studied in reverse. The new apparatus has already revealed even larger alignment effects because of successful removal of background collisions. For example, for He, the effect is 80% versus 50% in the old apparatus. Work in the future will investigate the effect of alignment on an elementary chemical reaction, such as $Ca^* + H_2$ with specific probing of the CaH product alignment. R. Schwenz (NSF Summer Faculty Fellow) is exploring new processes in Sr atoms for implementing similar alignment techniques and has completed a major study of near resonant transfer from the Sr(6p) state.

D. J. Donaldson and Leone have developed a successful method to study the rates of vibrational deactivation of vibrationally excited methyl radicals. A molecule such as acetone is photolyzed with the 193 nm output of a rare gas halide excimer laser to produce methyl radicals in selected vibrational states. The deactivation processes are followed by time-resolved infrared emission. With this method some of the first rates for state-selected vibrational deactivation of the free radical have been obtained with a variety of collision partners. The amount of data on free radical deactivation is extremely limited, and thus the value in this new method of measurement. The observed rates are very similar to measured rates for similar size "closed-shell" molecules, indicating that intramolecular vibrational relaxation may also be a dominant effect for relaxation of the radicals. These rates are important in basic combustion processes.

In separate experiments L. Cousins and Leone are studying the vibrational excitation and reaction processes of energetic H and D atoms, also produced by photolysis techniques. Preliminary results have been obtained on the vibrational excitation of HF and DF by collisions of 2 eV H atoms with these molecules. A new apparatus is being developed to carry out these fast atom experiments under crossed beam conditions, so that single collision results are achieved. In addition, new sources of fast atoms will be developed, such as from laser ablation or desorption from surface films.

H. Meyer, R. Dressler, V. Bierbaum and Leone have succeeded in making the first measurements of the alignment produced in a molecular ion by collisions when the ion is subjected to an external field. A pulsed, linearly polarized dye laser is used to probe the plane of rotation of N_2^+ ions drifted in helium at several field strengths. The ions are preferentially aligned such that their rotation plane is 5% more probable parallel to the field direction at only a few volts per cm in 0.5 Torr of He; this can be explained on the basis of the anisotropy in the repulsive part of the potential interaction. The effect might have been larger were it not for the isotropic long range ion-polarizability interaction. New experiments will investigate molecules with much larger molecular structures, where the effects of alignment are expected to be greater.

Ion-Molecule Collision Dynamics - S. R. Leone

Ions are important in all kinds of media such as plasmas, lasers, and the upper atmosphere. This program is designed to advance the state-of-the-art in measurement capability in ion reaction dynamics and other ion collision processes. The results included here are in many cases the only determinations of product state distributions for elementary ion-molecule reactions at thermal energies.

G. H. Lin, J. Maier and Leone completed several new studies on the rotational state distributions of charge transfer reactions, $Ar^+ + N_2$ and $N^+ + CO$. In both cases it was found that the higher vibrational states are born with high rotational excitation, as opposed to the v=0 state, which has low rotational excitation. The results indicate a dual channel mechanism for these charge transfer processes. The lowest v=0 state is formed by a Franck-Condon long range collision, whereas the higher vibrational states result from a more intimate collision complex mechanism.

A. Langford, Bierbaum and Leone completed a detailed study of the contribution of the $N^+ + O_2$ ion reaction to the green and red emissions of the aurora. It was established that this ion reaction produces less than 0.1% of its O atoms in the green-emitting $O(^1S)$ state. However, the $N^+ + O_2$ reaction does form $O(^1D)$ in high yield, contributing about 15% to the red emission observed in the aurora.

D. Sonnenfroh and Leone have completed a first rotationally resolved study of a thermal energy Penning ionization process, namely $Ne^* + N_2$, which forms N_2^+ in v=0-3. The rotational state distributions in all v states are found to be nearly Franck Condon, which seems to be the overwhelmingly dominant mechanism for this Penning process.

Photofragmentation and Neutral Reaction Dynamics - S. R. Leone

Photofragmentation processes are of special interest to chemists because they represent the latter "half" of chemical reactions. The initial state preparation is more well-defined in photoexcitations, however, and thus these processes are more amenable to theoretical treatment. In addition, photofragmentation can be used to prepare a wide variety of reactive radicals and atoms for basic studies of reaction dynamics.

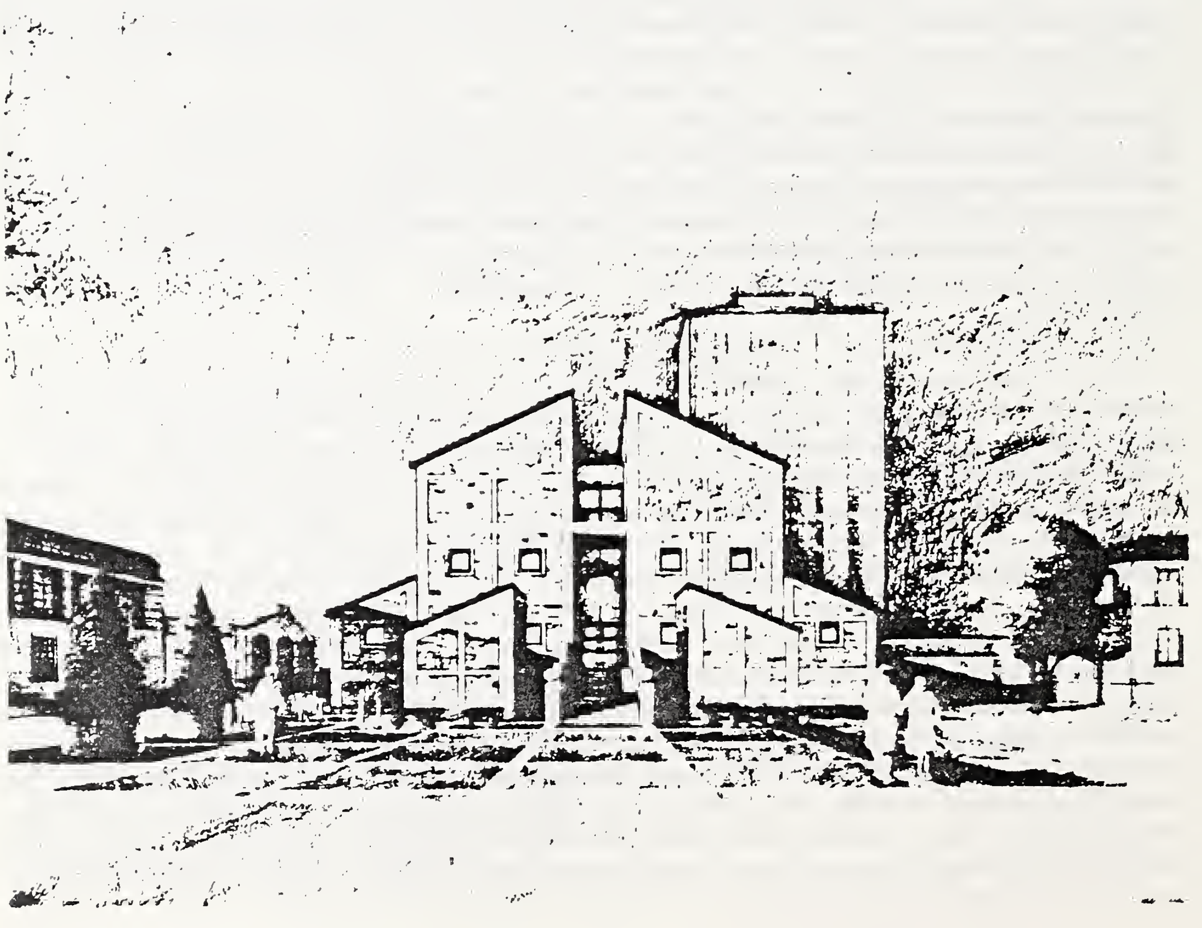
In last year's report, Leone presented a new method to obtain highly accurate quantum yields and branching fractions of electronically excited atoms. The method involves a time-resolved, laser gain-versus-absorption measurement, which samples the initial yield and compares it to a total atom yield at a slightly later time. The crucial point is the probing of the "coupled" pair of states with the same laser beam. The method achieved yields of Br and Br^* that were accurate to a few percent with relatively little effort. During this year, the same method has been applied with a sensitive diode laser probe system at 1315 nm in the near infrared to study the yields of spin-orbit states in I atoms. New work was carried out by W. Hess and Leone. A commercially available InGaAsP communications diode laser was tuned to the I atom transitions, stabilized to the transition of interest, and transient gain and absorption signals were observed upon photolysis of C_3F_7I and CH_3I. A detailed study was made for ICN as a function of wavelength. Accurate yields were obtained, clearing up many-year-old controversies concerning the absolute yields of I^* from these compounds. This general class of molecules is of interest for solar-pumped laser systems, and future work will investigate novel compounds synthesized by C. Shiner of the CU Chemistry Department for use in these lasers. In addition, the tuning of these diode lasers for use in spectroscopy will be explored by insertion of antireflection coated diodes into an external resonator. The impact of the ready availability of these diode laser probes for important laser species such as I^* for laser diagnostics is apparent.

J. Smedley and Leone are investigating a long-standing problem dubbed "collisional release". In this process, a molecule of Br_2 is excited very near to its dissociation limit, and then collisions are allowed to dissociate the molecule upwards in energy. The researchers have obtained the first quantitative measurements of the rates of such processes. They use a high resolution pulsed dye laser along with single isotopes of bromine to excite a single state selectively up near the dissociation limit. A lengthy series of measurements is necessary to quantify the yield of the excited atoms, which is the indicator of the collisional release process. The researchers find that Br_2, Ar and Xe are all similarly efficient at dissociating the Br_2 when it is excited at energies from 1-5 kT below dissociation. The results can be explained by a model that calculates the total energy available in the collision. He atoms, however, are different, being much less efficient. This requires invoking the idea a "chaperone" effect in the dissociation.

J. Donaldson and Leone have set up a time-resolved Fourier Transform Infrared (FTIR) emission experiment to study photofragmentation of large polyatomic molecules. A high repetition rate excimer laser is used to pulse dissociate molecules that produce vibrationally and rotationally excited free radical species. The firing of the excimer laser is timed to the mirror sweep of the FTIR in such a way as to obtain a laser pulse ten microseconds before the sampling of the infrared detector. This time is short enough so that at low pressures in a jet, there are no collisions. Sophisticated background limited detectors are used to sample the weak emission. As a preliminary experiment, Donaldson and Leone have obtained the detailed vibrational distributions for the HCl product upon photolysis of vinyl chloride and trans-dichloroethylene in a flow tube. The first experiments have been highly successful and give excellent signal-to-noise. With the FTIR technique, it will be possible to quantify the extent of both vibrational and rotational excitation under high resolution in the fragmentation of many complex molecules.

Surface Scattering Dynamics - **S. R. Leone**

K. Carleton and Leone have started a new program to study the scattering and sticking properties of Ga atoms on metal surfaces from a basic point of view, but with an emphasis on semiconductor growth technology. A pulsed tunable dye laser is used to detect the Ga atom spin-orbit states as they scatter or desorb from a metal surface. Thus far, desorption of Ga atoms from Si(100) has been detected with high signal-to-noise, and the ultrahigh vacuum system with complete surface diagnostics has been tested and is working properly. The first experiments have obtained the desorption energy of Ga on Si to be 268 kJ/mole. This energy is important for the growth technology of GaAs on Silicon. Both spin-orbit states of Ga are found to be identically behaved, and the sticking coefficient at the growth temperature is unity. New experiments will focus on highly stepped silicon surfaces, which are important in the GaAs growth technology to minimize defects.



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*L. Rosenberg, "Modified perturbation theory for scattering in a laser field," Phys. Rev. A (submitted).

*L. Rosenberg, "Gauge-invariant approximations for scattering in a strong external field," Phys. Rev. A (submitted).

*A. Streater, J. Cooper and W. Sandle, "On time-dependent radiative transfer," J. Quant. Spectrosc. Radiat. Transfer (submitted).

*(C. P. O'Dea), C. L. Sarazin and (F. N. Owen), "Narrow-angle tail radio sources and the distribution of galaxy orbits in Abell clusters," Astrophys. J. (submitted).

*(R. E. White III) and C. L. Sarazin, "Star formation in X-ray cluster cooling flows," Astrophys. J. Suppl. (submitted).

*(R. E. White III) and C. L. Sarazin, "Numerical models of star formation in X-ray cluster cooling flows," Astrophys. J. Suppl. (submitted).

(I. Golub, G. Erez) and R. Shuker, "Cherenkov emission due to laser-induced moving polarization in sodium," Phys. Rev. Lett. (submitted).

*(Th. Sauter, W. Neuhauser, R. Blatt) and P. E. Toschek, "Observation of 'quantum jumps'," Phys. Rev. Lett. (submitted).

*(H. Schroder, K. Schultz) and P. E. Toschek, "On the line shapes of laser intra-cavity absorption," Opt. Commun. (submitted).

O. Vilhu and (D. Moss), "Magnetic braking in cool dwarfs," Astrophys. J. (submitted).

1985-1986 VISITING FELLOWS

Quantum Physics Division (525)

Visiting Fellow	Home Institution	Area of Work
James N.Bardsley	University of Pittsburgh Pittsburgh, PA	Atoms in strong oscillatory fields and non-equilibrium phenomena in ionized gases.
Michael J.Barlow	Department of Physics & Astronomy University College London London, United Kingdom	Properties of hot stars, physical properties of circum-stellar and inter-stellar dust.
Pierre Connes	Service d'Aéronomie du CNRS Verrières-le-Buisson France	High precision spectroscopic techniques and their applications to astronomy and to fundamental physics experiments.
Paul C. Engelking	Department of Chemistry University of Oregon Eugene, OR	Dipole interactions of molecules with electrons.
Francis Perkins, Jr.	Plasma Physics Laboratory Princeton University Princeton, NJ	Magneto-hydrodynamic theory and its applications to solar physics, magnetic fusion and astro-physics.
Weston J. Sandle	University of Otago Dunedin New Zealand	Optical bistability.
Craig L. Sarazin	Leander McCormick Obs. University of Virginia Charlottesville, VA	Cooling flows in clusters of galaxies.

1985-1986 VISITING FELLOWS

Quantum Physics Division (525)

Visiting Fellow	Home Institution	Area of Work
John P. Simons	Department of Chemistry University of Utah Salt Lake City, UT	Electronic structure of negative molecular ions; dynamical behavior of anions.
Sumner G. Starrfield	Department of Physics Arizona State University Tempe, AZ	Study of the nova outburst; evolution of both nova explosions and the hottest known pulsating variable stars
Peter E. Toschek	I. Institut für Experimentalphysik Universität Hamburg Hamburg, West Germany	Laser spectroscopy; cooling and study of trapped ions.
John Weiner	Department of Chemistry University of Maryland College Park, MD	Inelastic collision dynamics in simple systems.

1985-1986 RESEARCH FELLOWSHIP FOR TEACHERS

Jo Allan Beran	Texas A & I University Kingsville, TX	Environmental chemistry.

1985-1986 NBS/JILA EXCHANGE FELLOW

Daniel E. Kelleher	Atomic & Plasma Radiation Division Center for Radiation Res. National Bureau of Standards Gaithersburg, MD	Theoretical plasma spectroscopy problems.

1986-1987 VISITING FELLOWS

Quantum Physics Division (525)

Visiting Fellow	Home Institution	Area of Work
John Delos	Department of Physics College of William and Mary Williamsburg, VA	Theory of electron detachment and excited atoms in stong fields.
Klaus-Peter Dinse	Universität Dortmund Experimentelle Physik III Dortmund West Germany	High sensitivity detectors using lasers, optical/RF "Ramsey Fringes," and magnetic resonance.
Donald C. Griffin	Department of Physics Rollins College Winter Park, FL	Theoretical atomic structure and electron-ion collision theory.
Ivan Hubeny	Astronomical Institute Czechoslovak Academy of Sciences Ondřejov, Czechoslovakia	Stellar atmospheres, atomic processes, line scattering, numerical simulations.
John G. Kirk	Max Planck Institut für Astrophysik Garching, West Germany	Accreting neutron stars and the associated physics of strongly magnetized plasmas.
Dimitri Mihalas	Department of Astronomy University of Illinois Urbana, IL	The atmospheres of stars and the physical processes that occur in many astrophysical bodies.
Ron Naaman	Department of Isotope Research Weizmann Institute of Science Rehovat, Israel	Reaction dynamics in the presence of "solvent" molecules attached to one of the reactants.

1986-1987 VISITING FELLOWS

Quantum Physics Division (525)

Visiting Fellow	Home Institution	Area of Work
Norman Ramsey	Department of Physics Lyman Laboratory of Physics Harvard University Cambridge, MA	Precision measurements, atomic and molecular physics.
Hideyuki Saio	Department of Astronomy Faculty of Science University of Tokyo Tokyo, Japan	Stability and evolu-of stars.

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

D. Z. Anderson	William Bickel Department of Physics University of Arizona Tucson, AZ
M. C. Begelman	Moshe Elitzur University of Kentucky Lexington, KY
	Julian Krolik Johns Hopkins University Baltimore, MD
	R. V. Wagoner Stanford University Stanford, CA
P. L. Bender	Feridoun Rabet University of Tabriz, Iran
P. S. Conti	C. DeLoore Astronomical Institute Brussels, Belgium
	Huib Henrichs Astronomical Institute University of Amsterdam The Netherlands
	H.J.G.L.M. Lamers Space Research Laboratory Utrecht, The Netherlands
	Philip Massey KPNO/NOAO Tucson, AZ
	Nancy Morrison Department of Physics and Astronomy University of Toledo, OH

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

Conti (cont.)	Karl Van Der Hucht Utrecht, The Netherlands
	Nolan R. Walborn Space Telescope Institute Baltimore, MD
	D. Williams Edinburgh, Great Britain
J. Cooper	Stan Haan Department of Physics Calvin College Grand Rapids, MI
G. H. Dunn	D. S. Belic Belgrade University Belgrade, Yugoslavia
J. E. Faller	John Griffin National Geodetic Survey
	Jerry Gschwind Defense Mapping Agency Washington, D. C.
	Alan Joll Defense Mapping Agency Washington, D. C.
	J. Makinen Finnish Institute of Geodesy Helsinki, Finland
	T. Quinn Bureau International des Poids et Mesures Sèvres, France
	C. Speake Bureau International des Poids et Mesures Sèvres, France
A. Gallagher	Michael Harris Newcastle United Kingdom

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

Gallagher (cont.)	Edwin L. Lewis School of Physics The University Newcastle upon Tyne United Kingdom
	Goran Pichler Institute of Physics Zagreb, Yugoslavia
J. W. Gallagher Data Center	Steven M. Adler-Golden Spectral Sciences Inc. Burlington, MA
	Nils Anderson Physics Laboratory H. C. Ørsted Institute Copenhagen, Denmark
	Douglas O. Heddle Department of Physics Royal Holloway College University of London, U.K.
	Ingolf V. Hertel Institut für Molekülphysik Freie Universität Berlin Berlin, West Germany
	Michael Morrison Department of Physics & Astronomy University of Oklahoma Norman, OK
	Jeffrey I. Steinfeld Department of Chemistry Massachusetts Institute of Technology Cambridge, MA
J. Hall	Jean-Marie Chartier Bureau International des Poids et Mesures Sèvres, France

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

Hall (cont.)	R. Felder Bureau International des Poids et Mesures Sèvres, France
	H. Jeff Kimble Department of Physics University of Texas at Austin Austin, TX
	Christophe Salomon Ecole Normal et Superieure Paris, France
S. R. Leone	Pavel Rosmus Fachbereich Chemie der J. W. Goethe-Universitat Frankfurt am Main West Germany
	Richard Schwenz Department of Chemistry University of Northern Colorado Greeley, CO
J. L. Linsky	Suzanne Hawley Department of Astronomy University of Texas at Austin Austin, TX
	Osmi Vilhu Observatory and Astrophysics Laboratory University of Helsinki Helsinki, Finland
R. A. McCray	Moshe Elitzur Department of Physics & Astronomy University of Kentucky Lexington, KY
	Timothy Kallman High Energy Astrophysics NASA-Goddard Space Flight Center Greenbelt, MD

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

McCray (cont.)	Julian Krolik Department of Physics & Astronomy Johns Hopkins University Baltimore, MD
	Peter G. Sutherland Department of Physics McMaster University Hamilton, Ontario, Canada
	Hai Shou Yang Astrophysics Division Geophysics Department Peking University Beijing, PRC
D. W. Norcross	Michael Morrison Department of Physics University of Oklahoma Norman, OK
S. J. Smith	George Basbas, Editor Physical Review & Physical Review Letters Ridge, NY
	John Brandenburger Department of Physics Lawrence University Appleton, WI
	Dan Elliott School of Electrical Engineering Purdue University Lafayette, IN
	Murray Hamilton University of Strathclyde Glasgow Scotland
	Harold Metcalf Physics Department SUNY, Stony Brook, New York

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

J. Toomre	Kumar Chitre Tata Institute for Fundamental Research Bombay, India
	Douglas Gough Institute of Astronomy University of Cambrige Cambridge, England
	Edgar Knoblock Department of Physics University of California Berkeley, CA
	Michael Proctor Department Applied Mathematics & Theoretical Physics University of Cambridge Cambridge, England
	Nigel Weiss Department Applied Mathematical & Theoretical Physics University of Cambridge Cambridge, England
	Jean-Paul Zahn Observatory of Pic du Midi Toulouse, France
C. Wieman	Richard Watts SUNY, Stony Brook New York

CONFERENCES SPONSORED

Quantum Physics Division (525)

Division of Chemical Physics Symposia, at New York APS Meeting, March 1987. S. R. Leone, organizer, "Innovative Chemical Processes on Semiconductors and Surfaces."

Atomic Physics Program Contractors' Workshop for the Division of Chemical Sciences, Office of Basic Energy Sciences, DoE Boulder (JILA), April 14-15, 1986. Drs. S. J. Smith, D. Norcross, and A. Gallagher organizers.

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

Informal Seminars

A. V. Phelps (JILA) - Series of 6 Seminars on Gas Discharge Physics.

A. V. Phelps (JILA) - Excitation and Ionization in Discharges in Argon of Very High Eln and Low Pressures, (lunchtime seminar).

Cool Stars Seminars

Roberto Viotti (Istituto Astrofisica Spaziale, Frascati, Italy) - New Methods of of Analysis of Fe II Lines in Emission Line Stars and FE II Spectral Line Synthesis, December 18, 1985.

John Heise (Space Research Laboratory, Utrecht, Netherlands) - EXOSAT Observations of Hot White Dwarfs, January 15, 1986.

Helene Frisch (Observatoire de Nice, Nice, France) - Radiative Transfer and Frequency Redistribution, February 12, 1986.

Mark Giampapa (National Solar Observatory, Tucson, Arizona) - Current Research on the Coolest M Dwarf Stars, March 5, 1986.

Leon Golub (Smithsonian Astrophysical Observatory) - High Resolution X-Ray Imaging using Multilayer Normal Incidence Optics, March 27, 1986.

David Muchmore (Institute for Theoretical Astrophysics, Heidelberg, West Germany) - Dynamic Effects of CO Molecules in Solar Type Atmospheres, April 2, 1986.

Ilkka Tuominen (Helsinki University Observatory, Helsinki, Finland) - Solar Dynamics as a Guide to Stellar Activity Cycles, August 6, 1986.

Phillip Judge (Department of Theoretical Physics, Oxford University, Oxford, England) - UV Spectroscopy of Cool Giant Stars, August 27, 1986.

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

Special JILA Seminars

George Basbas (JILA Visitor) - How Physical Review Letters Works, October 1, 1985.

Jabez McClelland (NBS, Gaithersburg) - Spin-Polarized Superelastic Scattering From Na(3P), October 1, 1985.

Dan F. Walls (University of Waikato, New Zealand) - Squeezed States, October 25, 1985.

W. J. Sandle (University of Otago) - Steady-State Optical Switching, November 7, 1985.

Sze-Keung Kwong (Caltech) - Theory and Applications of Photorefractive Materials, November 20, 1985.

M. A. Gubin (P. N. Lebedev Phys. Lab., USSR) - Stabilization of HeNe Lasers, November 21, 1985.

Gerd Rempe (Sektion Physik der Univ. München, W. Germany) - Recent Progress on the "Single Atom Maser," November 22, 1985.

R. J. Ballagh (University of Otago, New Zealand) - Competitive Interaction of σ^+ and σ^- Modes in Non-Linear Optics, December 11, 1985.

Peter R. Wilson (University of Sydney) - Proposed Series of Workshops on the Solar Minimum, January 21, 1986.

V. B. Sheorey (Physical Research Laboratory, India) - Quantum Chaos? January 30, 1986.

Antonije Dulcič (University of Zagreb) - Modulation of the Continuum Levels in Strong Laser Fields, February 19, 1986.

Richard More (Lawrence Livermore National Laboratory) - Resonances and Pressure Ionization, April 4, 1986.

Gerd Leuchs (University München, West Germany) - Recent Advances in the Gravity Wave Detector at Garching, April 28, 1986.

Michael Allan (University of Fribourg, Switzerland) - Resonances in Electron-Molecule Collisions, April 28, 1986.

Special JILA Seminars (cont.)

Shri Kulkarni (California Institute of Technology) - Optical Identification of Binary Pulsars, April 28, 1986.

Alex Martin (University of Rochester) - Laser Spectroscopy of Radioactive Atoms Using Photon Correlation Techniques, May 12, 1986.

Marc Levenson (IBM Almaden Research Center) - Production of Squeezed States of Light Using Optical Fibers, May 30, 1986.

Udo Buck (Max Planck Institute für Stroemungsforschung) - Crossed Beam Studies of Cluster Molecules, August 7, 1986.

JILA Colloquia

Bob Byer (Stanford) - Progress in Diode Laser Pumped Solid State Lasers, October 8, 1985.

Alan Pine (NBS, Gaithersburg) - Tunable Laser Spectroscopy of Hydrogen-Bonded and van der Waals Complexes, October 22, 1985.

Jack Simons (University of Utah) - How the Anions Shake Rattle and Roll Until the Electrons Detach, November 5, 1985.

F. Fleming Crim (University of Wisconsin) - Studies of State-to-State Unimolecular Reactions, December 3, 1985.

Theodore Madey (NBS, Gaithersburg) - Recent Applications of Electron Stimulated Desorption From Surfaces, January 28, 1986.

John Fenn (Yale University) - Information From Deliberate Leaks: Studies of Free Jet Expansions, February 18, 1986.

David King (NBS, Gaithersburg) - Molecule-Surface Dynamics, March 4, 1986.

William Klemperer (Harvard University) - Structure and Vibration of Van der Waals Molecules, March 18, 1986.

Daniel Kelleher (NBS, Gaithersburg) - Line Shapes and Shifts: in Plasmas, in Electric Fields, in Photoionization, in the Foothills, April 8, 1986.

JILA Colloquia (cont.)

Robert G. Littlejohn (University of California, Berkeley) - Semiclassical Evolution of Wavepackets, April 17, 1986.

R. J. Celotta (NBS, Gaithersburg) - New Techniques in Microscopy: Scanning Tunnelling in Polarized Electron Microscopy, April 22, 1986.

J. Gallagher (National Optical Astronomy Observatories) and J. Beckers (NOAO) - Planning the National New Technology Telescope, May 5, 1986.

Norman Bardsley (JILA Visiting Fellow, University of Pittsburg) - The Stark Effect Revisited, May 6, 1986.

Lin Mollinauer (AT&T Bell Laboratories) - Solitons in Optical Fibers, the Soliton Laser, and the Future of Fiber Communications, September 9, 1986.

Peter Toschek (JILA Visiting Fellow, Universität Hamburg) - Absorption by the Number: Recent Spectroscopy of Trapped Ions, September 23, 1986.

Joint JILA/Astrophysics, Planetary and Astronomical Sciences Colloquia

Reinhardt Mundt (Max-Planck Institut für Astronomie) - Jets From Pre-Main Sequence Stars, December 2, 1985.

Craig Sarazin (JILA Visiting Fellow, Leander McCormick Obs., University of Virginia) - Cooling Flows in Galaxies and Clusters of Galaxies, December 9, 1985.

Bob Wagoner (Stanford) - Supernovae as Probes of the Universe, February 3, 1986.

James Imamura (University of Oregon) - Short Time Scale Variabilities in Accreting White Dwarfs, February 10, 1986.

Sumner Starrfield (JILA Visiting Fellow, Arizona State University) - Stellar Explosions From a Nova Point of View, February 11, 1986.

Carl Heiles (University of California, Berkeley) - Supernovae vs. Models of the Interstellar Medium, February 17, 1986.

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

Joint JILA/Astrophysics, Planetary and Astronomical Sciences Colloquia (cont.)

Sterl Phinney (Caltech) - Continuum Radiation From Active Galaxies, February 24, 1986.

Osmi Vilhu (JILA Member) - Contact Binary Stars, February 25, 1986.

Andrew Hamilton (Princeton University) - X-Rays From Young Supernova Remnants, February 26, 1986.

Ed Bertschinger (University of California, Berkeley) - The Role of Conductivity in Cooling Flows in Clusters of Galaxies, February 27, 1986.

William Fowler (Caltech) - Topics in Nuclear Astrophysics, March 3, 1986.

Shuji Deguchi (University of Illinois) - Polarization of Astrophysical Masers, March 5, 1986.

Chris McKee (University of California, Berkeley) Winds From Accretion Disks, March 10, 1986.

Francis W. Perkins (JILA Visiting Fellow, Princeton University) - The Theory of Tokamak Interiors, March 11, 1986.

David Abbott (JILA) - Theory of Radiation-Driven Mass Loss, March 12, 1986.

Larry Esposito (APAS/LASP) - Voyager Encounter With Uranus, March 13, 1986.

Julian H. Krolik (Johns Hopkins University) - Radiation Pressure-Driven Shocks in Winds From Hot Stars, March 18, 1986.

Mike Jura (University of California, Los Angeles) - Mass Loss From Red Giants: Causes and Consequences, April 7, 1986.

Shri Kulkarni (Caltech) - Geminga - An Old Radio Pulsar?, April 28, 1986.

Jeffrey L. Linsky (JILA) - The Proposed AXAF Mission: The Next Generation of X-Ray Instrumentation in Space, May 12, 1986.

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

Joint JILA/Astrophysics, Planetary and Astronomical Sciences Colloquia (cont.)

Ake Nordlund (Copenhagen University Observatory) - Simulations of Compressible Convection and Line Formation in Solar Granulation, September 15, 1986.

Michael Barlow (JILA Visiting Fellow, University College London) - The Properties of Planetary Nebulae and Their Central Stars in the Magellanic Clouds, September 16, 1986.

Nigel Weiss (Cambridge University) - Spatial Structure and Temporal Chaos in Nonlinear Convection, September 22, 1986.

Craig Wheeler (University of Texas, Austin) - Peculiar Type I Supernovae, September 29, 1986.

Chemical Physics Colloquia

David Kelly (Colorado State University) - Picosecond Studies of the Recombination and Relaxation Dynamics of Diatomic Molecules in Solution, September 27, 1985.

Paul Engelking (JILA Visiting Fellow, University of Oregon) - CH_3N in a Corona Excited Supersonic Expansion, October 4, 1985.

Thomas Miller (University of Oklahoma) - Flowing Afterglow Studies of Ion-Ion Recombination, October 11, 1985.

Glen T. Evans (Oregon State University) - Dynamics in Dense Fluids of Polyatomic Molecules, October 25, 1985.

Shaul Mukamel (University of Rochester) - Intramolecular Line Broadening-Spectroscopy Without Eigenstates, November 1, 1985.

Eldon Ferguson (NOAA) - Vibrational Relaxation of Molecular Ions, November 8, 1985.

David W. Pratt (University of Pittsburgh) - Triplet States in Supersonic Jets, November 22, 1985.

Peter Escherick (Sandia National Laboratory) - Stimulated Raman Spectroscopy for Ultrahigh Resolution Gas Phase Studies, December 6, 1986.

Chemical Physics Colloquia (cont.)

Pavel Rosmus (Frankfurt University, West Germany) - March 7, 1986.

Marsha I. Lester (University of Pennsylvania) - March 14, 1986.

W. R. Gentry (University of Minnesota) March 21, 1986.

Stephen V. ONeil (JILA) - Cl + H + e: Choose Two (Bound States of HCl^-), April 11, 1986.

Bruce Kay (Sandia National Laboratory) - Rotational Inelastic Gas-Surface Scattering: NH_3 From W(1,0,0) and Au(1,1,1), April 25, 1986.

J. T. Hougen (NBS) - Hydrogen Migration: Tunneling Effects in the Infrared Spectrum of Protonated Acetylene $C_2H_3^+$, May 2, 1986.

J. Lisy (University of Illinois) - Vibrational Predissociation Spectroscopy of Molecular Clusters, May 9, 1986.

T. Dyke (University of Oregon) - Molecular Beam Spectroscopy of Hydrogen Bonded and Van der Waals Complexes, May 16, 1986.

R. Harris (University of California, Berkeley) - The Dynamics of Handedness and Tunneling in Condensed Media, June 6, 1986.

INVITED TALKS

Quantum Physics Division (525)

G. H. Dunn, "Dielectronic Recombination: The process and its signatures, " NATO Advanced Study Institute on the Physics of Electron-Ion and Ion-Ion Collisions, Domain "Les Masures," Han sur Lesse, Belgium, October 1, 1985.

G. H. Dunn, "Measurement of Dielectronic Recombination: Beams Experiments, NATO Advanced Study Institute on the Physics of Electron-Ion and Ion-Ion Collisions," Domaine "Les Masures," Han sur Lesse, Belgium, October 2, 1985.

G. H. Dunn, "Measurement of Dielectronic Recombination: Plasma Experiments, NATO Advanced Study Institute on the Physics of Electron-Ion and Ion-Ion Collisions, Domaine "Les Masures," Han sur Lesse, Belgium, October 3, 1985.

G. H. Dunn, "Excitation and Ionization in Electron-Multicharged Ion Collisions: Experiment," Oak Ridge National Laboratory, Workshop on Atomic Physics with Stores Cooled Heavy Ion Beams, Oak Ridge National Laboratory, Oak Ridge, Tennessee, January 14, 1986.

G. H. Dunn, "Atomic Physics at JILA," Institute of Physics, Belgrade, Yugoslavia, February 18, 1986.

G. H. Dunn, "Inelastic Collisions of Electrons With Ions," Physics Department, Justus-Liebig-Universität Giessen, Giessen, West Germany, February 21, 1986.

G. H. Dunn, "Playing the Mating Game with Electrons and Ions," Space Physics Department, Rice University, Houston, Texas, May 2, 1986.

G. H. Dunn, "Overview of Electron-Ion Collisions," International Seminar on Dynamic Processes of Highly Charged Ions, Fuji, Japan, August 22, 1986.

G. H. Dunn, "Tuneable Resonances: Dielectronic Recombination," Joint U.S. - Japan Workshop in Fusion Collaboration Program, Resonance Effects in Electron-Ion Collisions: A New Contribution of A&M Processes to Fusion, Institute of Plasma Physics, Nagoya University, Nagoya, Japan, September 2, 1986.

J. E. Faller, "Perspectives of Experimental Gravitational Physics, BIPM (Bureau International des Poids et Mesures, Sèvres, France, November 7, 1985.

INVITED TALKS

Quantum Physics Division (525)

J. E. Faller, "New and Emerging Measurement Techniques with Applications to Geophysics and Geodesy," Istituto di Miniere e Geofisica applicata, University of Trieste, Trieste, Italy, November 12, 1985.

J. E. Faller, "Absolute Gravimeters and Laser Gravitational Wave Antennas," Physikalische-Technische Bundesanstalt, Braunschweig, West Germany, November 19, 1985.

J. E. Faller, "Comments on the Re-evaluation of the Eötvös Data--Has a Fifth Force Been Observed?" Division 724 Colloquium, National Bureau of Standards, Boulder, Colorado, January 31, 1986.

J. E. Faller, "Eötvös Re-visited," Harvard University, Boston, Massachusetts, February 10, 1986.

J. E. Faller, "The JILA Absolute Gravity Instruments," 1986 American Geophysical Union's Spring Meeting, Baltimore Convention Center, Baltimore, Maryland, May 1986.

J. E. Faller, "The New JILA Absolute Gravimeters," CPEM 1986 Meeting, National Bureau of Standards, Gaithersburg, Maryland, June 23, 1986.

J. E. Faller, "Terrestrial Eötvös Experiments, GRII Conference, Stockholm, Sweden, July 8, 1986.

J. E. Faller, "Past and Future (Absolute Gravity) Comparisons: Some Thoughts," 12th Meeting of the International Gravity Commission, Toulouse, France, September 23, 1986.

J. E. Faller, "Status of and Progress Report on the New JILA Absolute Gravimeter," 12th Meeting of the International Gravity Commission, Toulouse, France, September 25, 1986.

A. C. Gallagher, "Silane Plasma Chemistry," Polaroid Corporation, Boston, Massachusetts, February 14, 1986.

A. C. Gallagher, "Collisional Line Shapes in Gases," Holstein Symposium, UCLA, Los Angeles, California, March 29, 1986.

A. C. Gallagher, "Surface Reactions in Discharge and CVD Deposition of a-Si:H," Materials Research Society Spring Meeting, Palo Alto, California, April 16, 1986.

A. C. Gallagher, "Issues Concerning Hydrogenated Amorphous Silicon Surfaces," National Bureau of Standards, Gaithersburg, Maryland, June 6, 1986.

INVITED TALKS

Quantum Physics Division (525)

A. C. Gallagher, "Doppler-Free Line Broadening," 8th International Line Shapes Conference, Williamsburg, Virginia, June 11, 1986.

A. C. Gallagher, "Laser Spectroscopy of Inelastic Collisions," First Symposium on Laser Spectroscopy, Pecs, Hungary, August 28-30, 1986.

A. C. Gallagher, "Surface Reactions in Silane Discharges," Symposium on Ionized Gases, Shibenik, Yugoslavia, September 2-5, 1986.

K. B. Gebbie, "Quantum Physics Division, JILA," NBS Second Non-technical Talk, National Bureau of Standards, Boulder, Colorado, June 25, 1986.

J. L. Hall, "Is $\delta\lambda/\lambda << 10^{-9}$ Really Possible with a Lambdameter?" and "Stable Lasers: Progress, Applications, and Dreams," National Bureau of Standards, Gaithersburg, Maryland, December 4, 1985.

J. L. Hall, "Stabilizing Lasers for Applications in Quantum Optics," Fourth International Symposium on Quantum Optics, Hamilton, New Zealand, February 1986.

J. L. Hall, "Stable Lasers and Slow Atoms," Colloquium, Department of Physics, Princeton University, Princeton, New Jersey, April 17, 1986.

J. L. Hall, "Phase-Stable Lasers: Progress and Applications," XIV International Conference on Quantum Electronics, Moscone Center, San Francisco, California, June 10, 1986.

J. L. Hall, "Phase-Stable Laser Stabilization Experiments," Conference on Precision Electromagnetic Measurements, National Bureau of Standards, Gaithersburg, Maryland, June 26, 1986.

J. L. Hall, Laser Applications in Fundamental Physics," 3-Lecture Series at the Nordic Summer School, Sonderborg, Denmark, August 11-15, 1986.

J. L. Hall, "Stable Lasers: Progress and Applications," University of New Mexico, Albuquerque, New Mexico, September 19, 1986.

S. R. Leone, "Laser Probing of Energy Transfer and Chemical Reaction Dynamics," Chemistry Department, Texas A&M, College Station, Texas, October 9, 1985.

S. R. Leone, "Laser Probing of Energy Transfer and Chemical Reaction Dynamics," Chemistry Department, University of Texas at Austin, Austin, Texas, October 10, 1985.

INVITED TALKS

Quantum Physics Division (525)

S. R. Leone, "Laser Probing of Energy Transfer and Chemical Reaction Dynamics," Department of Chemistry, University of Michigan, Ann Arbor, Michigan, October 22, 1985.

S. R. Leone, "Alignment Effects on Electronic Energy Transfer in Atomic Calcium-Rare Gas Collisions," International Laser Science Conference, Dallas, Texas, November 21, 1985.

S. R. Leone, "State-Selected Ion-Molecule Chemistry and Energy Transfer," Chemistry Department, University of California, Davis, Davis, California, January 14, 1986.

S. R. Leone, "Product States and Alignment Effects in Chemical Dynamics," Chemistry Department, University of California, Berkeley, Berkeley, California, January 15, 1986.

S. R. Leone, "Laser Probing of Energy Transfer and Chemical Reaction Dynamics," Chemicstry Department, Stanford University, Stanford, California, January 16, 1986.

S. R. Leone, "Laser Studies of Chemical Reaction Dynamics," Chemistry Department, University of Denver, Denver, Colorado, February 27, 1986.

S. R. Leone, "Laser Studies of Chemical Reaction Dynamics," University of Kansas, Lawrence, Kansas, March 25, 1986.

S. R. Leone, "Product States and Alignment Effects in Chemical Dynamics," American Chemical Society, University of Wisconsin, Madison, Wisconsin, April 2, 1986.

S. R. Leone, "Dynamics of Ion-Molecule Reactions," Sanibel Symposium, Snowbird, Utah, April 23, 1986.

S. R. Leone, "Optical Studies of Product State Distributions in Thermal Energy Ion-Molecule Reactions. I. Infrared Chemiluminescence," NATO Meeting on Ion-Molecule Chemistry, Les Arcs, France, July 1986.

S. R. Leone, "Optical Studies of Product State Distributions in Thermal Energy Ion-Molecule Reactions. II. Laser Induced Fluorescence," NATO meeting on Ion-Molecule Chemistry, Les Arcs, France, July 1986.

S. R. Leone, "Laser Probing of the Dynamics of Alignment Processes in Collisional Energy Transfer," University of Fribourg, Fribourg, Switzerland, July 1986.

INVITED TALKS

Quantum Physics Division (525)

S. R. **Leone**, "Infrared Probing of Chemical Dynamics," University of Bern, Bern, Switzerland, July 1986.

S. R. **Leone**, "Laser Probing of the Dynamics of Alignment Processes in Collisional Energy Transfer," University of Orsay, Paris-Sud, France, July 1986.

S. R. **Leone**, "Transient Gain-Versus-Absorption Laser Probing of Spin-Orbit States, Kinetics and Dynamics," IX International Gas Kinetics Meeting, Bordeaux, France, July 1986.

J. L. **Linsky**, "The Space Telescope High Resolution Spectrograph Guaranteed Time Observing Program," Department of Astrophysical, Planetary, and Atmospheric Sciences, University of Colorado, Boulder, Colorado, October 9, 1985.

J. L. **Linsky**, "Physics of Partial Redistribution and Radiative Transfer in Stellar Atmospheres," Third International Conference/Workshop on the Radiative Properties of Hot Dense Matter, Sponsored by Naval Research Lab., Williamsburg, Virginia, October 14, 1985.

J. L. **Linsky**, "NASA's Proposed AXAF Mission: The Next Generation of X-Ray Instrumentation in Space and Its Capabilities for X-Ray Spectroscopy of Stellar Coronae, NBS Colloquium Series, National Bureau of Standards, Gaithersburg, Maryland, January 17, 1986.

J. L. **Linsky**, "Magnetic Fields in Late-Type Stars: New Measurement Techniques and the Role of Fields in Heating Chromospheres and Coronae," Astronomy and Astrophysics Center, University of Chicago, Chicago, Illinois, February 5, 1986.

J. L. **Linsky**, "The Proposed AXAF Mission: The Next Generation of X-Ray Instrumentation in Space," JILA and the Department of Astrophysical, Planetary, and Atmospheric Science, University of Colorado, Boulder, Colorado, May 12, 1986.

J. L. **Linsky**, "Mass Loss of Late-Type Stars as a Function of Position in the H-R Diagram," Institute of Astronomy, Catania University, Catania, Italy, June 16, 1986.

J. L. **Linsky**, "Mass Loss of Late-Type Stars as a Function of Position in the H-R Diagram," IAU Symposium No. 122 Circumstellar Matter, Heidelberg, Germany, June 25, 1986.

INVITED TALKS

Quantum Physics Division (525)

J. L. **Linsky**, "Activity in Warm Stars: IUE Observations of Early F Dwarfs," International Symposium on New Insights in Astrophysics, University College London, London, England, July 14, 1986.

J. L. **Linsky**, "The Proposed LYMAN Far Ultraviolet Spectroscopic Explorer," International Symposium on New Insights in Astrophysics, University College London, London, England, July 16, 1986.

J. L. **Linsky**, "Magnetic Fields in Cool Stars: Recent Measurements and the Effects of Fields on Atmospheric Structure, Department of Physics, Arizona State University, Tempe, Arizona, November 25, 1986.

D. J. **Nesbitt**, "IR Laser Absorption Spectroscopy of Van der Waals Molecules," Department of Chemistry, University of New Mexico, Albuquerque, New Mexico, February 26, 1986.

D. J. **Nesbitt**, "IR Laser Absorption Spectroscopy of Van der Waals Molecules," Los Alamos National Laboratory, Los Alamos, New Mexico, February 27, 1986.

D. J. **Nesbitt**, "IR Laser Absorption Spectroscopy of Van der Waals Molecules," Sandia National Laboratory, Albuquerque, New Mexico, February 28, 1986.

D. J. **Nesbitt**, "IR Laser Spectroscopy of Weakly Bound Complexes," NBS-Staff Seminar Series, National Bureau of Standards, Gaithersburg, Maryland, May 30, 1986.

D. J. **Nesbitt**, "IR Laser Vibrational Predissociation Studies of Van der Waals Clusters," Gas Phase Ion Chemistry Symposium, Regional ACS Meeting, Denver, Colorado, June 10, 1986.

D. J. **Nesbitt**, "IR Laser Absorption Spectroscopy of Van der Waals Complexes in Slit Supersonic Expansions," XVII Informal Conference on Photochemistry, Boulder, Colorado, June 23, 1986.

D. W. **Norcross**, "Vibrational Excitation of HF Molecules by Slow Electron Impact: Effects of Polarization, 38th Gaseous Electronics Conference, Naval Postgraduate School, Monterey, California, October 16, 1985.

D. W. **Norcross**, "Alkali Atoms - The Salt of Electron Collision Physics," Department of Physics, University of Oklahoma, Norman, Oklahoma, February 20, 1986.

INVITED TALKS

Quantum Physics Division (525)

A. V. Phelps, "Electron Transport and Collision Processes in Gases," Department of Chemical Engineering, University of Syracuse, Syracuse, New York, April 15, 1986.

A. V. Phelps, "Models of Electric Discharges at Very High E/n," GTE Laboratories, Inc., Waltham, Massachusetts, April 17, 1986.

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Physics Division (525)

P. L. Bender, Member, Fundamental Physics and Chemistry Panel, Space Science Board Study: Major Thrusts in Space Science: 1995-2015.

P. L. Bender, Member, Gravitation and Cosmic Physics Panel, Physics Survey Committee of the National Research Council.

P. L. Bender, Associate Editor, Journal of Geophysical Research.

P. L. Bender, Member, American Geophysical Union Committee on Fellows.

P. L. Bender, Member, Earth Observing System Science Steering Committee, NASA.

P. L. Bender, Member, Working Group 1 on Recent Plate Movements and Deformation, Inter-Union Commission on the Lithosphere.

P. L. Bender, Member, Crustal Dynamics Working Group, NASA.

G. H. Dunn, Member, National Research Council Committee on Atomic and Molecular Science.

G. H. Dunn, Member, Executive Committee, Division of Electron and Atomic Physics, American Physical Society.

G. H. Dunn, Member, Panel on New Instruments and Facilities in Atomic and Molecular Science, CAMS.

G. H. Dunn, Chairman, Nominating Committee, Division of Electron and Atomic Physics, American Physical Society.

G. H. Dunn, Chairman, Ad-hoc Committee on Atomic Data, for CAMS.

G. H. Dunn, Member, Selection Committee, Davisson-Germer Prize of the American Physical Society.

G. H. Dunn, Co-organizer, NATO Advanced Study Institute on Physics of Electron-ion and Ion-Ion Collisions.

G. H. Dunn, Co-organizer, U.S. - Japan Workshop on "Resonance Effects in Electron-Ion Collisions: A New Contribution of A&M Processes to Fusion," Institute of Plasma Physics, Nagoya University, Nagoya, Japan, September 1-2, 1986.

G. H. Dunn, Member, Panel on Scientific Opportunities for the Use of Cooled Heavy Ion Storage Rings, Committee on Atomic and Molecular Science, National Research Council.

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Physics Division (525)

J. E. **Faller**, Member, Working Group II of the International Gravity Commission.

J. E. **Faller**, Member, Special Study Group 3.86, "Estimation of Absolute Gravimetric Determinations," of the International Gravity Commission.

J. E. **Faller**, Member, Special Study Group 3.87, "Development of World-Wide Absolute Gravity Net," of the International Gravity Commission.

J. E. **Faller**, Member, U. S. Interagency Gravity Standards Committee.

J. E. **Faller**, Member, Management Operations Working Group on Lunar Ranging.

J. E. **Faller**, Member, Physics Departments' "Geophysics Committee".

J. E. **Faller**, Member, External Awards Subcommittee of the American Geophysical Society.

A. C. **Gallagher**, Member, Army Basic Research Steering Committee.

J. L. **Hall**, Delegate, Consultative Committee for the Definition of the Meter (BIPM), Sèvres, France, 1970 - present.

J. L. **Hall**, Member, International Steering Committee for Conferences on Laser Spectroscopy.

J. L. **Hall**, Member, NBS Committee for NBS Precision Measurement Grants.

J. L. **Hall**, Member, Ad hoc Oversight Committee for Air Force Ring Laser Gyro Program.

J. L. **Hall**, Member, Advisory Committee to the Global Oscillation Group, National Solar Observatory.

J. L. **Hall**, Member, A&M&O Subcommittee of Physics Division, Academy of Science.

D. G. **Hummer**, Member, Editorial Board, Computer Physics Communications.

D. G. **Hummer**, Member, Steering Committee of the United Kingdom Collaborative Computational Project on Stellar Atmospheres.

D. G. **Hummer**, Co-Director, International Stellar Opacity Project.

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Physics Division (525)

S. R. **Leone**, Vice Chairman, Division of Chemical Physics, American Physical Society, 1986-1987.

S. R. **Leone**, Editorial Advisory Board, Chemical Reviews, 1982-1988.

S. R. **Leone**, Associate Editor, Journal of Chemical Physics, 1984-1987.

S. R. **Leone**, Committee on Atomic and Molecular Science, National Research Council, 1986-1989.

S. R. **Leone**, Executive Committee, Division of Physical Chemistry, American Chemical Society, 1984-1987.

S. R. **Leone**, Editorial Advisory Board, Journal of Physical Chemistry, 1984-1987.

S. R. **Leone**, Member, NRC Committee, Army Research Office Review Board, 1984-1988.

J. L. **Linsky**, Member, Users' Committee, National Solar Observatory.

J. L. **Linsky**, Member, Users' Committee, International Ultraviolet Explorer Satellite.

J. L. **Linsky**, Member, Management and Operations Working Group, Solar and Heliospheric Physics Section, NASA.

J. L. **Linsky**, Chairman, Management and Operations Working Group, Astronomy and Relativity Section, NASA.

J. L. **Linsky**, Co-Investigator, High Resolution Spectrograph, Space Telescope.

J. L. **Linsky**, Member, Far Ultraviolet Spectrograph Explorer Science Working Group.

J. L. **Linsky**, Member, Scientific Organizing Committee, IAU Symposium No. 122, Circumstellar Matter, Heidelberg, Germany, June 23-27, 1986.

J. L. **Linsky**, Member, Editorial Board, Solar Physics.

J. L. **Linsky**, Member, Committee to Study the Long-Range Scientific Directions of Large-Aperture Ground-Based Solar Astronomy, Association of Universities for Research in Astronomy (AURA).

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Physics Division (525)

J. L. **Linsky**, Member AURA/NSF Study of the Scientific Goals and Priorities of the National Solar Observatory, AURA and NSF.

J. L. **Linsky**, Interdisciplinary Scientist on the Advanced X-Ray Astrophysical Facility (AXAF) and Member of the AXAF Science Working Group, NASA.

J. L. **Linsky**, Member, Astrophysics Council, NASA.

J. L. **Linsky**, Member, IUE Long Range Planning Committee.

J. L. **Linsky**, Member, National Optical Astronomy Observatory (NOAO) Director's Advisory Committee.

J. L. **Linsky**, Member, Committee on Coordinated Ground-Based and Space Observing, NOAO.

J. L. **Linsky**, Chairman, Scientific Organizing Committee, Fifth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, Boulder, Colorado, July 7-10, 1987.

J. L. **Linsky**, Member, Scientific Organizing Committee, International Symposium on New Insights in Astrophysics, London, England, July 14-16, 1986.

J. L. **Linsky**, Chairman, Steering Committee, Synoptic High Resolution Spectroscopic Observing Group.

J. L. **Linsky**, Member, Committee to Study the Long Term Goals for the National Optical Astronomical Observatory, Association of Universities for Research in Astronomy (AURA).

J. L. **Linsky**, Member, Scientists on Spaceborne Interferometry, NASA.

J. L. **Linsky**, Chairman, Infrared Astronomy Project Concepts Evaluation Panel, NASA.

J. L. **Linsky**, Member, Astrophysics Data Operations Study Committee, Goddard Space Flight Center, NASA.

J. L. **Linsky**, Co-Investigator, Space Telescope Imaging Spectrograph, NASA.

D. W. **Norcross**, Member, Panel on Theoretical Atomic and Molecular Sciences of the Committee on Atomic and Molecular Sciences of the National Research Council.

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Physics Division (525)

D. W. **Norcross**, Member, Working Group Supervising Collaborative Computational Project 2 (Continuum States of Atoms and Molecules) of the U. K. Science and Engineering Research Council, 1983 - present.

D. W. **Norcross**, Member, Publications Committee, Division of Electron and Atomic Physics of the American Physical Society, 1985-1986.

S. J. **Smith**, Member, Organizing Committee, Tenth International Conference on Atomic Physics, Tokyo, Japan, 1986.

S. J. **Smith**, Editorial Board, Metrologia.

S. J. **Smith**, Chairman, Organizing Committee, Fourth International Conference on Multiphoton Processes, Boulder, 1987.

CONSULTING

Quantum Physics Division (525)

P. L. Bender

Dr. Bender is consulting with the University GPS Consortium concerning the accuracy of determining tectonic motions with signals from the Global Positioning System satellites.

J. L. Hall

Dr. Hall is consulting with the Theoretical Astrophysics Group at Caltech in the area of laser techniques for gravity wave detection, and informally with colleagues in industry involved with stable laser design and application, and also consults with:

U. S. Air Force Academy - supervision of Graduate Students Working on Laser Stabilization and Laser Ring Gyros,

Ad hoc Oversight Committee for Air Force Ring Laser Gyro Program,

Advisory Committee to the Global Oscillation Network Group, National Solar Laboratory.

D. G. Hummer

Dr. Hummer consults for the X-ray laser project at Livermore and Los Alamos Laboratories.

S. R. Leone

Dr. Leone does consulting with TRW on certain optical and laser problems involving high power systems.

CONSULTING

Quantum Physics Division (525)

J. L. Linsky

Dr. Linsky consults with NASA concerning (1) future programs in the area of ultraviolet and infrared astronomy, (2) future programs in solar and heliospheric physics, (3) operations and long range planning for the International Ultraviolet Explorer satellite, (4) definition of the proposed LYMAN Far Ultraviolet Spectroscopic Explorer satellite, (5) definition of the proposed Advanced X-ray Astronomical Facility, (6) calibration and initial operations of the Space Telescope High Resolution Spectrograph, (7) data operations for future missions, (8) interferometry from space, and (9) future infrared astronomy missions.

Dr. Linsky consults with the National Optical Astronomy Observatory (NOAO) and the Association of Universities for Research in Astronomy (AURA) concerning (1) operation of the National Solar Observatory and Sacramento Peak Observatory, (2) planning for coordinated ground-based and space observations, (3) potential need for a large-aperature ground-based solar telescope, (4) planning for synoptic high resolution spectroscopic observations, and (5) the long term goals of the NOAO.

D. W. Norcross

Dr. Norcross is consulting with the Theoretical Atomic and Molecular Physics Group at the Lawrence Livermore Laboratory on problems related to laser modeling, and is a Visiting Scientist (consultant) to Division T-4 of the Los Alamos Laboratory on problems related to electron collisions with atoms, ions, and molecules.

A. V. Phelps

Dr. Phelps does informal consulting and advising with DoD and DoE laboratories and their industrial and university contractors in the area of atomic and molecular processes in high power switches, laser induced breakdown and charged particle beam propagation. For the Lawrence Livermore National Laboratory this has been formalized by the granting of support for a postdoc.

OTHER AGENCY RESEARCH

Quantum Physics Division (525)

P. L. Bender	JPL	Integrated water vapor calibration development.
P. L. Bender	NASA	Detailed translocation analysis of regional Lageos crustal movement data.
P. L. Bender	NASA	Determination of worldwide tectonic plate motions and large scale intra-plate distortions.
P. L. Bender & J. E. Faller	NASA	Laser gravitational observation in space.
G. H. Dunn	DOE	Determine atomic, molecular, and nuclear data pertinent to the magnetic fusion energy program.
J. E. Faller	AFGL	An absolute gravity experiment.
J. E. Faller	AUSTRIA	Construction of an absolute gravity apparatus.
J. E. Faller	DMA-N	Absolute "G" co-op program.
J. E. Faller	HANNOVER	Construction of an absolute gravity apparatus.
J. E. Faller	MERADCOM	Fabrication of two gravity gradiometers for subsequent field testing and evaluation.
J. E. Faller	NASA	Laser lunar ranging multi-lens telescope.
A. C. Gallagher	AFOSR	Electronic energy transfer processes in the alkali/alkaline earth metal vapors.
A. C. Gallagher	DOE	Spectroscopic diagnostics of electron-atom collisions.
A. C. Gallagher	SERI	Diagnostics of a glow discharge used to produce hydrogenated amorphous silicon films.
K. B. Gebbie & J. Toomre	AFGL	Solar oscillations and convective flows as probes of structure in the subphotosphere.

OTHER AGENCY RESEARCH

Quantum Physics Division (525)

K. B. Gebbie & J. Toomre	NASA	Basic research in solar physics: Energy transport in the solar envelope and atmosphere.
K. B. Gebbie & J. Toomre	NASA	X-ray bright points on the quiet sun and rapid UV brightening in active regions.
J. L. Hall	AF ACAD	Stabilization of diode and gas lasers.
J. L. Hall	ONR	Precision atomic beam spectroscopy using stabilized lasers.
D. G. Hummer	NASA	Spectral Formation.
D. G. Hummer	NSF	Theory and observation of expanding atmospheres of early type stars.
S. R. Leone	ACS	Infrared laser excitation and fluorescence of intramolecular vibrational relaxation in hydrocarbons.
S. R. Leone	AFOSR	State-resolved dynamics of ion-molecule reactions in a flowing afterglow.
S. R. Leone	AFOSR	Electronic energy transfer processes in the alkali/alkaline earth metal vapors.
S. R. Leone	AFWL	Diode laser probing of energy transfer in XeF.
S. R. Leone	ARO	Excimer laser photolysis studies of translation-to-vibration energy transfer.
S. R. Leone	DOE	Time-resolved free radicals and laser-initiated chain reactions.
S. R. Leone	NASA	Innovative methods for the measurement of I* quantum yields and kinetics by diode laser gain-versus-absorption.
S. R. Leone	NSF	State-resolved molecular dynamics.
J. L. Linsky	NASA	Advanced X-ray Astrophysical Facility (AXAF).

OTHER AGENCY RESEARCH

Quantum Physics Division (525)

J. L. Linsky	NASA	Analysis of EXOSAT satellites observation of stellar coronae.
J. L. Linsky	NASA	Analysis of Einstein X-ray observatory observations of stellar coronae (6 grants).
J. L. Linsky	NASA	International Ultraviolet Explorer studies of astronomical sources (2 grants).
J. L. Linsky	NASA	Basic research in solar physics (2 grants).
J. L. Linsky	NASA	Hubble Space Telescope High Resolution Spectrograph (2 grants).
D. J. Nesbitt	ACS	State-resolved infrared vibrational dynamics of supersonic expansion cooled molecules.
D. J. Nesbitt	AFOSR	Infrared transition moments and collisional dynamics.
D. J. Nesbitt	NSF	Direct IR laser absorption spectroscopy in linear supersonic jets.
D. J. Nesbitt	RES CORP	State-resolved laser infrared absorption studies of molecular sublimation dynamics.
D. W. Norcross	DOE	Atomic and molecular collision processes.
D. W. Norcross	DOE	Electron impact excitation of atomic ions.
A. V. Phelps	AFWAL	Detection of excited states by laser induced fluorescence.
A. V. Phelps	LLL	Non-equilibrium electrons in gases.
S. J. Smith	DOE	Near resonant absorption in intense, fluctuating laser fields.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

P. L. Bender

October 14-17, 1985 - Washington, D.C.
Attended a meeting of NASA Lunar Ranging Working Group, and a meeting of NASA Crustal Dynamics Working Group.
Sponsor: NASA Goddard.

October 27-30, 1985 - Boston, Massachusetts.
Attended a Workshop on Imaging Interferometry in Space.
Sponsors: National Research Council, NASA Goddard.

December 7-12, 1985 - San Francisco, California.
Attended a meeting of the U.S. Geodynamics Committee, a meeting of the American Geophysical Union Fellows Committee, and the American Geophysical Union Fall Meeting.
Sponsor: NASA Goddard.

January 27-30, 1986 - Los Angeles, California.
Attended meeting of the Space Science Board Task Group on Fundamental Physics and Chemistry.
Sponsor: NASA Goddard.

March 21-27, 1986 - El Paso, Texas; Los Angeles, California.
Attended a meeting of NASA Lunar Laser Ranging Working Group (El Paso);
Attended a meeting of the NASA Crystal Dynamics Working Group (Los Angeles).
Sponsors: NASA.

May 19-24, 1986 - Washington, D. C.
Attended Spring meeting of the American Geophysical Union and Reviewed accomplishments and observing plans for the NASA Crustal Dynamics Project.
Sponsor: NASA Goddard.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

G. H. Dunn

January 12-15, 1986 - Oak Ridge, Tennessee.
Attended an NRC Committee Meeting on the "Evaluation of Building A Storage Ring in the U.S. and presented an invited talk.
Sponsor: Department of Energy.

February 7-15, 1986 - Obertraun, Austria; Belgrade, Yugoslavia; Giessen, West Germany.
Attended the Fifth Symposium on Atomic and Surface Physics (SASP) and presented an invited lecture (Obertraun);
U. S. monitor of two NBS/Yugoslav projects, Visited project with R. Janev and D. Belic and visited project with J. Kurepa (Belgrade);
Visited the laboratories of A. Muller and E. Salzborn at the University of Giessen (Giessen);
Sponsors: Fifth Symposium on Atomic and Surface Physics; U.S. Embassy, Belgrade, Yugoslavia; University of Giessen.

March 9-11, 1986 - Washington, D. C.
Attended meeting of the Committee on Atomic and Molecular Science, National Research Council.
Sponsor: National Academy of Sciences.

May 1-2, 1986 - Houston, Texas.
Presented an invited colloquium at the Space Science Department, Rice University.
Sponsor: Rice University.

August 20-September 2, 1986 - Susono, Shizuoka-ken; Tokyo; Nagoya; Japan.
Presented an invited paper at the International Seminar on Dynamic Processes of Highly Charged Ions (Susono, Shizuoka-ken);
Attended X International Conference on Atomic Physics (Tokyo);
Co-organizer of U.S.-Japan Workshop on "Resonance Effects in Electron-Ion Collisions--A New Contribution of Atomic and Molecular Processes to Fusion" (Nagoya).
Sponsor: Department of Energy

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

J. E. Faller

October 14-16, 1985 - Washington, D. C.
Attended Management Operation Working Group for Lunar Laser Ranging at Goddard Space Flight;
Attended the Crustal Dynamics Investigators Meeting.
Sponsor: NASA Goddard.

December 9-13, 1985 - San Francisco, California.
Attended AGU Meeting;
Attended MOW G Meeting.
Sponsor: NASA Goddard.

February 9-10, 1986 - Boston, Massachusetts.
Presented an invited talk at Harvard University.
Sponsors: Harvard University, U.S. Army Belvoir Research and Development Center.

February 11-12, 1986 - Colorado Springs, Colorado.
Consulted with personnel at the Air Force Academy and supervised a student's talk.
Sponsor: U. S. Army Belvoir Research and Development Center.

March 21-25, 1986 - Ft. Davis, Texas; Pasadena, California.
Attended NASA Lunar Laser Working Group Meeting at the McDonald Observatory (Ft. Davis);
Attended meeting of the NASA Crustal Theory Working Group at the Jet Propulsion Laboratory (Pasadena).
Sponsor: NASA Goddard

May 17-22, 1986 - Baltimore, Maryland.
Attended American Geophysical Union Meeting and presented an invited talk.
Sponsor: Defense Mapping Agency, Hydrographic/Topographic Center.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

Faller (cont.)

July 3-16, 1986 - Hanover, West Germany; Stockholm, Sweden; Helsinki, Finland.
Visited The Torge Institute for Earth Measurements where JILA-made gravimeter is housed (Hanover);
Attended the 11th International Meeting on Gravitation and Relativity and gave an invited talk (Stockholm);
Visited with Professor Kakurri at the Finish Geodetic Institute (Helsinki).
Sponsor: AF Geophysics Laboratory

September 16-27, 1986 - Paris, France; Toulouse, France.
Visited Dr. Quinn, Dr. Speake, and Dr. Sakuma at the International Bureau of Physical Measurements (Paris);
Attended the 12th Meeting of the International Gravity Commission and presented 2 invited papers (Toulouse).
Sponsor: Defense Mapping Agency, Hydrographic/Topographic Center.

A. C. Gallagher

February 2-14, 1986 - Boston, Massachusetts.
Presented an invited talk at Polaroid Corporation.
Sponsor: Polaroid Corporation.

April 14-18, 1986 - Palo Alto, California.
Attended the Material Research Society's Spring Meeting and presented an invited talk.

J. L. Hall

February 10-19, 1986 - Hamilton, New Zealand.
Discussed laser problems with staff of Waikato University, including Professor Dan Walls and Professor D. Warrington.
Sponsor: The University of Waikato.

April 16-18, 1986 - Princeton, New Jersey.
Presented an invited lecture at Princeton University entitled "Slow Atoms and Stable Lasers."
Sponsor: Princeton University.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

Hall (cont.)

May 8-30, 1986 - Shanghai, China; Hefei, China; Shanghai, China; Beijing, China.
Gave lectures at East China Normal University (Shanghai);
Visited Hefei Institute of Optics and Fine Mechanics (Hefei);
Continued lectures (Shanghai);
Visited National Institute of Metrology (Beijing).
Sponsor: World Bank.

August 1-15, 1986 - Aarhus, Sonderborg, Denmark.
Visited Professor O. Poulsen at Aarhus University and interacted with laser and atom beam specialists of his group (Aarhus);
Presented 3 invited lectures at Nordic Summer School on Laser Applications in Fundamental Atomic and Molecular Physics (Sonderborg).
Sponsors: University of Aarhus and the Nordic Summer School of Physics.

D. G. Hummer

December 3-19, 1985 - London, England.
Attended a meeting of the Opacity Project and reported on his work on internal partition functions for dense plasmas;
Discussed ongoing and future work in Opacity Project with Professor M. J. Seaton;
Worked with Dr. P. J. Storey on collisional-radiative recombination theory and wrote a second paper in series on this work.
Sponsor: NASA.

August 3-9, 1986 - Santa Cruz, California.
Attended the Conference on Strongly Coupled Plasmas at the University of Santa Cruz and presented an invited paper on "An Equation of State for Stellar Envelopes with an Occupation Probability Formalism for Internal Partition Functions."
Sponsor: NASA

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

S. R. Leone

October 8-11, 1985 - College Station and Austin, Texas.
Presented departmental colloquium at Texas A&M (College Station);
Presented departmental colloquium at the University of Texas at Austin (Austin).
Sponsors: Texas A&M University and University of Texas at Austin.

October 21-23, 1985 - Ann Arbor, Michigan.
Presented departmental colloquium at the University of Michigan.
Sponsor: The University of Michigan.

January 11-17, 1986 - Sacramento, Berkeley, and Stanford, California.
Visited the University of California, Davis, and presented a seminar (Sacramento);
Visited the University of California, Berkeley, and presented a seminar (Berkeley);
Presented a seminar at Stanford University (Stanford).
Sponsors: University of California, Davis; University of California, Lawrence Berkeley Laboratory; and Stanford University.

March 24-26, 1986 - Lawrence, Kansas.
Visited the University of Kansas and gave an invited departmental colloquium.
Sponsor: The University of Kansas.

March 31 - April 1, 1986 - Las Vegas, Nevada.
Attended the Division of Chemical Physics meeting at the American Physics Society Meeting.
Sponsor: The American Physical Society.

April 1-3, 1986 - Madison, Wisconsin.
Presented an invited colloquium for the local American Chemical Society and visited the University of Wisconsin.
Sponsor: American Chemical Society.

Leone (cont.)

April 21-24, 1986 - Snowbird, Utah.
Attended the Sanibel Symposium and presented an invited talk.
Sponsors: University of Florida and University of Utah.

May 7-8, 1986 - Washington, D.C.
Received the Arthur S. Flemming Award.
Sponsor: Washington Jaycees.

July 12-26, 1986 - Fribourg, Bern, Switzerland; Paris, Bordeaux, France.
Visited the University of Fribourg and presented a seminar (Fribourg);
Visited the University of Bern and presented a seminar (Bern);
Visited the University of Orsay and presented a seminar (Paris);
Presented a lecture on laser probing of photofragmentation dynamics at the International Gas Kinetics Conference (Bordeaux).
Sponsors: Fribourg Schweiz University, Bern University, Orsay University, and 9th International Symposium on Gas Kinetics.

October 1 - November 13, 1986 - Tokyo, Sendai, and nearby cities in the Tohoku District; Nagoya, Okazaki, Kyoto, Nara, and other cities in the Kyushu District; Hiroshima, Okazaki, Tokyo, Japan.
Six-week Fellowship from the Japanese Society for the Promotion of Science (JSPS) during which time Dr. Leone will visit various universities and laboratories:

(1) University of Tokyo:
Professor Soji Tsuchiya, Department of Pure and Applied Sciences,
Professors Kuchitsu, Kondow, Tominaga, and Tasumi, Department of Chemistry.

(2) Tokyo Technical Institute:
Professors Tanaka, Obi, Sato in the department of Chemistry.

(3) Keio University:
Professor Kaya, Department of Chemistry.

Leone (cont.)

(4) Institute for Physical Chemistry Research: Drs. Kasuya, Takami, and Arai.
(5) Institute for Environmental Studies: Drs. Akimoto, Washida, and Inoue.
(6) Tohoku University, Sendai: Professor Ito, Department of Chemistry, Professor Sato, Scientific Institute of Measurements, Professor Takebe, Department of Nuclear Engineering.

Deliver lectures and collaborate on experiments. (Tokyo, Sendai, and other nearby cities);
Attend the Chemical Reaction Dynamics Symposium and give an invited talk (Nagoya);
Visit the Institute for Molecular (IMS) Science and visit labs, give invited talks, and collaborate on IR diode laser studies of excimer laser photochemistry with Professor Hirota (Okazaki);
Give talks at labs and universities (Kyoto, Nara);
Visit Professor T. Ogawa (Kyushu University) and other laboratories and universities in various cities (Kyushu District);
Visit Professor Saito at Hiroshima University (Hiroshima);
Visit the IMS (Okazaki);
Sponsor: Japanese Society for the Promotion of Science

J. L. Linsky

October 7, 1985 - Tucson, Arizona.
Represented the National Solar Observatory Users' Committee at a meeting of the Association of Universities for Research in Astronomy Visiting Committee;
Presented concerns of the NSO Users Committee to the AURA Visiting Committee.
Sponsor: National Optical Astronomy Observatories, Association of Universities for Research In Astronomy, Inc. (AURA).

Linsky (cont.)

October 10-20, 1985 - Washington, D.C.; Norfolk, Virginia; El Paso, Texas.
Attended a meeting of IUE Satellite Long Range Planning Committee at NASA, Goddard (Washington, D.C.);
Attended meeting on the Radiative Properties of Hot Dense Matter and gave an invited paper (Norfolk);
Attended Fourth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun (El Paso, Texas).
Sponsors: Creative Management Associates Inc., Naval Research Lab, National Optical Astronomy Observatories (AURA), NASA George C. Marshall Space Flight Center.

October 30 - November 5, 1985 - Washington, D.C.; Baltimore and Greenbelt, Maryland.
Attended a meeting of the AXAF Science Working Group at Goddard Space Flight Center (Washington);
Attended a meeting of the Space Telescope Local Interstellar Medium Consortium (Baltimore);
Attended a meeting of the Management and Operations Working Group at Goddard Space Flight Center (Greenbelt).
Sponsors: NASA George C. Marshall Space Flight Center and NASA Goddard.

December 4-6, 1985 - Washington, D. C.
Attended meetings at NASA Headquarters on Space Station and AXAF;
Attended meeting of the Astrophysics MOWG at Goddard Space Flight Center.
Sponsor: Battelle.

January 5-10, 1986 - Houston, Texas.
Attended a meeting of the American Astronomical Society and presented one invited and several contributed papers.
Sponsors: NASA George C. Marshall Space Flight Center and NASA Goddard.

Linsky (cont.)

January 19-24, 1986 - Tucson, Arizona; Huntsville, Alabama.
Attended a meeting of the National Solar Observatory Users Committee (Tucson);
Attended a meeting of the AXAF Science Working Group at Marshall Space Flight Center (Huntsville).
Sponsors: National Optical Astronomy Observatories (AURA) and NASA George C. Marshall Space Flight Center.

January 29-31, 1986 - Tucson, Arizona.
Attended meeting of the National Optical Astronomy Observatory's Directors Advisory Committee.
Sponsor: National Optical Astronomy Observatories (AURA).

February 3-5, 1986 - Washington, D.C.; Chicago, Illinois.
Consulted with Dr. Ken Dere at the Naval Research Lab conerning analysis of HRTS data (Washington D.C.);
Attended meeting of Astrophysics Management and Operations Working Group at Goddard Space Flight Center (Washington, D.C.);
Visited Astronomy Department of the University of Chicago (Chicago).
Sponsors: Battelle and The University of Chicago.

February 18-21, 1986 - Washington, D. C.
Attended a meeting of the NASA Solar and Heliospheric Management and Operations Working Group at Goddard Space Flight Center.
Sponsor: Battelle.

March 2-4, 1986 - Washington, D. C.
Attended a meeting of the Astronomy/Relativity Management Operations Working Group.
Sponsor: NASA Goddard.

Linsky (cont.)

March 23-26, 1986 - Washington, D. C.
Chairman "Infrared Project Concepts Review" for NASA.
Sponsor: Battelle.

April 9-11, 1986 - Huntsville, Alabama.
Attended a meeting of the AXAF Science Working Group.
Sponsor: NASA George C. Marshall Space Flight Center.

April 16-22, 1986 - Washington, D. C.
Attended a meeting of the Astrophysics Management Operations Working Group to discuss Space Telescope Imaging Spectrometer;
Attended a meeting of the Space Telescope High Resolution Spectrograph Team.
Sponsors: Battelle and NASA Goddard.

May 5-6, 1986 - Cambridge, Massachusetts.
Attended a meeting of the AXAF Science Working Group at the Center for Astrophysics.
Sponsor: NASA George C. Marshall Space Flight Center.

June 23-27, 1986 - Heidelberg, West Germany.
Attended IUE Symposium No. 122 on Circumstellar Matter.
Sponsor: University of Heidelberg.

August 3-6, 1986 - Sunspot, New Mexico; Baltimore, Maryland.
Attended a meeting of the National Solar Observatory User's Committee (Sunspot);
Attended meeting of the Astronomy/Relativity Management Operations Working Group (Baltimore).
Sponsors: National Optical Astronomy Observatories (AURA) and NASA Goddard.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

David J. Nesbitt

February 26-28, 1986 - Albuquerque, New Mexico.
Presented invited talk at Department of Chemistry, University of New Mexico;
Presented invited talk at Sandia National Laboratories;
Presented invited talk at Los Alamos National Laboratories.
Sponsor: Los Alamos National Laboratory.

April 20-24, 1986 - Snowbird, Utah.
Attended the Snowbird Conference and presented an invited talk.
Sponsors: University of Utah and University of Florida.

D. W. Norcross

October 14-16, 1985 - Monterey, California.
Attended 38th Annual Gaseous Electronics Conference at the Naval Postgraduate School and presented a talk.
Sponsor: Department of Energy.

February 19-21, 1986 - Norman, Oklahoma.
Presented an invited colloquium at the University of Oklahoma.
Sponsor: University of Oklahoma.

A. V. Phelps

April 14-18, 1986 - Syracuse, New York; Boston, Massachusetts.
Presented an invited seminar at the Department of Chemical Engineering, University of Syracuse (Syracuse);
Visited GTE Laboratories, Incorporated and presented an invited seminar (Boston).
Sponsors: Syracuse University and GTE Laboratories, Inc.

UNIVERSITY AND DEPARTMENT COMMITTEE MEMBERSHIPS

Quantum Physics Division (525)

P. L. Bender — Thesis Committees for:

D. N. de Vries
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P. T. Keyser
Physics Department, University of Colorado

M. D. Rayman
Physics Department, University of Colorado

B. Shahid-Saless
Physics Department, University of Colorado

S. J. Walter
Physics Department, University of Colorado

T. M. Van Dam
Geological Sciences Department, University of Colorado

G. H. Dunn — Graduate Committee, Department of Physics

JILA Shops Committee

Member, several thesis & examinations committees

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Physics Department, University of Colorado

Graduate Advisor for:

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Physics Department, University of Colorado

R. Robertson
Physics Department, University of Colorado

G. Schinn
Physics Department, University of Colorado

K. B. Gebbie

Thesis Committee for:

D. Haber
Astrophysical, Planetary and Atmospheric Sciences Department, University of Colorado

JILA Executive Committee

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Chairman, Thesis Committees for:

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Physics Department, University of Colorado

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Physics Department, University of Colorado

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Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

S. McCandless
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

S. Voels
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

S. R. Leone

Chairman, Graduate Admissions Committee, Department of Chemistry

Final Ph.D. Defense Committee for:

G. Lin
Physics Department, University of Colorado

JILA Executive Committee

J. L. Linsky

University Space Science and Policy Task Force

Search Committee for a faculty position in Theoretical Astrophysics, Department of Astrophysical, Planetary, and Atmospheric Sciences

Thesis Committees for:

T. Bastian
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

UNIVERSITY AND DEPARTMENT COMMITTEE MEMBERSHIPS

Quantum Physics Division (525)

Linsky (cont.)

P. L. Bornmann
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

J. Neff
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

S. Saar
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

D. J. Nesbitt

Co-Chairman, JILA Colloquium Committee

JILA Data Center Advisory Committee

Library Committee, Department of Chemistry

Faculty Secretary, Department of Chemistry

Organizing Committee, Physical Chemistry Workshop

D. W. Norcross

JILA Executive Committee, January 1985 - December 1986.

Chair, JILA Computing Committee

Comprehensive Exam Committee, Department of Physics

JILA Data Center Advisory Committee.

Computing Committee, Department of Physics

Thesis Committee for:

T. Gorczyca
Physics Department, University of Colorado

UNIVERSITY AND DEPARTMENT COMMITTEE MEMBERSHIPS

Quantum Physics Division (525)

A. V. Phelps — Thesis Committees for

- J. F. Benage
  Physics Department, University of Colorado
- R. H. Chatham
  Physics Department, University of Colorado
- J. Doyle
  Physics Department, University of Colorado
- M. O'Callaghan
  Physics Department, University of Colorado
- R. M. Robertson
  Physics Department, University of Colorado
- G. Schinn
  Physics Department, University of Colorado
- G. Lin
  Chemistry Department, University of Colorado

S. J. Smith — Member, JILA Executive Committee

Member, Chemical Physics Committee, Department of Physics

Member, JILA Building Committee

GRADUATE STUDENTS AND POSTDOCTORAL RESEARCH ASSOCIATES SUPERVISED

Quantum Physics Division (525)

	Graduate Students	Postdoctoral Research Associates
P. L. Bender	J. H. Lyou S. D. Swartz S. J. Walter	M. A. Vincent
G. H. Dunn	S. Jefferts M. Schauer K. Timmer E. Wahlin	B. DePaola N. Djurić K. Rinn D. Swenson
J. E. Faller	P. Keyser M. McHugh T. Niebauer	
A. C. Gallagher	S. Davidson J. Doyle X. Han M. O'Callaghan R. Robertson G. Schinn	H. Chatham J. Kelly
J. L. Hall	M. Rayman M. Winters M. Zhu	J. M. Chartier C. Salamon N. C. Wong
D. G. Hummer	C. Hackman S. McCandliss S. Voels Y. Xu	D. C. Abbott
S. R. Leone	K. Carleton (NSF) L. Cousins W. Hess K. Knutsen G. H. Lin J. Smedley C. Taatjes E. Woodbridge	V. Bierbaum (25%) W. Bussert D. J. Donaldson (NSERC) R. Dressler R. Fletcher H. Meyer D. Sonnenfroh (NRC) K. Yamasaki

GRADUATE STUDENTS AND POSTDOCTORAL RESEARCH ASSOCIATES SUPERVISED

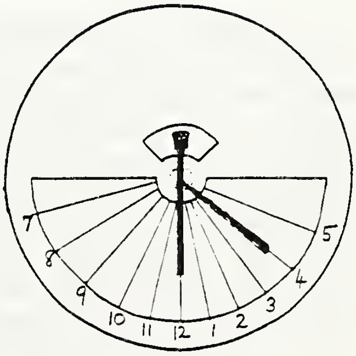
Quantum Physics Division (525)

	Graduate Students	Postdoctoral Research Associates
J. L. Linsky	P. Bornman J. Neff S. Saar	C. Armbruster J. Bookbinder A. Brown J. P. Caillault K. Carpenter S. Drake
D. J. Nesbitt	C. Lovejoy A. McIlroy A. Schiffman M. Schuder	
D. W. Norcross	T. Gorczyca H. Zhou	S. Alston J. Mitroy F. Parpia A. Pradhan
A. V. Phelps		B. Jelenković D. Scott B. Wedding
S. J. Smith	K. Arnett	A. Charlton M. Hamilton L. Westling

COURSES TAUGHT AT UNIVERSITY OF COLORADO

Quantum Physics Division (525)

J. L. Hall	Laser Stabilization - Physics 696
S. R. Leone	Chemistry 550 - Chemical Dynamics (Spring 1986)
	Physical Chemistry Laboratory Course - Development and construction of new experiments
D. J. Nesbitt	Chemistry 558 - Quantum Chemistry (Fall 1986)
D. W. Norcross	Recitation - Physics 111 (Fall 1985)
	Recitation - Physics 112 (Spring 1987)
S. J. Smith	Physics 112 - Elementary Physics



BACKGROUND ON JILA

Quantum Physics is the division through which NBS participates in the Joint Institute for Laboratory Astrophysics, a cooperative enterprise between NBS and the University of Colorado (CU). In collaboration with University faculty and visiting scientists, the Division conducts the kind of long-term, high-risk research on which the Bureau's ability to provide standards, measurements, and data ultimately depends. The Division's objectives include:

- Developing the laser as a refined measurement tool and applying it to tests of fundamental laws of physics such as the postulates of special and general and relativity.

- Improving the theory and instrumentation required to measure astrophysical and geophysical quantities such as the cosmic distance scale, the acceleration of the Earth's gravity, and the long distances involved in determining crustal movements.

- Researching new techniques for measuring interactions involving atoms and molecules, to provide data essential in areas such as nuclear fusion, advanced lighting, and laser development.

- Developing and applying measurement techniques to advance fundamental understanding of microscopic molecular processes such as those that occur in combustion and laser-initiated chemical reactions.

- Interacting with University faculty and visiting scientists to maintain expertise at the forefront of research in physics.

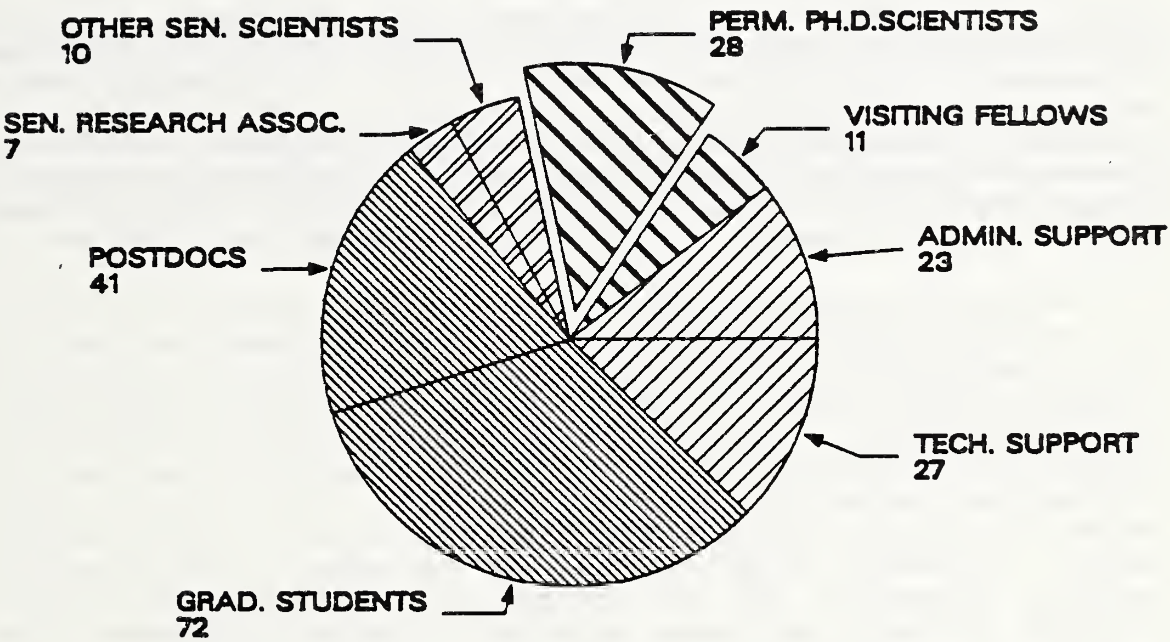
- Transferring the results of its research and the technology developed to the Nation's industries, universities and other government agencies.

- Exchanging ideas and skills with other scientists in NBS through visits, seminars and longer-term interchanges of personnel.

A direct outgrowth of the national space program in the early postwar period, JILA was formed in response to a report of the Space Science Board of the National Academy of Sciences. That report pointed to serious gaps in our basic understanding of the behavior of atoms and molecules in terrestrial, planetary, solar and stellar atmospheres. The unifying theme for the Institute therefore became the physics of gaseous atmospheres. Since then, however, JILA has responded to changing national needs and to the requirements of its parent organizations. Thus the Institute has become a world leader not only in atomic and molecular science and astrophysics but also in precision measurement, laser physics, and certain areas of geophysics.

JILA STAFFING 1896-1987

TOTAL - 219



The permanent senior scientists or "Fellows if JILA", of which there are currently 23, form a governing body that sets policy, subject to review by the Director of NBS and the President of the University. A Chairman, elected every two years by the Fellows, has much the same role as the chairman of an academic department. Assisted by an executive committee, he is responsible for operating the Institute within the policies set out by the Fellows. Of the 23 Fellows, 10 are fulltime faculty members from the Departments of Physics, Chemistry, and Astrophysical, Planetary and Atmospheric Sciences; 13 are NBS employees, of which 12 are in the Quantum Physics Division and 1 is in the Time and Frequency Division. Although these scientists work side by side, sharing facilities and responsibility for the success of the Institute, each remains officially responsible to his respective employer, NBS and its Director in one case, CU and the academic department in the other.

Through their adjoint faculty appointments, NBS scientists at JILA have both the opportunity and responsibility to teach courses and participate in other faculty activities. This gives them access to graduate and undergraduate students, some of whom become interested in pursuing research directed toward NBS goals. Of 72 graduate students in JILA, 38 are supervised in their research by NBS scientists; of 41 postdoctoral research associates, 24 work with NBS scientists. Some have subsequently joined NBS and now occupy positions of leadership; others are carrying the knowledge and skills acquired at NBS to the Nation's industries, universities and other government agencies. Of over 100 graduate students and research associates supervised by NBS staff at JILA during the past 8 years, 20% are now in industry, 20% in government agencies, and the remainder largely in universities.

Besides the graduate students and postdoctoral research associates, the Visiting Fellows Program is probably the single most important factor in maintaining an atmosphere of change and excitement in JILA. The Program provides partial funding for some ten internationally distinguished scientists a year to spend up to twelve months at JILA collaborating with resident scientists. Since its inception 24 years ago, the Program has become internationally renowned. More than 220 senior scientists from 29 foreign countries as well as the U.S. have participated. The number of applicants exceeds the number of positions typically by a factor of four; in accordance with the Memorandum of Understanding, applicants are chosen according to scholarly achievement, demonstrated interest in the scientific and technical objectives of JILA, and the recommendations of their peers.

For NBS and University researchers alike, perhaps the greatest attraction of JILA is the large concentration of scientific talent in atomic and molecular physics and closely related areas. Neither institution, with its broad responsibility for measurement in one case and for education in the other, could justify such a large number of senior scientists in a single area. Together these researchers are able to collaborate, exchange ideas and attract visiting scientists in a way that would be impossible for two smaller groups operating separately.

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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report summarizes the research and technical activities of the Center for Basic Standards during the Fiscal Year 1986. These activities include work in the areas of electricity, temperature and pressure, mass and length, time and frequency, quantum metrology, and quantum physics.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Astrophysics; atomic and molecular physics; chemical physics; electrical standards; fundamental constants; gravity measurements; laser physics; length standards; mass standards; pressure and vacuum standards; temperature standards; time and frequency standards; X-ray and gamma-ray wavelength standards

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