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Technical Activities 1987

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Center for Basic Standards
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U.S. DEPARTMENT OF COMMERCE, Clarence J. Brown, Acting Secretary
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ABSTRACT

This report summarizes the research and technical activities of the Center for Basic Standards during the Fiscal Year 1987. 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, 1986 to September 30, 1987. 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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TECHNICAL ACTIVITIES: ELECTRICITY DIVISION
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INTRODUCTION AND OVERVIEW

The Electricity Division (ED) concerns itself with 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 primary 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 systems; 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 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) for weapons systems, 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 measurement 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.

In practice, the Division's work falls within two major categories: (1) electrical dissemination services; and (2) fundamental electrical measurements. The focus of the former is the maintenance and dissemination of the basic electrical quantities such as voltage, resistance, and capacitance; that of the latter the realization of the SI electrical units and the development of standards based on phenomena such as the quantum Hall effect. An introduction and overview to electrical dissemination services immediately follows this introduction and overview of the Division.

The principal projects in the fundamental electrical measurements category are Realization of the SI Ampere, Realization of the SI Farad and Ohm, Josephson Voltage Standards, Quantized Hall Resistance, Gamma-P and the Fine-Structure Constant, and Fundamental Constants Data Center. (Details of the objectives, current activities, FY 87 accomplishments, and future plans for these and two other projects in this category are given in individual reports following those for the electrical dissemination services projects.)

The two principal goals of the above projects are (1) to determine the best possible values in SI units for the Josephson frequency-voltage quotient 2e/h and the quantized Hall resistance $R_H = h/e^2$; and (2) to put into place and bring to a highly efficient operational state improved and new apparatus to maintain the U.S. Legal Volt via the Josephson effect, the U.S. Legal Ohm via the quantum Hall effect, and the U.S. Legal Farad via the NBS calculable capacitor. The motivation is that the Consultative Committee on Electricity (CCE) of the International Committee of Weights and Measures (CIPM) plans to meet in September 1988 to adopt a new value for 2e/h consistent with the SI, and a value for R_H consistent with the SI, to be used by all national standards laboratories, starting January 1, 1990, to define and maintain their national representations of the volt and ohm, respectively. This will lead to about a 9 ppm increase in the U.S. Legal Volt and about a 1.6 ppm increase in the U.S. Legal Ohm. While these changes in the U.S. legal units will be disruptive for the user community, the long-term benefits of international uniformity of electrical measurements and their consistency with the SI should outweigh the considerable cost of implementing the changes.

There has been good progress in all of the fundamental electrical measurements projects this year as the individual project reports attest. Especially noteworthy is the development of a Josephson array voltage standard system to maintain the U.S. Legal Volt (it is now done on a weekly basis since Feb. 1987 with an uncertainty of less than 0.02 ppm); the discovery of the cause of a gross systematic effect in the NMR portion of the proton gyromagnetic ratio (gamma-p) experiment; and the completion publication, and wide distribution of the 1986 least-squares adjustment of the fundamental physical constants. In general, all projects are now on the threshold of yielding useful results for the CCE to consider in adopting a new value for 2e/h and a value of $R_H = h/e^2$; and in establishing the means for maintaining routinely the U.S. legal units for voltage, resistance, and capacitance with high accuracy as well as consistency with the SI.

ELECTRICAL DISSEMINATION SERVICES: SUPPORT AND OPERATION
INTRODUCTION AND OVERVIEW

The goal of the work in this category is to enable all measurements of electrical quantities performed in the U.S. 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 calibration and MAP (measurement assurance program) 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. Moreover, 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 its sophisticated measurement capability, reflected in automatic ATE systems and high-quality electronic instrumentation. Advances and progress in these areas can be limited by measurement constraints, such as the nonavailability of electrical instruments of adequate accuracy. This condition can only be avoided if NBS maintains a strong R&D program to ensure the availability of adequate electrical measurement methods and standards for the instrumentation industry.

The measurement services offered by NBS in the electrical area include the calibration of primary standards of direct or DC voltage, direct current or DC resistance, impedance at audio frequencies, and alternating current and voltage, as well as MAP services for DC voltage and DC resistance. Some measurements are also done on AC ratio standards of the highest accuracy (inductive voltage dividers). In FY 87, 28 MAP transfers and approximately 2494 calibrations will have been performed on 1348 basic standards, as detailed at the end of this introduction and overview, for a total income of about $865 K for the year.

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 it Measurement Requirement and Education and Training Committees and interactions at regional meetings, as well as the National Workshop and Symposium.

In recognition of the problems likely to occur following the January 1, 1990 changes in the U.S. Legal Volt and Ohm, a committee has been formed to write and disseminate guidelines to assist the technical community in making the adjustments required to bring their instrumentation, standards, and procedures into compliance with the changes. The committee has met twice, approved a detailed outline for the guidelines, and is in the process of gathering background information. In the committee's view, action required of standards laboratories is straightforward. However, the magnitude of the change in the volt is large by comparison with the intended accuracies of much modern test equipment and some control systems as well. The most difficult part of the committee's job is to address situations germane to high-accuracy instrumentation and systems with embedded software control where the units, especially the volt, are incorporated in the software in a way transparent to the user and perhaps not recognized as such by the designer. Where possible, such situations and appropriate remedial action will be given via examples. The goal is to have a complete document, ready for "plugging in" the final values of the changes, by October 1988 when those values are finally decided. A first draft is to be completed by January 1988. The committee currently has 20 members representing various sectors of industry and government and seven from NBS. Electricity Division members participating in the committee are N. B. Belecki (Chairman), R. F. Dziuba, B. F. Field, and B. N. Taylor.

The military, 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 and projects funded by that Group.

Measurement services support activities fall into two broad categories: (1) the development of improved measurement methods and standards; and (2) the automation of the measurement systems used to carry out both calibrations and MAPs.

Work in the first category is directed toward improvement of the processes by which the electrical units are maintained, scaled, and disseminated. In the DC voltage area, the emphasis is on converting to the use of Josephson arrays to maintain the U.S. Legal Volt and on improved dissemination by developing advanced solid-state standards based on Zener diodes. The thrust in the DC resistance area is to improve scaling from the U.S. legal unit at 1 Ω to 1000 Ω and 6453.2 Ω for the SI ohm and quantized Hall resistance experiments, respectively. Both cryogenic current-comparators and Hamon devices are being employed in this effort. In the impedance area the focus is replacing aged bridges with new bridges that take advantage of modern electronics. One of these, an automatic capacitance bridge to replace the 1957-vintage Type-2 bridge, is nearing completion. In the AC-DC difference area, which supports AC voltage and current 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 second or automation category, several of the hardware systems have been completed; future activities are aimed at the construction of complex software systems to collect and analyze calibration data. This activity is particularly heavy in the voltage and AC-DC difference areas. The DC resistance automation activity has increased this year due to increased staff; work is progressing on three systems to calibrate resistance standards at the 10-k Ω level, in the range 100 Ω to 1 MΩ (somewhat less accurately), and in the range from 10^9 Ω up.

Details of the objectives, current activities, FY 87 accomplishments, and future plans for DC Voltage, DC Resistance, Impedance, and AC Voltage and Current are given in the following four project reports.

Estimated Calibration Workload -- FY 87

SP-250 51100's Resistance Measurements

521 Standard Resistors and Shunts
4 MAP Transfers

54100's Precision Apparatus

26 Inductive Voltage Dividers (44 tests)

52100's Impedance Measurements

188 Standard Inductors (277 tests)
163 Standard Capacitors (274 tests)

53100's DC Voltage Measurements

88 Standard Cell Enclosures (361 cells)
25 MAP Transfers
23 Unsaturated Cells
39 Zener-diode Based Standards (68 tests)

53300's Electrical Instruments (AC-DC)

51 Standard Thermal Converter Instruments (1144 points)

Estimated FY 87 Billing $865,000

DC VOLTAGE
[B. F. Field, M. R. McCaleb, J. E. Sims, Liu Ruimin (GS)]

OBJECTIVES: To disseminate the U.S. Legal Volt to industry and government laboratories via MAPs (measurement assurance programs) and the calibration of customer standards; to support the DC voltage needs of standards laboratories (and NBS), especially at 10 V, through research and development of calibration apparatus and improved voltage standards. Continuous research and development is required to support the increasingly accurate instrumentation available to industrial users.

CURRENT ACTIVITIES: (1) Calibration of customer standard cells sent to NBS, (2) operation of a DC voltage MAP at 1.018 V, (3) calibration of customer solid-state (Zener) standards at voltages other than 1.018 V, and (4) R&D on improved Zener standards. Items (1)-(3) require accurate (0.01 ppm) comparisons of customer or transport standards to NBS reference cells and the maintenance of a stable/predictable volt. Automated measurement systems are being used for these comparisons while the AC Josephson effect provides a reproducible volt. Item (4) consists of developing improved, transportable, solid-state standards with 0.05 ppm short-term stability at 10 V and 1.018 V. Improved solid-state voltage standards are needed to support increasingly accurate DC calibrators (4 ppm basic DC accuracy) that are now commercially available.

ACCOMPLISHMENTS: All NBS DC volt calibrations are now handled by one full-time person using three automated measuring systems; one for customer standard cells, one for MAPs, and one for solid-state references. We have simplified the software for the data analysis and added new quality control procedures. We replaced an unreliable Interdata minicomputer with a more modern VAX minicomputer and converted all the software needed to produce calibration reports to run on the VAX.

The month-to-month fluctuations of the volt have been reduced, and the reliability and ease of maintaining the volt will be improved because we are using a Josephson array and have completed two new standard cell enclosures. In February 1987 we started to maintain the U.S. Legal Volt using a series-connected array of Josephson junctions producing 1 V directly instead of a two-junction 100/1-ratio potentiometer system. Since the new system is easier to use, these measurements are now done weekly. The new standard cell enclosures are of the Cutkosky/Field design but with modernized control circuits. After cells are installed these will supplement our primary and working cell groups, replacing an inadequate commercial enclosure now in use.

Documentation of the standard cell calibration service is under revision and will be submitted for publication as an NBS Special Publication 250.

This year we completed a new automated measuring system for solid-state references to support an increasing solid-state calibration workload and to free the original system for Zener research. This additional system is a modified version of the original model developed at NBS. We also constructed, tested, and delivered four systems for the DoD. While at NBS all six systems (4 DoD, 2 NBS) were thoroughly compared and their results agreed to 0.03 ppm, well within their individual estimated uncertainties of 0.075 ppm (1σ).

In February 1987 we hired M. R. McCaleb to replace a departed staff member. He is vigorously pursuing a research program for the development of a transportable Zener standard. As part of this program the original automated Zener measurement system was refurbished by replacing the computer, revising the software, and constructing new mechanical and electrical fixtures to permit the testing of a large number of Zener diodes and 10/1.018 volt voltage dividers.

We have developed a set of guidelines for the design of solid-state DC voltage standards that detail what we believe is required in a modern voltage standard to supplant present standards based on standard cells. These guidelines were developed at the request of the DoD and submitted to them for comments. The guidelines may be used either to guide the design of future commercial products or the purchase of a standard and they are in the process of being published as an NBS Technical Note.

Based on the above guidelines we are developing a transportable solid-state voltage standard that should be capable of transferring the volt between two laboratories with an uncertainty of 0.1 ppm (1σ) or less. The basic design has been completed and we are currently testing diodes, voltage dividers, temperature control circuits, and other components for inclusion in the prototype. We are planning to use temperature-compensated Zener diodes mounted in TO-5 metal cans; fifty-six high-quality diodes have been obtained and specially mounted. Our previous tests of glass-packaged diodes have shown that their output voltages permanently shift anywhere from 2 to 30 ppm when they are subjected to temporary gross temperature changes (>10 °C).

A seventh seminar on MAP's for electrical quantities was held in San Jose, CA in October 1986. The 42 attendees participated in five days of lectures and hands-on workshops using computer-aided instruction covering statistics, voltage metrology, quality-control techniques, and NBS MAP procedures.

FUTURE PLANS: We will continue periodic review of the measurement systems and procedures for dissemination of the NBS volt. The VAX software will be revised as staff time permits to reduce further the time required for production of calibration reports.

For the development of transportable solid-state standards, two research paths will be pursued simultaneously, with the first aimed at providing a short-term solution. A design has been completed for a prototype standard using only existing available parts (references, dividers, etc.). If initial tests indicate that building a standard based on this design would be useful, several standards will be built and evaluated. Some of these may be used for a DC MAP at 10 V and 1.018 V and to replace deteriorating NBS standard cell transport enclosures.

The second part of the program, which will initially be of lower priority than the first, will concentrate on a longer-term solution. The three main parts of this solution will be as follows: (A) Current research indicates that resistive dividers contribute significantly to the instability of commercial standards. We will investigate scaling procedures, especially time-division dividers, and develop a substantial competency in this method. (B) We will develop algorithms to deal with "out-of-tolerance" references within multiple-reference standards to optimize the predictability of the "average" voltage of the standard. (C) We will continue to look into Zener diode packaging problems and eventually investigate problems specific to the solid-state physics of Zener diodes.

DC RESISTANCE
[R. F. Dziuba, P. A. Boynton, T. P. Moore, J. D. Neal, H. S. Winters]

OBJECTIVES: To maintain and to disseminate the unit of resistance for the U.S. Our goal is to provide industrial, educational, and governmental laboratories with state-of-the-art, accurate, and reliable resistance measurement services that are delivered in a timely, professional manner. To achieve this goal it is necessary to develop new and improved resistance standards and measurement techniques.

CURRENT ACTIVITIES: We calibrate resistors of decade values ranging from 10^{-4} to 10^{12} Ω. They are compared with NBS primary standards of the same nominal value. Resistance transfer standards, commonly known as Hamon boxes, provide accurate ratios of 10:1 and 100:1 for intercomparing our primary standards between different resistance levels. Special Hamon boxes are used to compare the NBS ohm to the 6453.20 Ω quantum Hall step. Improvements in our resistance scaling process will result in lower NBS uncertainties for customer and NBS calibrations. Completion of a cryogenic current comparator bridge will help to verify our scaling process.

The NBS ohm as embodied in our 1-Ω reference bank is about (1.60 ± 0.30) ppm less than the SI ohm as realized by calculable capacitor experiments. The NBS ohm drifts at a rate of about -(0.06 ± 0.02) ppm/year compared to the 6453.20 Ω-level of the quantized Hall resistance. Improvements in resistance scaling techniques will help pinpoint the value and drift of the NBS ohm to a few hundredths and a few thousandths of a ppm, respectively. This will affect the international adjustment of representations of the SI ohm planned for 1990.

Automation of the ring resistance bridge method will reduce the turn-around-time for calibrating customer Rosa-type resistors from 100 Ω to 1 MΩ. Automation of the 10 kΩ and capacitance-discharge high megohm customer calibration systems are also underway.

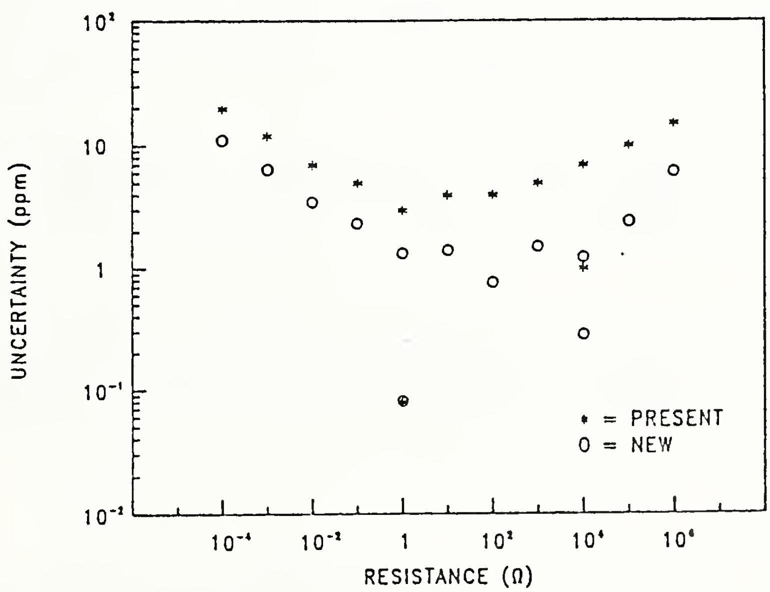
ACCOMPLISHMENTS: The figure compares the present and new NBS uncertainties for the various resistance levels. These new uncertainties will become effective before the end of CY 87 and are based on extensive measurements and uncertainty reevaluations carried out during the past year in connection with the documentation of our calibration services.

Our 1 Ω reference bank of resistors has been thoroughly analyzed; the results indicate seasonal variations of some resistors of a few hundredths ppm. We may be seeing the end of the useful life of these original Thomas 1 Ω resistors.

We determined the loading effect from 10 mW to 1 W for two Thomas 1 Ω resistors that are critical components in the new NBS determination of the proton gyromagnetic ratio.

We completed two special in-house transfers from 1 Ω to the 6453.20 Ω quantum Hall step as part of our collaborative effort with the quantum Hall effect group to monitor the stability of the NBS ohm.

CALIBRATION OF STANDARD RESISTORS



We repackaged and thoroughly characterized eight 10 kΩ standards to be used for international comparisons with other national laboratories in order to check scaling accuracy, and for MAP calibrations for U.S. clients.

We constructed a 1 kΩ/step Hamon resistance transfer standard to replace one that had a significant load coefficient. This improves our resistance scaling from 100 Ω to 10 kΩ and will reduce the uncertainty associated with scaling errors for customer 10 kΩ standard resistor calibrations.

We completed construction of the automated ring resistance bridge for comparing nominally-equal resistors from 100 Ω to 1 MΩ. We are comparing results obtained from this system to those obtained from the present DRRS (direct reading ratio set) bridge method. Differences between the results of the two methods have always been well within the NBS uncertainty.

FUTURE PLANS: Publish an NBS Technical Note on the NBS calibration service for DC standard resistors.

Complete the automation of the modified Kelvin bridge for comparing NBS and customer 10 kΩ standard resistors to a precision of 0.01 ppm. These measurements at the 10 kΩ-level constitute our second heaviest workload (next to the Thomas 1 Ω measurements) with over 1500 measurements/year. Completing this system will complete the automation of customer calibrations from 1 Ω to 1 MΩ.

Complete a prototype of the automated capacitance-discharge measurement system for high value resistors. This system will meet the demand for resistor calibrations above 1 TΩ.

Participate with other national laboratories in an international comparison of 1 Ω standards at BIPM in preparation for the adjustment of the ohm planned for 1990. Spearhead an international comparison at the 10 kΩ-level using NBS resistors.

Continue to collaborate on monitoring the stability of the NBS ohm using the quantum Hall effect. Collaborate with those involved in the absolute ohm experiment in order to determine a value for the NBS ohm in SI units.

Investigate the possibility of establishing a project to develop a new class of transportable DC resistance standards. The goal would be to develop standards that are less susceptible to environmental factors such as temperature, humidity, vibration, and shock as are existing standards.

IMPEDANCE
[Y. M. Chang, G. R. Jones, Jr., C. R. Levy, S. Tillett, G. Zdral (PSC)]

OBJECTIVES: To maintain working standards for impedance measurements, and related calibration facilities, in order to provide calibrations of client impedance standards - capacitors, inductors, inductive voltage dividers (IVDs) - over the broad range of values and frequencies and at the levels of accuracy required by the U.S. user community; to improve NBS capabilities in order to meet the current and future needs for impedance measurements of this community.

CURRENT ACTIVITIES: These include construction and testing nine capacitance bridges to automate and upgrade NBS calibration capability as well as that of the primary standards laboratories of the DoD and DoE; replacing obsolete equipment with modern electronic instrumentation to reduce calibration time and maintenance costs; documenting the impedance calibration services; re-establishing the capacitance MAP service at the 1 nF level to permit users of 1 nF-standards to achieve an accuracy of 1-2 ppm; and completing two bridges to calibrate inductors at frequencies up to 100 kHz. A variation of the classical Maxwell-Wien design, they employ IVDs and dynamic Wagner ground networks which also supply the bridge power.

ACCOMPLISHMENTS: The first four capacitance bridges have been completed except for the mounting of reference capacitors and tuning of the current pumps used to prevent loading of the primary transformers. A contract has been recently let to New Systems Technology Corp. to complete the construction of the last five of the nine bridges. The remaining work on the first four bridges - adjusting the current pumps used to prevent transformer loading, installing the fused-silica reference capacitors, and calibrating the bridges - is currently underway.

To upgrade the overall capability of the impedance laboratory, tests are being run to replace the old generator and detector used with the Maxwell-Wien inductance bridge with a new synthesizer, amplifier, and a phase-locked detector. A new oscilloscope and a counter for general use have been ordered, tested, and accepted. A new automated commercial capacitance bridge was also ordered. While it was intended for testing as a possible MAP standard, it has been used for trouble-shooting and component testing. Another will be ordered by the end of the FY. Testing was completed on the automated thermometer bridge bought last FY and the bridge is now in regular service. New benches have been received and installed along with new power circuits.

Documentation covering the calibration of standard capacitors and inductive voltage dividers is complete except for the error analysis, most especially in the case of inductive voltage divider calibrations. The capacitance documentation is being reviewed by Y. M. Chang, a new staff member. All documents are being polished in preparation for publication, provided the uncertainty analyses can be handled in a satisfactory manner.

A commercial capacitance bridge (Andeen-Hagerling Model 2500) was demonstrated at NBS last autumn and appeared to have transport uncertainties smaller than 1 ppm. The largest discrepancy from NBS values seen in the measurement of various capacitors in the lab was 0.8 ppm, the A-H measured values being based on a 2-year old calibration of another bridge through the Air Force primary standards laboratory. An A-H 2500 was bought and checked by using it to measure check standards immediately after their calibration with the NBS Type-2 Bridge. A discrepancy at 100 pF in the A-H 2500 and changes in results when co-axial chokes are used are being investigated. The bridge's response to temperature and humidity changes is being measured.

A meeting was held with representatives of ESI and LCIE (the French national standards laboratory in the electrical area) about the new ceramic capacitors to be made by ESI France and the measurement capabilities required to support their incorporation into automated capacitance test equipment systems to be made in the U.S. We await a prototype of these improved capacitors since they could be the basis for an improved transport standard. However, an earlier ceramic-dielectric capacitor from ESI France was evaluated using the A-H 2500 and found to have a high humidity dependence.

Calibration measurements were made on the ground network for one of the new inductance bridges to determine the digital-to-analog converter settings required for the network to produce the appropriate voltage ratio for each of the values of inductance needed to be calibrated. Software to do the tests was written. Several wiring problems with the ground circuit have been identified and are being corrected. The current effort is focused on finalizing the ground circuit.

FUTURE PLANS: Complete installation of capacitors, calibrate, and test four capacitance bridges. Complete construction, less reference capacitors and ovens, of five other automated capacitance bridges.

Replace the line conditioner used for powering various capacitance and inductance bridges in the impedance lab. Install a phase-locked amplifier system as a detector for the Type-2 capacitance bridge, and improve the bath used to contain the fused-silica reference capacitors. Prepare for the incorporation of the new automated capacitance and inductance bridges into the calibration service.

Publish capacitance, inductance, and inductive voltage divider calibration documentation as NBS Internal Reports. Document the new inductance bridge and automated capacitance bridge.

Finish testing the A-H 2500 as a transport standard by shipping it to several standards labs. If these tests indicate its suitability as a transport standard, reinstate the capacitance MAP service. Test prototype ceramic-dielectric capacitors as received.

Complete the ground circuit for the new inductance bridge. Complete assembly of and begin testing the prototype bridge.

AC VOLTAGE AND CURRENT
[J. R. Kinard, C. B. Childers, J. R. Hastings, T. E. Lipe, Ti-Xiong Cai (GS), T. G. Nordin (GS)]

OBJECTIVES: To establish and maintain NBS primary and reference standards for AC-DC difference; to maintain working standards of AC-DC difference and related comparator systems in order to provide calibrations of AC-DC difference for client thermal voltage and current converters (TVCs and TCCs); and to support the needs of standards laboratories using state-of-the-art AC digital meters and calibrators by conducting research and development into improved methods and apparatus.

CURRENT ACTIVITIES: These include improving the NBS primary, reference, and working standards of AC-DC difference and their associated measurement systems, the study and fabrication of TVCs for use in the megahertz region to provide reduced calibration uncertainty, construction and testing of an automated TCC comparator system, preparation of user orientated documentation, and arrangement of an international TVC intercomparison.

ACCOMPLISHMENTS: Significant improvements have been made in the AC-DC difference calibration service this past year. As a result of a continuing study of the NBS primary, reference, and working standards of AC-DC difference, the uncertainties for the calibration of TVCs and TCCs have been reduced. The uncertainties have been lowered by as much as 50 %, depending on the voltage, current, and frequency involved. Almost all uncertainties for voltages below 100 V up to 1 MHz have been reduced. The complete matrix of the new uncertainties and calibration ranges is given in the table.

Due to the development of new automated comparator systems and an expanded inventory of working thermoelements, the need for scheduling calibrations on a queue, which was as long as nine months, has been eliminated. Calibration requests are now essentially accepted on demand.

Two projects are well underway which are aimed at not only the production of new knowledge regarding TVCs and TCCs, but also the publication of tutorial notes directed specifically to the user community. The first project concerns the recharacterization of TVCs after thermoelement replacement and will provide a method and algorithm for laboratories to determine new AC-DC differences without the complete recalibration of a TVC set. The second study concerns the interaction of current shunts and thermoelements. A guest scientist, Mr. T. Nordin, supported by Holt Instruments Laboratories, Inc., is conducting this latter effort. He has also assembled the first version of an automated comparator system for TCCs.

Considerable progress has been made in the characterization of TVCs in the megahertz region. A guest scientist, Mr. Ti-Xiong Cai, from the Shanghai Institute of Testing Technology, P.R.C., is contributing to both the theoretical and experimental work on this project. A semi-automated comparator system has been built, and measurements are being taken in the range 100 kHz-100 MHz on newly constructed and existing TVCs. Close coordination and liaison is maintained with Mr. Gregorio Rebuldela at the NBS Boulder Laboratory for this work.

A document has been prepared describing the NBS standards and methods used to support the AC-DC difference calibration service. Publication is expected later this year, probably as a part of the Special Publication 250 series.

An initial step has been made in a program to provide travelling thermal-converter standards to support in-house checking of a laboratory's TVC and TCC calibration capability. A multirange TVC has been transported to the Navy Primary Standards Laboratory East in Washington, DC, and the results of the exchange are being studied. The instrument will be sent to additional labs if it proves to be suitable.

Arrangements have been made for an international intercomparison of coaxial TVCs in the 1 MHz region between NBS and the National Institute of Metrology and Shaoxing Industry Research Institute, China. The converters have been characterized but plans to have the instruments hand-carried to China became impractical. The transfer will go ahead as soon as appropriate arrangements can be made.

FUTURE PLANS: Continue work on user-oriented tutorial notes regarding recharacterization of TVCs after thermoelement replacement and the combination of AC-DC differences for passive shunts and thermoelements. Proceed with theoretical and experimental studies of TVC structures in the 1 MHz region. Prepare a tutorial short course on AC-DC measurements for presentation at the Measurement Science Conference in January, 1988. Begin the study of new multijunction-thermal-converter working standards and amplifier-aided designs. Continue the program of visits and consultations with major users including DoD laboratories. Transport travelling standards to additional laboratories for evaluation. Ship coaxial TVCs to Mr. Huang Di-Xiang at Shaoxing Industry Research Institute and to Mrs. Zhin Zhin at the National Institute for Testing Technology, China. Maintain accurate and timely AC-DC difference calibration service.

AC-DC DIFFERENCE CALIBRATION SERVICE

Frequency:	2-5 Hz	5-20 Hz	20-20k Hz	20-50 kHz	50-100 kHz	0.1-0.5 MHz	0.5-1 MHz
Voltage Limits(V)	50	100	1000*	1000	1000*	100	100
Current Limits(A)	0.05	0.05	18[a]	16			
UNCERTAINTY (parts per million)[b]							
Multirange TVCs							
> 100 V			50	70	100		
≦ 100 V	200	100	30*	50*	70*	100*	200*
Coax Single Range							
TVCs > 100 V			20	30	50		
5 V ≦ x ≦ 100 V	200	100	15[c]*	25*	40*	100*	200*
< 5 V	200	100	20	30	50	100*	200*
Special[d]							
5 V ≦ x ≦ 100 V			10				
TCCs							
> 5 A			100	150*			
50 mA < x ≦ 5 A			50	70*			
≦ 50 mA	200	100	50	70*			

*Indicates reduced uncertainty or extended voltage range, compared to the previous NBS calibration service.

[a]5 A at 20 Hz, increasing to 18 A from 100 Hz to 5 kHz; 16 A above 5 kHz. 20 A shunts are calibrated at less than rated current.

[b]The lower uncertainty applies at the crossover frequencies. Uncertainties may be increased if the AC-DC differences are large or affected by self-heating or other instability.

[c]20 ppm from 20 Hz to 100 Hz, 15 ppm at 100 Hz and above.

[d]Normally available by prearrangement for coaxial, single range TVCs between 100 Hz and 20 kHz. An additional cost and a longer turnaround time at NBS are required.

REALIZATION OF THE SI AMPERE

[P. T. Olsen, R. E. Elmquist, with G. R. Jones, Jr., W. D. Phillips, E. R. Williams]

OBJECTIVES: To realize the SI definition of the ampere to an accuracy of one part in 10^7. A realization of the SI ampere with a given uncertainty is equivalent to determining the Josephson frequency-voltage quotient 2e/h in SI units to essentially the same uncertainty.

This experiment is critical because measurements of various fundamental constants indicate serious inconsistencies between past direct realizations of the ampere and indirect determinations based on such 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 provide the Consultative Committee on Electricity (CCE) the means to select a new, international value for 2e/h to be used worldwide for maintaining representations of the volt starting January 1, 1990.

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 magnetic 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 (i.e., field generating) coil. Second, we measure the force exerted on the movable coil by the field-generating coil 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 in the movable coil, 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 voltage-displacement/time (i.e., velocity) measurement.

ACCOMPLISHMENTS: The installation of a new movable (or suspended) coil made a dramatic improvement in the measurement of force as well as some improvement in the voltage-velocity ratio. The original suspended coil was designed for the superconducting magnet field-generating coil which can provide a magnetic field 100 times stronger than the present oil-cooled room-temperature field-generating coil. It became apparent from early measurements that with a few refinements, the apparatus could yield a competitive measurement without the superconducting magnet. The new suspended coil readily allowed an increase in the force by a factor of 10 and a decrease in the scatter of the voltage measurements by a factor of 3. The new suspended coil alone reduced the typical standard deviation of the mean of a single weighing measurement from 1-2 ppm to 0.1-0.3 ppm. Likewise, the standard deviation of the mean of a single voltage measurement went from a typical 0.8-1.2 ppm to 0.3-0.5 ppm.

A considerable amount of electronic damage occurred when the Non-magnetic Building was struck by lightning. The main computer and interface unit never satisfactorily performed again. It became necessary to replace that computer with a dedicated unit. This replacement consumed well over a half year during which ampere measurements were not possible.

The intervening time was used to improve greatly all the electronics associated with the experiment and to construct and introduce various pieces of automation equipment. As a result, the weighing and velocity measurements are fully automated, and the apparatus to allow switching between measurement modes is currently being constructed.

A new balance wheel with optically polished quartz inserts has been installed. Bands consisting of sixty filaments of a platinum-tungsten alloy feed off tangentially from the quartz inserts to support each side load.

FUTURE PLANS: Statistically, the present ampere apparatus has the potential of producing an ampere result with an uncertainty of about 0.5 ppm. But we must convince ourselves that the result is in fact the truth and contains no significant systematic error. To do this, many measurements will be made under a wide variety of experimental conditions; perturbations will be deliberately introduced into the experiment and unexpected changes studied. Within the year, we expect to be able to report a result to the CCE with an uncertainty considerably less than 1 ppm based on the room-temperature magnet. We will then reduce the uncertainty by about an order of magnitude by installing the superconducting magnet since it will enable the force to be increased from 100 g to 1 kg and the voltage from 20 mV to 1 V.

REALIZATION OF THE SI FARAD AND OHM
[J. Q. Shields, L. H. Lee, with G. R. Jones, Jr., H. P. Layer (523)]

OBJECTIVES: 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 SI or 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 NBS calculable capacitor was completed a number of years ago and is the most accurate 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 refurbishing, re-evaluating, and using this equipment for a new determination of the absolute farad and ohm with slightly improved accuracy. Other activities include maintenance of the NBS unit of capacitance (the U.S. Legal Farad) at the 10 pF level, and participation in international comparisons of capacitance and resistance standards.

ACCOMPLISHMENTS: The voltage source and detector systems for the NBS calculable capacitor have been completely modernized with a new synthesizer, power amplifier, isolation/step-up transformer, pre-amplifier, phase-sensitive detector, and computer for data acquisition and analysis. Various parts of the optical interferometer system have been significantly upgraded to provide finer, more continuous adjustments for the tilt of the bottom interferometer flat and for the laser beam direction, expansion, and collimation.

A recently replaced laser tube showed 1 x 10^{-9} stability over a two week period. Calibration of the laser is made while in operation using a transportable, iodine-stabilized He-Ne laser provided by H. Layer of the Length and Mass Division which the system is designed to accommodate.

The overall calculable capacitor system is now such that daily measurements of a 10 pF, transportable capacitor can be made following one or two days start-up and preliminary measurements. The standard deviation for approximately five hours of measurements is 0.005 ppm. This is about three times greater than would be expected from the precision of the detector system alone and apparently results from calculable capacitor changes. Although the average of the two cross capacitors should be constant, the individual capacitors can and do change significantly due to slight changes in temperature and the force of the PTFE guide ring. In addition, smaller changes in the average of the two cross capacitors are present and are believed to result mainly from changes in the nonuniform response of the PZT/photo-transducer system.

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 considerably less than 0.1 ppm by mid CY 88. Subsequent work will concentrate on reducing the uncertainties in the measurements to the one or two parts in 100 million level (if possible) and to improving and otherwise upgrading the apparatus to make the measurements easier to carry out. This is especially true for the determination of the 10 pF transportable capacitor against the calculable capacitor since this is the approach which will be used routinely to maintain the U.S. Legal Farad even after the implementation of the quantized Hall resistance as the means for maintaining the U.S. Legal Ohm starting January 1, 1990. 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 (the Australian National Standards Laboratory) is also planned, and possibly comparisons between NBS and other national laboratories as well.

JOSEPHSON VOLTAGE STANDARDS
[R. L. Steiner, B. F. Field, J. Toots]

OBJECTIVES: To maintain the NBS or U.S. Legal Volt to an accuracy of 1-2 parts in 10^8 via the AC Josephson effect in superconductors; to conduct associated research, e.g., to refine the procedures and test the components for an optimum volt-maintenance system, to simplify the DC voltage calibration of high precision digital voltmeters, and to fabricate superconducting devices for voltage standard applications. There is close collaboration on these secondary objectives with the Electromagnetic Technology Division's Cryoelectronics Group, NEL-Boulder, the Physikalisch-Technische Bundesanstalt (PTB), West Germany, and the Electrotechnical Laboratory (ETL), Japan.

Meeting these objectives provides not only improvements in the maintenance of the NBS volt, but also better accuracy in national voltage measurements through coordinated industrial and military use of similar voltage calibration systems.

CURRENT ACTIVITIES: A new DC volt-maintenance system is now used to maintain the U.S. Legal Volt. This system is based on a Josephson array device of over 2000 junctions, as fabricated by the Boulder group. Under millimeter wave (70-100 GHz) irradiation, the device generates many thousands of quantized voltage steps proportional to the frequency, where the assigned ratio is $2e/h = 483593.42\ \text{GHz}/V_{NBS}$. With the array generating 1.018 V, commercial Zener reference standards are calibrated. This allows weekly calibration of the primary and secondary standard cell baths (used to calibrate client standards) through the fully automated cell measurement system.

The array system's performance and accuracy when employing computerized voltage step selection and various types of microwave sources, digital voltmeters (DVMs), and low thermal switches is being analyzed to optimize the system's general ease of use, cost effectiveness, and accuracy. Other array devices of different designs and materials, which were fabricated by Hypres, Inc. and the Electrotechnical Laboratory (ETL) of Japan, have been received for testing.

Since the Josephson array is capable of generating many voltages, it can be used as a highly accurate voltage divider. The array system has been used to calibrate several resistive divider networks. Work on an automated procedure to calibrate the linearity and gain of several types of DVMs with better than 6 digit precision is under way.

ACCOMPLISHMENTS: Since February 10, 1987, the Josephson array has served as the basis of the NBS volt. Figure 1 shows the calibrated average value of standard cell groups 17 and 1500. When fitted to the predicted linear drift in the cells, the standard deviation of the measurements is 0.015 ppm. The measurement system has been semi-automated to record and analyze data, and to standardize the operation and monitor run errors. A weekly calibration of the standard cell groups is now done with only about two staff hours total time expenditure. The previous operation took about 16 staff hours and was thus performed once a month at most.

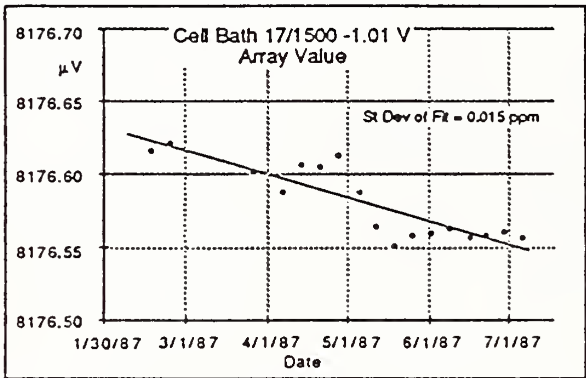


Figure 1

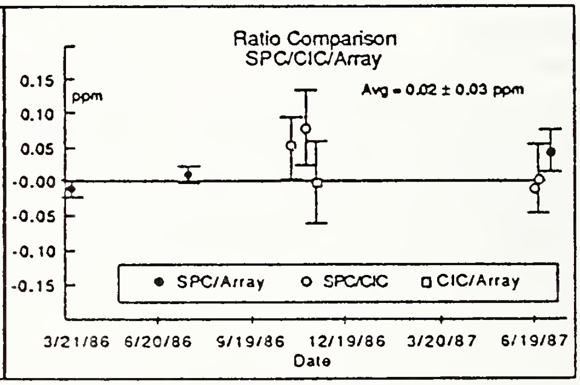


Figure 2

The Boulder Josephson array has been proven to be linear to within about (0.02 ± 0.03) ppm (Fig. 2) in tests against two independent resistive 100:1 divider networks. One, a Cascade Interchange Comparator (CIC), is a self calibrating string built up from matching consecutive resistors (10 Ω:10 Ω, 10 Ω + 10 Ω:20 Ω, etc.). The second, a Series-Parallel Comparator (SPC), is based on a Hamon network of ten 100 Ω resistors. This instrument was used previously as part of the regular volt-maintenance system. It originally showed a discrepancy when compared to the array of about 0.15 ppm, until a 0.15 µV thermal offset error was traced to a bad connection in the SPC. A series of tests between all three instruments compared the relative ratios of each resistive network and the array device, from 10.18 mV to 1.018 V. All three agreed within a standard deviation of 0.03 ppm, which is the typical measurement error for the available resistive dividers.

A preliminary procedure for the calibration of high precision DVMs using an array has been defined and tested. A number of steps from -1 V to +1 V are selected by a computer. Then the voltages measured directly by the DVM under test are used to calculate its gain and linearity error. An 80 point test takes about 30 minutes, with very minimal operator adjustment (of microwave power). This is a significant time savings over standard procedures, further enhanced by eliminating the need to calibrate a resistive reference divider. The fact that the array voltages are calculable values makes all this possible.

The final commercial 1 ppm voltage standard developed for the Calibration Coordination Group (CCG) of the DoD has been completely tested and shipped to the Navy Western Standards Laboratory. A probe with a tested replacement Josephson device is undergoing final leak testing before shipment to the Navy Eastern Standards Laboratory.

FUTURE PLANS: Maintenance of the U.S. Legal Volt using the Josephson array system will continue. A second complete array system is being built. This will serve as a backup for the system dedicated to volt maintenance, an independent system for periodic checks of the primary system, and a research tool for testing new components and measurement techniques, e.g., DVM calibration. Also, a direct comparison of two side-by-side systems will help establish the actual measurement accuracy of array-based systems.

Collaboration with NBS Boulder, PTB, and ETL will continue. System modifications will be worked out should the new 10 V arrays produced by Boulder be successful. Any improvements in electronic components will be coordinated to keep the NBS Boulder and Gaithersburg laboratories compatible.

Further development of the DVM calibration routine will proceed. Programming instructions for a variety of voltmeters is necessary. Also needing study is the compatibility between the array and some voltmeters. Those DVMs with problem characteristics such as input terminal noise or insufficient isolation from ground may require modifications to the measurement system.

The thin film laboratory vacuum systems will be repaired. With some modifications to the existing deposition systems, it should be possible to resume fabrication of superconducting films, including attempts at new high transition temperature films.

QUANTIZED HALL RESISTANCE

[M. E. Cage, C. T. Van Degrift, Dingyi Yu (GS), with R. F. Dziuba, W. J. Bowers (522)]

OBJECTIVES: To develop a resistance standard based on the quantum Hall effect (QHE) with an accuracy of 0.01 ppm to serve as the basis for the NBS or U.S. Legal Ohm (Ω_{NBS}); to determine the fine-structure constant α to the same and unprecedented accuracy, thereby rigorously testing quantum electrodynamic (QED) theory.

The QHE has the potential of providing the most accurate QED-independent value of α, as well as an SI or absolute resistance standard based on fundamental constants of nature. It would thus permit a definitive test of QED as well as allow NBS to maintain the U.S. unit of resistance continually to very high accuracy in SI units. Moreover, through the Consultative Committee on Electricity (CCE), the QHE will become the international basis for national representations of the ohm starting January 1, 1990.

CURRENT ACTIVITIES: The method involves measurements of R_H, the quantized Hall resistance (QHR) in a two-dimensional electron gas realized in the inversion layers of GaAs/AlGaAs heterojunction devices when they are cooled below 4.2 K in the presence of a strong magnetic field perpendicular to both the current flow (I) and the Hall voltage (V_H). At each Hall step the resistance $R_H = V_H/I$ is quantized, and can be expressed as $R_H = h/e^2 i = \mu_0 c/2\alpha i \simeq 25{,}812.80/i\ \Omega$, where h is the Planck constant, e is the elementary charge, i is a quantum number, μ_0 is the permeability of vacuum, and c is the speed of light.

Currently we are: (1) using an 8 T magnet and the QHE to monitor the national unit of resistance; and (2) assembling a new QHE laboratory, including a sample preparation facility, which will allow us to monitor the national unit of resistance with a 13 T magnet and 0.3 K ^{3}He refrigerator system while enabling us to expand our basic research using a second system capable of attaining magnetic fields of 15 T and temperatures down to 30 mK with a dilution refrigerator.

ACCOMPLISHMENTS: We have constructed, tested, and used a new automated QHR measurement system that potentiometrically compares R_H with nominally-equal, temperature-controlled, wire-wound reference resistors R_R. The typical total root-sum-square one-standard-deviation uncertainty is 0.007 ppm, three times smaller than for our automated QHR bridge system. The new system has three independent levels of electrical shielding and thus the exceptional leakage resistance of $3 \times 10^{12}\ \Omega$.

We continued to monitor Ω_{NBS}; its drift rate is still about -0.054 ppm/year.

The QHE Working Group of the CCE requested that the national laboratories submit a set of suggested guidelines for making reliable QHR measurements. We submitted a lengthy document separated into two sections: (1) sample handling and characterization tests (cool-down procedures, contact resistance measurements, temperature and current dependence measurements, and flatness of the Hall steps); and (2) tests of QHR measurement systems (leakage resistance measurements, detector gain and linearity problems, and sample-reference resistor interchange errors).

A large fraction of FY 87 was devoted to the design, construction, installation, and testing of components for the new QHE laboratory. There are seven different vacuum systems, as well as gas-handling facilities for

^4He, ^3He, Ar, and N_2 gases. A vacuum control panel and gas distribution system was built and tested. This enables us to interconnect and coordinate all the vacuum and gas systems, and to monitor them with a residual gas analyzer. The large collection of vacuum lines required for the mechanical pumps, diffusion pumps, turbo-molecular pumps, control panels, etc., was completed and leak tested.

There will be a top-loading ^3He-^4He dilution refrigerator for the 15 T research magnet and a ^3He refrigerator for the 13 T standards magnet. Detailed designs were completed for both refrigerators; they will be nearly identical so that the ^3He refrigerator can be upgraded to a dilution refrigerator if the need ever arises. The dilution refrigerator is being assembled and vacuum tested.

The design work was completed for the vacuum-extraction sample probes. Most of the components for six probes have been machined. The probes for the research magnet and the standards magnet will be identical.

Standards-quality QHR samples continue to be difficult to obtain. There are several potential suppliers of heterostructure films grown on single-crystal wafers, but they do not have the time or the incentive to define Hall geometries on the wafers and to make electrical contacts on the samples that remain ohmic at cryogenic temperatures in high magnetic fields. We therefore began the design of, and the procurement of the parts for, a sample preparation facility to perform these tasks.

FUTURE PLANS: The 13 T standards magnet has just been delivered. We will thoroughly test it and then use it to make QHR measurements of the $i = 2$ and $i = 4$ Hall plateaus on the same sample. The 15 T research magnet system has not yet been delivered because the vendor has had problems making the most demanding of the four segments. They are now on the fourth attempt.

FY 88 will be devoted mainly to ensuring that NBS provides the best possible value of R_H to the CCE in preparation for the worldwide adoption on January 1, 1990 of the QHE as the basis for national representations of the ohm. We have achieved our goal of being able to compare R_H with nominally-equal resistors R_R with an uncertainty of less than 0.01 ppm. We will now concentrate on improving the accuracy of the step-down procedure for comparisons between R_R and Ω_{NBS}. Our goal is to reduce this uncertainty to 0.01-0.02 ppm and to tie our measurements as closely as possible to the NBS calculable capacitor realization of the SI ohm.

GAMMA-P AND THE FINE-STRUCTURE CONSTANT

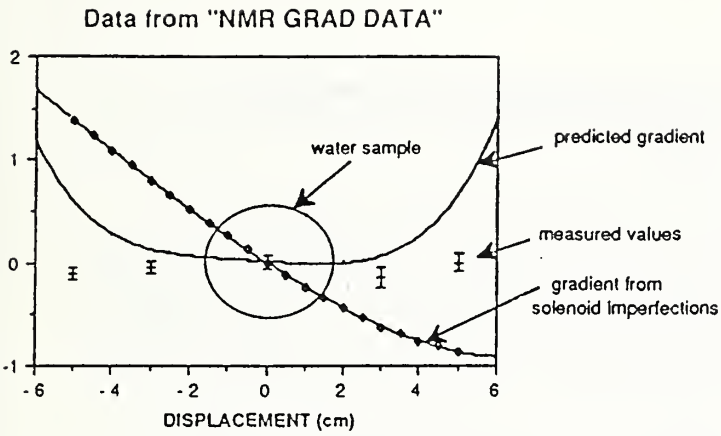
[E. R. Williams, Sheng Ye (GS), H. Sasaki (GS), with G. R. Jones, Jr., P. T. Olsen, W. D. Phillips, V. E. Bower (GS)]

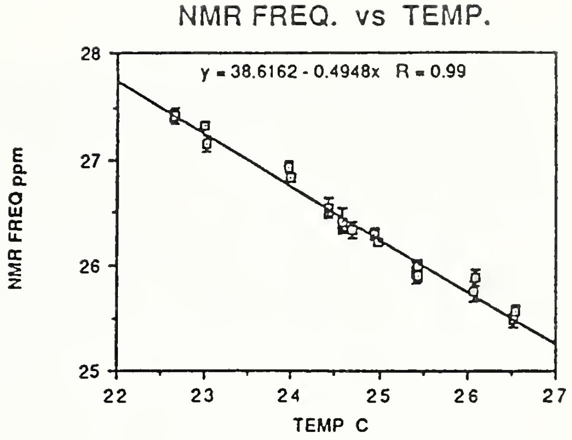
OBJECTIVES: To determine the proton gyromagnetic ratio γ_p' to an accuracy of a few parts in 10^8, thereby obtaining a value of the fine structure constant α to an accuracy of 0.02-0.03 ppm (the prime indicates protons in a spherical sample of pure H_2O at 25 °C). This will extend tests of quantum electrodynamics (QED), the Josephson effect, the quantum Hall effect, and test our ability to monitor and maintain the NBS electrical units. This improved value will be one of the most important contributions to choosing the value of the quantized Hall resistance R_H to be adopted by international agreement through the Consultative Committee on Electricity (CCE) for maintaining laboratory representations of the ohm during the next few decades.

CURRENT ACTIVITIES: The γ_p' experiment has two parts: First, we measure accurately the dimensions of a precision solenoid, so that we can calculate the magnetic field at the solenoid center when we pass a known current through it; second, we measure the NMR frequency of an H_2O sample placed in this field while measuring the solenoid current in NBS units. The ratio of the NMR frequency to the calculated field is γ_p'.

ACCOMPLISHMENTS: At the end of FY 86 we were stymied by a systematic effect that made taking NMR frequency measurements impossible. We finally located the problem; it was caused by a voltage-dependent leakage inside a piece of stone used to hold the return leads to the solenoid. It was difficult to detect because of the low resistance of the solenoid in parallel. Once discovered, it was easy to correct. The system has been steadily improved; we can now obtain 0.02 ppm precision in both the frequency measurements and the transfer-of-current measurements to the electrical standards maintained in the Metrology Building, 1.5 km from our experiment. Figure 1 shows the NMR frequency versus the solenoid temperature plotted as ppm changes in the frequency. Figure 2 shows the measured and predicted magnetic field gradient around the solenoid center. Both are in good agreement with predictions from the dimensional measurements. Now that both the NMR and the dimensional measurements are working, we must combine the two so that they are made nearly at the same time. In fact, we already have a preliminary value for γ_p', but it will not be publishable until a tedious evaluation of possible systematic errors is completed.

In addition to obtaining good NMR results, we have developed a way to eliminate one of the major remaining sources of uncertainty: the possible correction for magnetic impurities in the solenoid coil form. We have demonstrated that the entire solenoid can be measured with a special three-coil probe. With this probe we measured a small section cut from the solenoid at the time of manufacture. We found $\chi = (0.37 \pm 0.05) \times 10^{-6}$ cgs units which agrees with the value measured on a small sample using a SQUID susceptometer. After we complete the other measurements, we will pass our solenoid through this new detector.





In Japan E. R. Williams worked with the ETL on their γ_p' experiment. During his two month stay they introduced the technique used at NBS to eliminate frequency-dependent effects in measuring precision-solenoid dimensions and used NBS programs to improve the field uniformity for their NMR. Unfortunately, the ETL experiment will be limited to an accuracy of about 0.5 ppm by the short length of their solenoid. A similar problem limited the last NBS measurement, but the NBS solenoid was a little longer and cooling fluid allowed some current compensation to increase its effective length so that an accuracy of 0.2 ppm was obtained.

During his stay in Japan Dr. Williams conceived of a new method to measure e^2/h using a storage ring. Dr. T. Tomimasu of ETL has promised one month's use of ETL's storage ring for this experiment including the personnel to run it.

FUTURE PLANS: We expect to have our measurements sufficiently complete that a value can be given in the Conference on Precision Electromagnetic Measurements (CPEM) abstract that we will submit in January 1988. We will continue testing for systematic effects into late spring. We will then disassemble the apparatus so we can pass it through the susceptibility coils. We will present our results at CPEM and, of course, submit a recommended value for R_H to the CCE. We expect the relative uncertainty of R_H to be less than 5 in 10^8.

LASER COOLING AND TRAPPING OF NEUTRAL ATOMS
[W. D. Phillips, P. L. Gould, P. D. Lett, and H. J. Metcalf (GS)]

OBJECTIVES: To develop techniques for and to study the physics of laser cooling and trapping of neutral atoms. Motional effects, such as Doppler and transit time, limit the performance of high resolution spectroscopy. Cooling and trapping of atoms can reduce or eliminate these effects. Our work on neutral atoms is thus complementary to similarly motivated work on ions in the Time and Frequency Division. Cooling and trapping of neutral atoms also opens the possibility for studies in areas such as Bose-Einstein condensation, atomic collisions at unprecedentedly low energies, confinement of neutral antimatter, atom-surface interactions, and manipulation of atoms and atomic beams.

CURRENT ACTIVITIES: We have developed a laser cooling technique which produces continuous or pulsed slow atomic Na beams. Monovelocity beams down to tens of m/s are available, as are stopped atoms with millikelvin effective temperatures. We have magnetically trapped the laser cooled atoms and we have demonstrated deflection and focussing of laser cooled atomic beams.

ACCOMPLISHMENTS: During the past year we have demonstrated the first continuous loading of optical molasses and achieved atomic densities of $10^8/cm^3$, two orders of magnitude larger than has been reported for pulsed loading. The optical molasses is formed at the intersection of three pairs of counterpropagating laser beams. The cooling of these beams is so strong that atomic motion is damped as if the atoms were in a viscous fluid. Atoms reaching the molasses from our continuous atomic beam source "stick" in it for times longer than 0.5 s, resulting in a dramatic build-up of atomic density, to $10^8/cm^3$ or more. The density in the molasses is considerably enhanced by techniques we have recently developed for the enhanced continuous extraction of slow atoms from our Zeeman-tuned laser decelerator.

From simple considerations we can predict how the molasses confinement time should vary with parameters such as laser tuning and the degree of intensity imbalance between the opposing laser beams. We find that the molasses should work best when the laser is tuned about a half linewidth from resonance (where sensitivity to detuning is maximum) and should work very poorly with even small imbalances of a few percent. In fact we find that the optimal detuning is 2-3 linewidths and the molasses is relatively insensitive to imbalance. The performance is generally better than predicted by a simple theory, and more complete theories, taking into consideration strong field effects, do not alter the character of the predictions. At the moment we have no explanation for the anomalous results.

Using our continuously loaded molasses we have loaded a new kind of optical trap. Two opposed, focused laser beams provide a longitudinal, radiation pressure restoring force, while the dipole force provides transverse confinement. Heating due to standing waves is avoided by alternating the two laser beams in time, and cooling is provided by the molasses during times when both trapping beams are off. The trap has a volume of $10^{-4} cm^3$ and so is about 10^3 times larger than the pure dipole trap demonstrated last year at Bell Labs.

We have continued attempts to observe the molasses phenomenon in a vapor cell with no success. After ruling out factors having to do with the optical quality of the windows, tuning errors, and collisions, we are led to speculate that the vapor may be in a non-equilibrium state which is missing very slow atoms. This could be due to a relatively low energy barrier in the atom-surface binding potential. We are considering experiments designed to test this hypothesis.

FUTURE PLANS: We plan further studies of both molasses and the optical trap. Additional measurements to be made on the molasses include the atomic temperature as a function of experimental parameters. Preliminary observations indicate that the temperature is lower than it ought to be based on the simple theory, and this may give a clue to the explanation of the anomalously good results. With the optical trap, we have the entire range of measurements to make, since as of this writing only a first observation has been made. Well depth, lifetime, temperature, confinement, and capture volumes, all need to be measured as a function of experimental parameters.

Both molasses and the laser trap will be used for collision experiments. They offer a unique opportunity to study ultra-low-energy collisions, and we will be looking for associative ionization and radiative association in Na-Na collisions at millikelvin temperatures in collaboration with colleagues from the University of Maryland.

We are also considering, in cooperation with colleagues in the Time and Frequency Division, experiments to test the hypothesis that atoms at sufficiently low energy will reflect specularly from sufficiently cold surfaces. This could lead to a bottle-type frequency standard, but without the variable wall shift problems associated with hydrogen masers.

We also expect to return to experiments on magnetic trapping, especially investigations of laser cooling in traps. These experiments were deferred this past year because of the interesting results with optical molasses.

Finally, work on the use of diode lasers to cool and trap neutral atoms will be initiated with the arrival of NRC Postdoctoral Research Associate R. N. Watts.

FUNDAMENTAL CONSTANTS DATA CENTER

[B. N. Taylor]

OBJECTIVES: To provide an international information center within the U.S. for work in the general area of precision measurement and fundamental constants (PMFC), to analyze the consistency of measured values of the fundamental physical constants resulting from different experiments, and to obtain recommended values of fundamental constants for international use.

This is an important field for NBS because of the close relationship 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. One of the purposes of this project is to provide assistance and guidance in the PMFC area to both NBS staff and university scientists, in particular, to advise them on the potential impact of the experiments they are considering carrying out and to keep them informed of related work currently underway in various laboratories throughout the world.

CURRENT ACTIVITIES: These 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, the NAS/NRC Advisory Committee on Fundamental Constants and Standards, and the Josephson Effect and the Quantum Hall Effect Working Groups of the Consultative Committee on Electricity (CCE); and (4) answering inquiries from both within and without NBS relating to the PMFC field.

ACCOMPLISHMENTS: Extensive material was prepared on the best values of the Josephson frequency-voltage quotient $2e/h$ and quantized Hall resistance h/e^2 for the 17th session of the CCE. After attending the meeting as NBS representative, a talk on its profound results was presented at the annual meeting of the National Conference of Standards Laboratories and a paper prepared for and published in the Jan./Feb. issue of the NBS Journal of Research.

In collaboration with E. R. Cohen, Rockwell International, the 1986 Least-Squares Adjustment of the Fundamental Physical Constants (LSAFPC86) was completed and a report prepared and published as CODATA Bulletin 63 (Pergamon Press, Nov. 1986). The LSAFPC86 represents a major advance over its 1973 counterpart; the uncertainties of the recommended values have been reduced by roughly an order of magnitude due to the enormous advances made throughout the PMFC field since 1973.

Extensive efforts were made to distribute widely the new adjustment and the resulting set of recommenced values. About 400 copies of the CODATA Bulletin were mailed to individual scientists throughout the world. A general news release led to articles in Science, the New York Times, the Christian Science Monitor, Science News, as well as other newspapers, magazines, and journals. The 1986 recommended values were reprinted in their entirety along with a summary of the CODATA Bulletin text in the March/April issue of the NBS Journal of Research. A similar summary with a condensed table of values appeared in the May issue of Europhysics News and will appear in the August issue of Physics Today. A slightly revised version of CODATA Bulletin 63 was prepared for publication in the October issue of the Reviews of Modern Physics. A wallet card giving the 1986 recommended values was prepared and published as NBS Special Publication 731

FUTURE PLANS: The wide dissemination of the new adjustment and set of recommended values will continue.

A more detailed paper on the LSAFPC86 will be prepared and submitted for publication in the Journal of Physical and Chemical Reference Data.

I will prepare for and attend the 1988 Conference on Precision Electromagnetic Measurements (CPEM) to be held in Japan and three associated meetings: that of the CODATA Task Group on Fundamental Constants, the CCE Working Group on the Josephson Effect, and the CCE Working Group on the Quantum Hall effect. New results relating to the fundamental constants will be presented at CPEM 88 and subsequently used to develop improved best values for the Josephson frequency-voltage ratio $2e/h$ and quantized Hall resistance h/e^2 to be used internationally for volt and ohm maintenance purposes, respectively. The Josephson Effect and quantum Hall Effect Working Groups of the CCE will meet at the time of CPEM to review the relevant data and calculate best values.

PRECISION **MEASUREMENT GRANTS**
[NBS Precision Measurement Grants Committee: R. D.Deslattes, J. L. Hall, B. N. Taylor (Chairman), D. J. Wineland]

OBJECTIVES: To award each year two new $30 k Precision Measurement Grants (PMGs) and to renew each year four existing PMGs. (The PMGs are renewable for two additional years beyond the initial year, at NBS' option.)

The NBS PMG program was initiated in 1970 and is funded by the NBS Director. PMGs are awarded to scientists in U.S. academic institutions in order to (1) promote and encourage fundamental research in the field of precision measurement and fundamental constants and train future measurement-oriented scientists, and (2) foster contacts between NBS scientists and those researchers in the academic community who are actively engaged in such work. While NBS has much research underway in this field, there is considerable expertise and relevant work in U.S. 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.

CURRENT ACTIVITIES: PMG candidates are 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 and the Outside Advisory 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 two recipients are selected. The criteria used to evaluate 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 87. 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 and higher degrees in physics (about 850). Good proposals were received from 30 candidates, five of whom were chosen to submit final, full proposals. The following are the two recipients selected, their institutions, and project titles:

Wiley P. Kirk, Texas A&M University
Quantized Hall Resistance and Fine-Structure Constant Investigations: A Study of Uncertainty Contributions

John D. Morgan III, University of Delaware
High Precision Calculation of Helium Atom Energy Levels

The aim of Kirk's research is to investigate mechanisms that contribute uncertainties to the establishment of resistance standards and the determination of the fine-structure constant based on the quantum Hall effect. Three types of error sources will be studied: parallel conduction, temperature-dependent-shifts, and sample dependent effects.

The aim of Morgan's research is the high-precision calculation of the energies of the ground and excited states of the helium atom (or other light helium-like ions) to match the recent advances in experimental laser spectroscopic studies of transitions between these states with a precision of better than 10^{-4} cm^{-1}.

For FY 87, the Outside Advisory Committee consisted of Professors Crampton, Fairbank, Larson, and Ritter.

The following grants were renewed in FY 87: G. Gabrielse, Harvard University, 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; Frederick R. Raab, University of Washington, Atomic Physics Tests of Gravity and the Equivalence Principle; and Daniel R. Stinebring, Princeton University, High Precision Timing of Millisecond Pulsars. The work of Gabrielse was especially successful this year -- he demonstrated the trapping of antiprotons in a Penning trap for the first time (the grant was initially awarded in FY 86).

FUTURE PLANS: FY 88 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 26-31, 1986, San Jose, CA.

INVITED TALKS

N. B. Belecki, "Changes in the U.S. Legal Units of Voltage and Resistance," Los Angeles Chapter, Precision Measurements Association, Los Angeles, CA, Nov. 1986.

N. B. Belecki, "Precautions in the Use of Gas-Dielectric Capacitance Standards," Los Angeles Chapter, Precision Measurements Association, Los Angeles, CA, Nov. 1986.

N. B. Belecki, "History of the U.S. Legal Volt," Symposium for Innovation in Measurement Science, Instrument Society of America, Geneva, NY, August 1987.

M. E. Cage, "The Quantum Hall Effect and its Application as a Resistance Standard," American Physical Society, Williamsburg, VA, Nov. 1986.

M. E. Cage, "The Quantum Hall Effect," Department of Physics Colloquium, Lehigh University, Bethlehem, PA, Dec. 1986.

M. E. Cage, "The Quantum Hall Effect and its Application as a New Resistance Standard," National Conference of Standards Laboratories 1987 Workshop and Symposium, Denver, CO, July 1987.

R. F. Dziuba, "The NBS Ohm: Past-Present-Future," 1987 Measurement Science Conference, Irvine CA, Jan. 1987.

R. F. Dziuba, "The NBS Ohm: Past-Present-Future," 1987 Symposium for Innovation in Measurement Science, Instrument Society of America, Geneva, NY, August 1987.

B. F. Field, "Instrumentation for the Measurement of the Quantized Hall Resistance Standard," Symposium for Innovation in Measurement Science, Instrument Society of America, Geneva, NY, August 1987.

P. L. Gould, "Confinement of Ultra-Cold Atoms in Optical Molasses," Department of Physics Colloquium, University of Connecticut, Storrs, CT, March 1987.

P. L. Gould, "Cooling and Confinement of Atoms Using Laser Radiation," IXth Vivilov Conference on Nonlinear Optics, Novosibirsk, USSR, June 1987.

P. L. Gould, "Laser Cooling and Deflection of Atomic Beams," XIth International Symposium on Molecular Beams, Edinburgh, Scotland, July 1987.

W. D. Phillips, "Cooling, Stopping and Trapping Atoms," NBS, Boulder, CO, Sept. 1986.

W. D. Phillips, "Cooling, Stopping and Trapping Atoms," University of North Carolina, Physics Colloquium, Raleigh, NC, Sept. 1986.

W. D. Phillips, "Radiative Forces on Atoms," Physics Department Colloquium, University of Iowa, Iowa City, IA, Nov. 1986.

W. D. Phillips, "Laser-Cooling and Trapping Atoms," Physics Department Colloquium, Towson State University, Towson MD, Dec. 1986.

W. D. Phillips, "Laser Cooling of Atomic Hydrogen," Workshop on Cooling, Condensation, and Storage of Hydrogen Cluster Ions, SRI International, Palo Alto, CA, Jan. 1987.

W. D. Phillips, "Cooling and Trapping Atoms: Reducing the Motional Limits of Atomic Measurement," American Physical Society, New York, March 1987.

W. D. Phillips, "Optical Cooling and Trapping," National Research Council, Ottawa, Canada, April 1987.

W. D. Phillips, "Historical Introduction to Radiative Forces" Collège de France, Paris, May 1987.

W. D. Phillips, "Laser Cooling of Atomic Beams," Collège de France, Paris, May 1987.

W. D. Phillips, "Optical Traps and Molasses," Collège de France, Paris, June 1987.

W. D. Phillips, "Realization of the Ampere of the Systéme International," College de France, Paris, June 1987.

W. D. Phillips, "New Measurements with Optical Molasses," Eighth International Conference on Laser Spectroscopy, Are, Sweden, June 1987.

W. D. Phillips, "Optical Traps and Optical Molasses," National Physical Laboratory, Teddington, England, June 1987.

W. D. Phillips, "Optical Cooling and Confinement of Atoms," U.S.-Japan Seminar on Quantum Mechanical Aspects of Quantum Electronics, Monterey, CA, July 1987.

R. L. Steiner, "Josephson Arrays," Sandia National Laboratory, Albuquerque, NM, March, 1987.

R. L. Steiner, "Calibration of Voltage Standards Using a Josephson Array," National Conference of Standards Laboratories 1987 Workshop and Symposium, Denver, CO, July 1987.

R. L. Steiner, "Instrumenting Josephson Arrays for Use as Primary Voltage Standards," Symposium for Innovation in Measurement Science, Instrument Society of America, Geneva, NY, August, 1987.

R. L. Steiner, "Maintenance of the U.S. Legal Volt with a Josephson Array at NBS," Electrotechnical Laboratory, Tsukuba, Japan, Sept. 1987.

R. L. Steiner, "The Superconducting Josephson Array Voltage Standard," University of Puget Sound, Takoma, WA, Sept. 1987.

B. N. Taylor, "Possible Changes in the Electrical Units: Report on the September 1986 Meeting of the Consultative Committee on Electricity," National Conference of Standards Laboratories 1986 Workshop and Symposium, Gaithersburg, MD, Oct. 1986.

B. N. Taylor, "Impact of Quantum Phenomena on Fundamental Constants and Electrical Units," XXIInd General Assembly of the International Union of Radio Science, Tel Aviv, Israel, Sept. 1987.

C. T. Van Degrift, "The New NBS Quantum Hall Effect Laboratory," Electrotechnical Laboratory, Tsukuba, Japan, Sept. 1987.

C. T. Van Degrift, "Precision Measurements Using Tunnel Diode Oscillators," National Research Laboratory of Metrology, Tsukuba, Japan, Sept. 1987.

E. R. Williams, "Realization of the Ampere and Determination of the Fine-Structure Constant Based on the Gyromagnetic Ratio of the Proton," XXIInd General Assembly of the International Union of Radio Science, Tel Aviv, Israel, Sept. 1987.

E. R. Williams, "Testing Physical Theories Using Precision Electrical Measurements," Electrotechnical Laboratory, Tsukuba, Japan, Oct. 1986.

E. R. Williams, "Realizing Electrical Standards: A problem in Precision Dimensional Metrology," presented to Committee for Systematizing Nanometer Technology, at the Tokyo Institute of Technology, Ookayama, Japan, Nov. 1986.

PUBLICATIONS FY 87

1. <u>In Print</u>

N. B. Belecki, "Conference on Precision Electromagnetic Measurements," J. Res. Natl. Bur. Stand. <u>91</u>, No. 4, pp. 235-236 (July-August, 1986).

L. 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., <u>IM-35</u>, No. 4, pp. 383-386 (Dec. 1986).

M. E. Cage, "Experimental aspects and metrological applications of the quantum Hall effect," Chapter II in <u>The Quantum Hall Effect</u>, Ed. by R. E. Prange and S. M. Girvin (Springer-Verlag, New York, 1986) pp. 37-68.

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. <u>IM-36</u>, No. 2, pp. 222-225 (June 1986).

E. R. Cohen and B. N. Taylor, "The 1986 adjustment of the fundamental physical constants, a report of the CODATA Task Group on Fundamental Constants," CODATA Bulletin 63, 36 pp. (Pergamon Press, Oxford, Nov. 1986).

E. R. Cohen and B. N. Taylor, "The 1986 CODATA recommended values of the fundamental physical constants," J. Res. Natl. Bur. Stand. <u>92</u>, No. 2, pp. 85-95 (March-April 1987).

E. R. Cohen and B. N. Taylor, "Fundamental physical constants, 1986 adjustments," Europhys. News <u>18</u>, No. 5, pp. 65-68 (May 1987).

E. R. Cohen and B. N. Taylor, "Fundamental physical constants, 1986 CODATA recommended values" (a wallet card giving values of selected constants from the 1986 CODATA set of recommended values), E. R. Cohen and B. N. Taylor, Natl. Bur. Stand. (U.S.), Spec. Publ. 731 (July 1987).

R. F. Dziuba, "The NBS ohm: past-present-future," Proc. 1987 Meas. Sci. Conf., Session VI-A, pp. 15-27 (Jan. 1987).

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. <u>IM-36</u>, No. 2, pp. 258-261 (June 1987).

F. L. Hermach, J. R. Kinard, and J. R. Hastings, "Multijunction thermal converters as the NBS primary AC-DC transfer standards for AC current and voltage," IEEE Trans. Instrum. Meas. <u>IM-36</u>, No. 2, pp. 300-306 (June 1987).

K. B. Jaeger and B. N. Taylor, "U.S. perspective on possible changes in the electrical units," IEEE Trans. Instrum. Meas. <u>IM-36</u>, No. 2, pp. 672-675 (June 1987).

H. J. Metcalf and W. D. Phillips, "Electromagnetic trapping of neutral atoms," Metrologia 22, No. 4, pp. 271-278 (1986).
W. D. Phillips and H. J. Metcalf, "Atomic beams," in 1987 McGraw-Hill Yearbook of Science and Technology, Ed. by S. Parker (McGraw-Hill, New York, 1987), pp. 97-99.

W. D. Phillips and H. J. Metcalf, "Cooling and trapping atoms," Scientific American 256, No. 3, pp. 50-56 (March 1987).

B. W. Ricketts and M. E. Cage, "Quantized Hall resistance measurements at the National Measurement Laboratory, Australia," IEEE Trans. Instrum. Meas. IM-36, No. 2, pp. 245-248 (June 1987).

B. N. Taylor, "Possible changes in the U.S. legal units of voltage and resistance," J. Res. Natl. Bur. Stand. 91, No. 5, pp. 299-305 (Sept.-Oct. 1986).

B. N. Taylor, "Report on the 17th session of the Consultative Committee on Electricity," J. Res. Natl. Bur. Stand. 92, No. 1, pp. 55-61 (Jan.-Feb. 1987). Reprinted in Natl. Conf. Stand. Lab. (NCSL) Newslett. 27, No. 3, pp. 11-40 (July 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, No. 2, pp. 659-664 (June 1987).

2. In Press, In Review, or Nearing Completion

E. R. Cohen and B. N. Taylor, "The fundamental physical constants," Physics Today.

E. R. Cohen and B. N. Taylor, "The 1986 adjustment of the fundamental physical constants," Reviews of Modern Physics.

R. F. Dziuba, "Electricity Division DC resistance calibration services," NBS Special Publication 250.

B. F. Field, "Electricity Division standard cell calibration services," NBS Special Publication 250.

B. F. Field, "Solid-state voltage standard performance and design specifications," NBS Technical Note.

B. F. Field, "Electricity Division solid-state reference calibration services," NBS Special Publication 250.

P. L. Gould, P. D. Lett, and W. D. Phillips, "New measurements with optical molasses," to be published in Laser Spectroscopy VIII, the proceedings of the Eighth International Conference on Laser Spectroscopy (Springer, Berlin, 1987).

P. L. Gould, P. D. Lett, and W. D. Phillips, "Continuously loaded optical molasses," in preparation.

J. R. Kinard, T. E. Lipe, and J. R. Hastings, "Electricity Division calibration services for AC-DC difference," NBS Special Publication 250.

J. R. Kinard and T. E. Lipe, "Recharacterization of thermal voltage converters after thermoelement replacement," NBS Journal of Research.

W. D. Phillips, P. L. Gould and P. D. Lett, "Cooling, Stopping and Trapping Atoms," Science.

W. D. Phillips, P. L. Gould and P. D. Lett, "Electromagnetic manipulation of atomic hydrogen," to be published in the proceedings of the Workshop on Cooling, Condensation, and Storage of Hydrogen Cluster Ions, University of Dayton Special Publication, 1987.

G. Marullo Reedtz and M. E. Cage, "An automated potentiometric system for precision measurement of the quantized Hall resistance," NBS Journal of Research.

B. N. Taylor, "New values for the constants of physics," Physics News in 1987.

B. N. Taylor, "Atomic constants," 1989 McGraw-Hill Yearbook of Science and Technology.

C. T. Van Degrift, S. M. Girvin, and M. E. Cage, "The quantum Hall effect," a Resource Letter for the American Journal of Physics.

E. R. Williams and T. Tominasu, "Measure h/e^2 by counting electrons or ions in a storage ring," Physics Letters.

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 (NCSL) 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 Education Liaison Committee.

N. B. Belecki, Chairman, National Committee on the Changes in the U.S. Legal Volt and Ohm. (R. F. Dziuba, B. F. Field, and B. N. Taylor are also members of the Committee).

R. F. Dziuba, member, Organizing Committee of the 1988 Conference on Precision Electromagnetic Measurements (to be held in Tsukuba, Japan), and Guest Editor for the Conference Proceedings to appear in IEEE Trans. Instrum. Meas. IM-38 (June 1989).

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, 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 and Standards 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 and Standards 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 of Weights and Measures (CIPM).

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 Work 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 the Executive Committee, Conference on Precision Electromagnetic Measurements (CPEM), and Comptroller of CPEM.

B. N. Taylor, Coordinator, Consultative Committee on Electricity (CCE) Working Group on the Quantum Hall Effect and member, CCE Working Group on the Josephson Effect.

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, Y. M. Chang, and C. R. Levy are collaborating with Electro Scientific Industries (ESI) in the evaluation of ceramic-dielectric capacitors for possible use as secondary standards and, more importantly, MAP transport standards.

M. E. Cage, C. T. Van Degrift, and R. F. Dziuba are collaborating with S. M. Girvin of the University of Indiana on the theoretical aspects of the quantum Hall effect.

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

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

B. F. Field is collaborating with a number of companies (John Fluke Mfg. Co., Standard Reference Laboratories, Vahalla Scientific, Yellow Springs Instruments, Compensated Devices) on the evaluation of improved solid-state voltage standards.

B. F. Field is 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 and calibration of commercial 10 V solid-state voltage standards as MAP transfer devices.

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

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

J. R. Kinard is collaborating with personnel from Ballantine Laboratories on the evaluation of coaxial thermal voltage converters.

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.

J. R. Kinard is collaborating with Mr. T. Nordin, C. P. D. Engineering, in the study of current shunt and thermoelement combinations.

J. R. Kinard is collaborating with Mr. D. Stollery, Thermal Techniques Ltd., Essex, U.K., on the improvement of thermal element design.

J. R. Kinard is collaborating with the staff of the Navy Primary Standards Laboratory East on improved methods for the intercomparison of thermal voltage converters.

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, P. D. Lett, 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 is serving on the Program Committee of the Third International Laser Science Conference.

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

W. D. Phillips participated in Panel discussions of "Cooling in Traps" and "Physics in Traps" at the Symposium on Physics of Stored and Trapped Particles, Stockholm, Sweden, June 1987.

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, are collaborating with K. Jaeger, Lockheed Missiles & Space Co., B.Barnaby, Sandia Laboratories, and G. Trinite, Navy Metrology Engineering Division, Corona, CA, on the construction of and operation procedures for Josephson array voltage standards at their respective laboratories.

R. L. Steiner is collaborating with T. Endo of the Electrotechnical Laboratory (ETL), Japan, on the testing of Josephson arrays. He will visit ETL for a week in Sept. 1987 to support the collaboration.

B. N. Taylor is collaborating with E. R. Cohen, Rockwell International, and the CODATA Task Group on Fundamental Constants, on various aspects of data analysis relevant to the fundamental physical constants.

E. R. Williams collaborated with H. Nakamura of the Electrotechnical Laboratory (ETL), Japan, on their proton gyromagnetic ratio and absolute ampere experiments. He received a research fellowship from the Japanese Industrial Technology Association for a two-month stay at ETL in the fall of 1986 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, Yugoslavia, under the U.S.-Yugoslavia Joint Board on Science and Technology.

TEMPERATURE AND PRESSURE DIVISION
SUMMARY OF ACTIVITIES
FISCAL YEAR 1987

DIVISION CHIEF'S OVERVIEW

DIVISION OFFICE ACTIVITIES

The Division secretarial staff and their general responsibilities are as follows:

1) Secretary to Division Chief: S. Ramboz
2) Secretary to Temperature Group: N. McBryde
3) Secretary to Pressure and Vacuum Group: J. Packard

The abrupt retirement of Ms. McBryde at the beginning of the fiscal year was followed by an unsatisfactory replacement and then, late in the fiscal year, by an excellent choice: A. Salazar. Thus, through the extraordinary efforts of the veterans Ms. Ramboz and Packard and the adroitness of Ms. Salazar, the Division was able to cope with an unusually heavy work load which included a bumper calibration year, several special calibration documents, and renovation of office word processing equipment and software. Thanks are due R. Kaeser for his assistance in the last category.

PERSONNEL

This year the Division saw the retirement of Mr. R. E. Edsinger from the gas thermometry program and the reduction in force of Mr. R. B. Dove from the low temperature and vacuum programs. Expansion of Division programs into new areas awaits the success of the Process and Quality Control Initiative for FY 88.

NEW PROGRAMS

For the first time in its history, the Division is employing the instrument of the Industrial Research Fellow to explore new areas of metrology. In fact, two such explorations were launched this past year. The first is in particle detection using super cooled superconductive colloids (A. Druckier, Applied Research Corporation). The second is in a new physical principle (speed of sound) for high temperature measurements (D. Varella, Thermosonics).

NEWS ON EXTANT PROJECTS

As has been the practice in past years, the Division activities are categorized into 7 categories which are reported below.

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 principal goals of the Optical Fiber Thermometer (OFT) program are: (1) to 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 (2) to 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 a basis for the formulation of a more accurate temperature scale over the interval 630 to 1064 °C.

The OFT is rather like an optical pyrometer in which the lens has been replaced by a long, slender light pipe that can be inserted directly into the hot zone of a high-quality blackbody source to capture and transmit the radiant flux. The light pipe (probe) is a single-crystal sapphire rod, nominally 1 mm diameter and 30 cm long. The wavelength interval is defined by a compound narrow-band interference filter (typically an 800 nm peak wavelength with a 25 nm bandwidth). The detector is a silicon photodiode. Because sapphire has a high index of refraction, the probe can capture significantly more flux than the optics of conventional pyrometers and, as a consequence, the OFT has greater sensitivity and can operate to lower temperatures than those instruments. Thus we expect to use the OFT at low temperatures (between the aluminum and silver points) and to compare it with conventional radiometers at temperatures where they are sufficiently sensitive (between the silver and gold points).

In principle, once the OFT is calibrated at a single temperature within its range, it can be used to determine thermodynamic temperatures over its entire range. In practice (excluding that caused by the uncertainty in the numeric value assigned to the calibration temperature) there are three major sources of error which limit its accuracy. In order of importance, these are: (1) uncertainties in the optical properties of the sapphire 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 combined uncertainty in the corrections for the spectral response and nonlinearity is estimated to be less than 100 ppm for the gold to silver freezing-point radiance ratio measured at 800 nm. (This uncertainty corresponds to an error of about 9 mK in the difference between the thermodynamic temperatures of the gold and silver freezing points.)

The optical properties of the probe that are significant for our OFT measurement are: (1) the reflectivity at the air-to-sapphire interface, (2) the attenuation of the transmitted radiant flux due to absorption in the probe, and (3) the 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.

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. The uncertainty in the correction for the reflectivity is estimated to be less than 50 ppm for the gold to silver freezing-point radiance ratio measured at 800 nm. (This uncertainty corresponds to an error of about 5 mK in the difference between the thermodynamic temperatures of the gold and silver freezing points.)

At present, we believe that the dominant source of error is that due to absorption and scattering processes which occur near the cylindrical surface of the rod. The rods are cut from single-crystal sapphire boules and then centerless ground to obtain the approximate diameter before the finishing of the cylindrical surface by either mechanical or flame polishing procedures. The grinding process leaves a finite damage layer of complex microfractures which propagate into the material to a depth (perhaps to several hundred micrometers) that depends upon the details of the operation. This damage layer, which is the major cause of the scattering, must be eliminated in the finishing step. The absorption characteristic of the rod is then due mostly to impurities incorporated into the crystal boule at the time it is grown.

We have developed several simple yet reliable experimental procedures which allow us to determine the absorption and scattering characteristics of the rods as a function of temperature and wavelength. During the last several years, we have examined candidate rods from all known sources using these and a variety of other techniques in order to identify causes of their unsatisfactory optical properties. Taking advantage of the results of these tests, one source has been able to significantly reduce the scattering characteristic of his rods. Rods from this source probably represent the ultimate quality available for the OFT experiments.

Three of these rods exhibit a range of total absorption and scattering which varies from a low value 0.3% (rod#2 at 800 nm) to a high value of 1.5% (rod #1 650 nm) of the flux measured at 850 °C.

Our experiments indicate that the scattering error is independent of both temperature and wavelength and corresponds to about 0.1% of the flux measured. We believe that we can confidently apply the results obtained through room-temperature experiments to estimate the error due to scattering at high temperatures. An estimated uncertainty of 5% in the scattering correction contributes 70 ppm error in the gold to silver freezing-point radiance ratio measured at 800 nm. (This uncertainty corresponds to an error of about 6 mK in the difference between the thermodynamic temperatures of the gold and silver freezing points.)

Our experiments indicate that the absorption error is dependent on wavelength and, unfortunately, tends to increase irreversibly with exposure of the rods in air at temperatures of 1000 °C or above. As a consequence, it will be necessary to continuously quantify the change in absorption of each rod during the course of the OFT experiments. The correction for absorption error is the largest of all and is also the most difficult to estimate. At the present time, we consider the uncertainty in the correction to be about 10%. For rod #2 at 800 nm this estimate contributes 300 ppm error in the gold to silver freezing-point radiance ratio. (This uncertainty corresponds to an error of about 26 mK in the difference between the thermodynamic temperatures of the gold and silver freezing points.) To reach the 20 ppm target accuracy for OFT temperature determination, the accuracy of the absorption experiments must be improved and the technique for estimating the correction must be refined so that the error in the correction is less than 150 ppm.

In August 1987, we will begin a joint experiment with the Radiometric Physics Division to intercompare the NBS gold and silver freezing-point standards used for resistance and thermocouple thermometry with those used for radiation thermometry. The measurements will be made using the NBS OFT together with the NBS Spectroradiometer. In addition, we expect the results to provide a value for the difference between the thermodynamic temperatures of the gold and silver freezing points which is accurate to 50 mK.

In response to inquiries regarding calibration services for commercial OFT'S, we are now prepared to provide "special" calibrations on IPTS-68, which also include a limited evaluation of the absorption and scattering characteristics of the probe.

I.B. HIGH-TEMPERATURE GAS THERMOMETRY

This project involves the evaluation of the differences between the Kelvin Thermodynamic Temperature Scale (designated t) and the International Practical Temperature Scale of 1968 (designated t_{68}). The region of interest is 0 °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 t_{68} by a superior temperature scale.

During the past fiscal year, we completed two types of new gas thermometer measurements to complement those reported last year. One group of new measurements was made using 0 °C gas-bulb filling pressures substantially below the 13.5 kPa pressure that had been chosen earlier as a compromise between minimizing the uncertainty arising from the imperfection of ^{4}He gas and minimizing the uncertainty arising from thermal transpiration in the gas-bulb capillary. In the new measurements, made using 0 °C filling pressures of 10 kPa and 7 kPa, the thermal transpiration corrections became as large as 0.1 °C; nevertheless, the $t-t_{68}$ results agreed well with those obtained earlier. All of the results obtained to date are shown in Figure 1.

A second group of new gas thermometer measurements re-explored the $t-t_{68}$ differences at two defining fixed points of the IPTS-68, the freezing points of Sn (232 °C) and of Zn (420 °C). These measurements were performed in order to further elucidate the small discrepancy discovered earlier between the original measurements at 457 °C published a decade ago by Guildner & Edsinger and the more recent ones that were obtained with somewhat different apparatus. The results, also shown in Figure 1, indicate that the discrepancy is approximately proportional to the Celsius temperature.

As we stressed in last year's report, the largest uncertainty in the results shown in Figure 1 arises from the fact that the thermal expansion of the gas bulb is not well known. During the past year, we have completed the re-construction of a dilatometer that is capable of ppm accuracy at temperatures as high as 700 °C. The apparatus is shown schematically in Figure 2. Temperature homogeneity of the sample chamber is enhanced above 400 °C by the inclusion of a potassium-based heat pipe as a liner for the electrically heated furnace. Preliminary tests indicate that the dilatometer operates in a satisfactory way under either manual or computer control. We have cut five pieces from the gas thermometer bulb used to obtain the data shown in Figure 1, and dilatometric measurements on samples prepared from these pieces are under way. Staffing for the project is now reduced to one person, following the retirement of R. E. Edsinger.

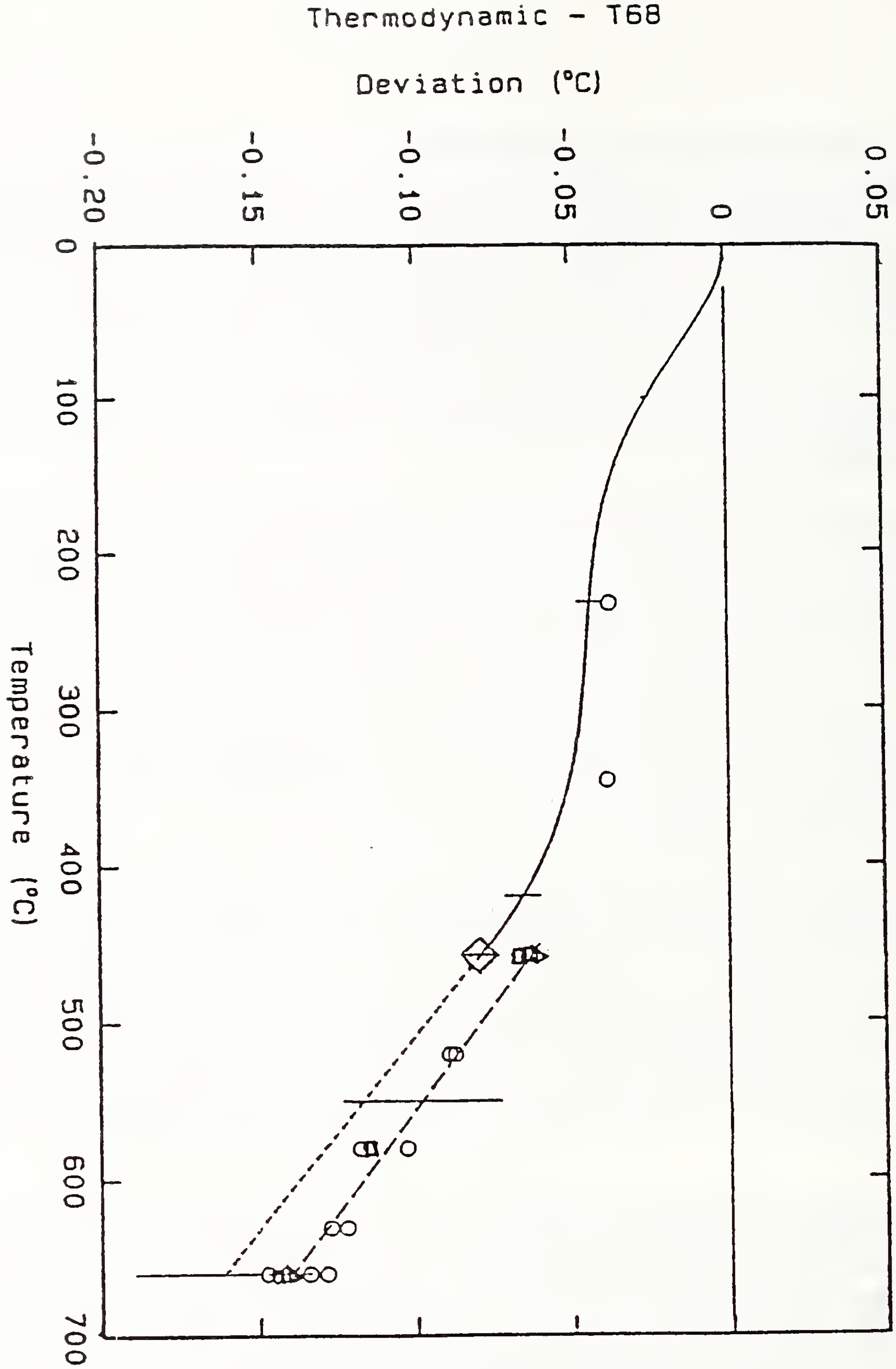


Figure 1. Differences between Kelvin Thermodynamic temperatures and IPTS-68 temperatures ($t-t_{68}$) above 0 °C. Solid line--NBS Gas Thermometry results of 1976. Diamond--Basis value of -0.08 °C at 457 °C currently in use for radiation thermometry determinations at higher temperatures (shorter dashes). Circles--current NBS gas thermometry results with nominal filling pressure 13.5 kPa. Triangles--New results with nominal filling pressure 10 kPa. Squares--New results with nominal filling pressure 7 kPa.

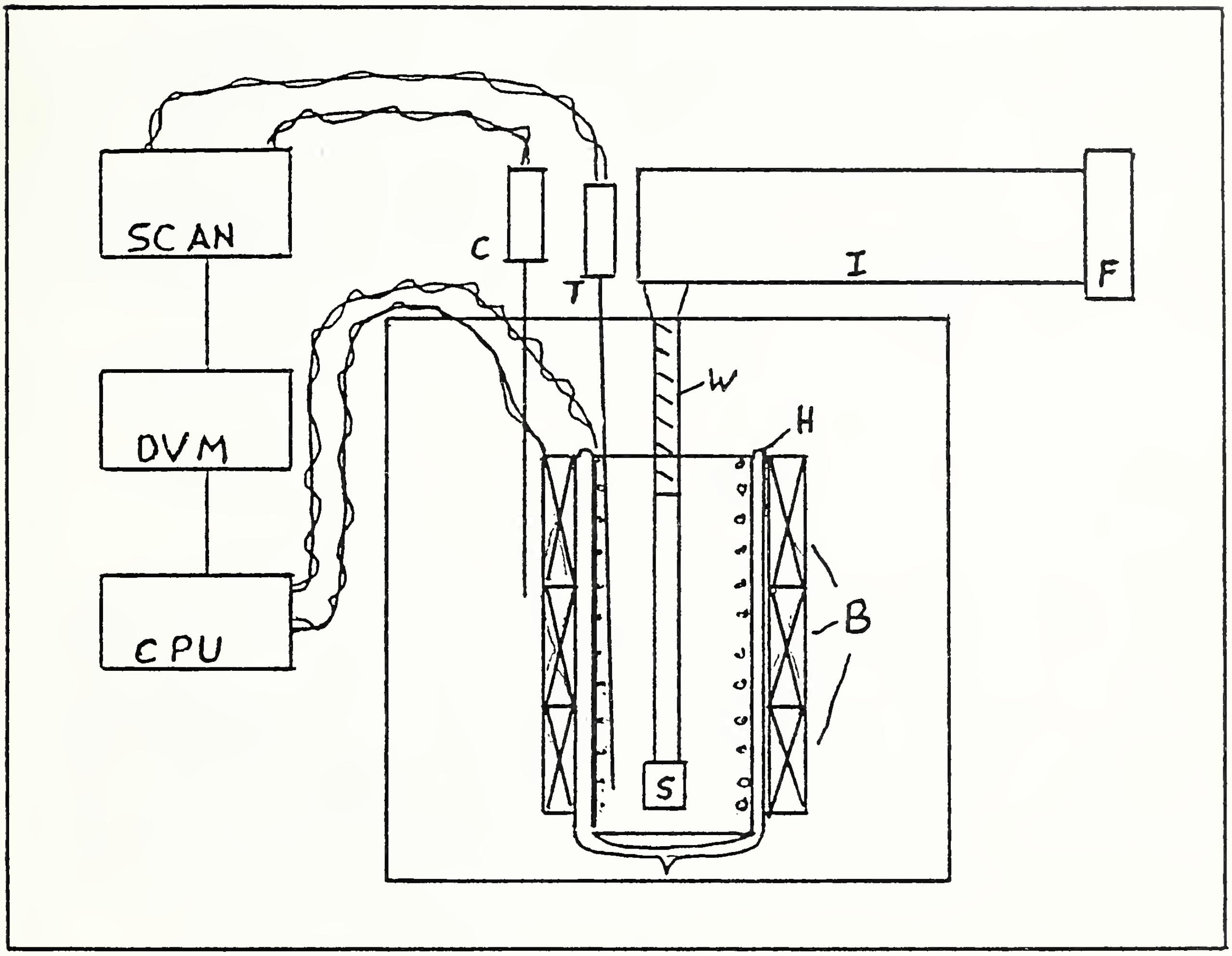


Figure 2. New thermal expansion apparatus. H--Heat pipe surrounding a copper tempering block and the sample assembly S. Bl--Band-type heaters outside heat pipe. W--Fused silica window for viewing sample. I--Merritt-Saunders Fizeau interferometer apparatus with film recorder for interference fringes (F). C--Control thermometer. T--Platinum resistance thermometer to indicate sample temperature. The sample temperature can be stabilized automatically within 0.001 °C of any temperature from about -20 °C to 700 °C

I.C. HIGH-TEMPERATURE PLATINUM RESISTANCE THERMOMETRY

The purpose of this project is to test high-temperature platinum resistance thermometers as a long needed and more precise replacement for thermocouple thermometry in defining a practical temperature scale. It is expected that such devices will be adopted in the definition of the 1990 temperature scale.

The retirement of J. Evans has seriously compromised this program. A reduced program will still be conducted by other Division members as they conduct other temperature scale studies (viz. Reilly on OFT and Mangum on PRT program).

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

1. Routine Calibrations

Approximately 220 thermocouples were calibrated for 100 customers during FY 87 producing approximately $110K in test fees.

2. Non-routine Tests

a. Thermometry for Jet Engines

With support from the U.S. Navy Metrology Engineering Center, NBS is now developing a calibration procedure for the Howell Instruments BH14101-40 JETCAL heater probe. This probe was specifically designed to test the thermocouple harness of T400-CP-400 and T400-WV-402 jet engines. These engines are manufactured by Pratt & Whitney of Canada and are the military version of the PT6T engine. The T400 engine is used in the Navy's UH-IN helicopter which is produced by Bell Helicopter Company. The thermocouple harness is manufactured by SEMCO Instruments, Inc. The probe had been previously designated by the Navy as "difficult to calibrate," due to lack of a reliable standard. This probe has an immersion depth of about one inch and the specified calibration temperature is 900 °C.

During FY 87, candidate "standard" thermocouples of both Type K and Type N were obtained from SEMCO. The thermocouples are enclosed in an Inconel sheath which is 18 inches in length. The location of the measuring junction relative to the sheath end closure has the exact specifications of the thermocouples in the T400 harness. Their length permits these thermocouples to be calibrated directly in the existing NBS metal freezing-point standards, as well as in the furnaces used for the NBS comparison calibrations. A new T400 engine thermocouple harness, plus nine individual engine thermocouple probes (for the PT6T-3 engine) which also have the same junction and sheath end closure specifications as those for the T400 harness were also acquired from SEMCO.

The calibration stability of the 18 inch long, Inconel sheathed, Type K and Type N thermocouples were determined when they were cycled repeatedly and rapidly between room temperature and 900 °C. In addition, such thermocouples were calibrated by comparison with Type S reference thermocouples and their repeatability was determined in the BH14101-40 heater probe. The calibrated thermocouples were fitted with an adapter to provide proper immersion in the heater probe and ensure that the assembly closely simulated the thermal loading of a T400 engine thermocouple. The calibration repeatability of several PT6T-3 engine thermocouple probes was also assessed in the BH14101-40 heater probe.

b. ASTM Committee Work

To assist ASTM Committee E20.04.02 with developing a new standard specification for Type N thermocouple wire, some additional emf stability tests with Type N and Type K thermocouples made from 0.128, 0.064, 0.032, 0.020, 0.0126, and 0.010 inch diameter wire (No. 8, 14, 20, 24, 28,. and 30 AWG, respectively) were carried out in accordance with procedures specified in Draft No. 4 of the proposed ASTM standard, E20-D-16. The emf changes in Type N and Type K thermocouples were determined during heating in air for 24 hours at the upper temperature limits recommended by the ASTM for the particular wire size (as described in section 5.3.4.3 of the proposed standard). In addition, the emf changes of Type N and Type K thermocouples of each wire size were determined when they were thermally cycled between room temperature and 550 °C as described in Section 5.3.4.2 of the proposed standard.

The emf changes in the Type N thermocouples of all six wire sizes after heating them for 24 hours in air at their recommended upper temperature limits were small and ranged from -5 to +37 microvolts (approximately -0.1 to + 1 °C, respectively). The changes found for the Type K thermocouples ranged from +57 to +115 microvolts, depending on the wire size and the test temperature.

A detailed report covering the test procedures and apparatus used and giving the stability data obtained was prepared, and it was presented at the ASTM Committee E20.04.02 meeting on May 14, 1987, in Cincinnati. The test results were used to set and support the allowable emf changes specified for such tests in the standard.

c. Evaluation of Ultrasonic Thermometer Probes

The calibration stability of several ultrasonic thermometer probes made by Thermosonics, Inc. was evaluated in the 1000 to 2400 °C range. Such thermometers operate on the principle that the velocity of sound in a medium is a unique function of temperature. An electrical exciting coil is coupled to a magnetostrictive rod and is used to produce high frequency ultrasonic waves which travel down the length of a temperature sensing rod joined to the magnetostrictive rod. Circumferential notches, which produce reflections of the acoustical waves, are machined in the sensing rod at locations where the temperature measurements are desired. By measuring the time between reflections and correlating it to temperature, a calibration curve is obtained and used to calculate values of temperature from reflection time measurements. Temperature profiles can be easily measured with such thermometers by locating several notches along the length of the sensor rod. Use of this physical principle may lead to more reliable temperature measurements than is presently realized by thermocouples for temperatures above 1800 °C in harsh environments.

The ultrasonic thermometer probes tested at NBS consisted of thoriated tungsten sensor rods (1.6 mm diameter) with notches located at about 5, 9, and 13 cm from the tip of the rod. The sensor rods were welded to 3.2 mm diameter magnetostrictive rods to give an overall probe length of about 90 cm. The sensor rods were protected within a tantalum sheath having a 6.4 mm outer diameter.

The ultrasonic thermometers were tested in helium-gas in a high-temperature calibration furnace. The thermometers were installed in a cylindrical blackbody. The temperature of the blackbody was determined with a transfer-standard optical pyrometer developed and constructed by the IMGC in Torino, Italy.

In this manner, the calibration stability of several ultrasonic thermometers during thermal cycling at temperatures up to 2400 °C was determined versus the blackbody. Their calibrations were found to be repeatable to within about 1/4% in the 1500 °C to 2400 °C range during three successive cycles of the thermometers between ambient temperature and 2400 °C. The calibration stability of one ultrasonic thermometer probe was also determined during heating in helium for 24 hours both at 2000 °C and at 2200 °C. The rate of change of the thermometer calibration was found to be about 0.1 °C/h at 2000 °C and about 1 °C/h at 2200 °C. Post-test examination of the thoriated tungsten sensor rod from this probe with an energy-dispersive X-ray analyzer revealed that it had become contaminated by tantalum transferred from the protective sheath. This contamination may explain the thermometer drift observed. Plans are under way to expand this study by means of an Industrial Research Associate program.

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 SPRT's	Calibrations by comparison against reference standards
78 K to 904 K	Long-Stem SPRT's	Calibrations by comparison against reference standards at 90 K and by use of fixed points (TP of H_2O and FP of Sn and Zn).

In the future, capsule PRT's to be calibrated over the range from 13.81 K to 273.16 K will be calibrated in the EPT-76 automated laboratory instead of in the manually-operated cryogenic calibration system in the PRT laboratory.

The new semi-automated laboratory for long-stem PRT's and for capsule PRT's for use above 90 K is still under construction.

Some specific accomplishments during this FY include:

(1) The documentation of the platinum resistance thermometer calibration service was revised, put in a format for publication as a supplement to SP 250, and will be submitted to the Washington Editorial Review Board (WERB) for publication by the end of FY 87.

(2) Tin and zinc fixed-point cells are used in the calibration of SPRT's and since there was a critical shortage of these in the PRT Laboratory, several new cells of each were constructed. There are 9 new cells (7 for long-stem and 2 for capsule SPRT's) of tin and 7 new cells of zinc, filled with 99.9999+ % pure metals (SRMs 741 and 740, respectively). The new Sn cells were tested during the past year and the testing of the Zn cells will be completed next year. A paper will be written next year on the results of the tests of the Sn and Zn cells.

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

(4) A grand total of 70 SPRT's were calibrated by the end of July of this year and 17 are on hand awaiting calibration. The fees for these 87 SPRT's amount to $142,343.00.

During the calibrations of these SPRT's, 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 SPRT's.

(5) The contract with the Navy (of CCG) for the NBS to evaluate the "best" commercial IPRT's (i.e., non-SPRT's) at temperatures from 0 to 650 °C was completed and a report written.

(6) Two Ag cells, one belonging to NBS (PRT laboratory) and one to IMGC (Italy), were compared directly in heat pipe furnaces moved into and put into operation in the PRT laboratory. This gave us considerable experience in handling and making measurements on HTPRT's at the Ag freezing point (962 °C) and with operating heat pipe furnaces. The NBS cell (Ag-79-1) appears to be significantly purer than the IMGC cell (Ag Lei 3). Analysis of the data is in progress.

(7) A contract with the Navy (of the CCG) for the NBS to evaluate several resistance bridges designed for use with SPRT's was completed and a report written. Four types of bridges were investigated, an F-18 from ASL, an ATB 1250 from Neil Brown Instrument Systems (EG&G), and the two types of Cutkosky automatic bridges from NBS. A brief report on the ac-dc effect as measured at NBS was written also to the CCG.

(8) A fixed point at the melting point of indium is urgently needed for calibration of capsule SPRT's, to provide a more accurate calibration of long-stem SPRT's for the most accurate and precise work needed in research, and to provide a check on the routine calibration of SPRT's. With this in mind, we have been making 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 SPRT's and capsule SPRT's. Each cell contains 1500 g of indium encased in a Teflon inner container located in a stainless steel outer container. These cells will be used in a furnace, currently being constructed, in the PRT Calibration Laboratory to provide a freezing point to be used as a check point in the routine calibration of SPRT's. Data obtained on these cells are currently being analyzed and it is expected that a paper describing the results of the investigation will be written during the next year. Preliminary results indicate the pressure dependence of indium to be 4.95 ± 0.05 mK/std. atm. and the freezing-point temperature to be 156.6341 °C.

(9) The components for a furnace designed for use with the indium cells described in (8) have been constructed and are currently being assembled. When completed, the furnace will be installed in the PRT Calibration Laboratory for use in routine calibrations of SPRT's.

(10) Some furnaces used for pre-heating SPRT's close to the temperatures of calibration prior to their insertion into freezing-point cells are currently being constructed.

II.C. LABORATORY THERMOMETERS

Approximately 760 liquid-in-glass thermometers and 11 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 60.

J. Wise participated in the 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. In recognition of her service to the ASTM, Ms. Wise received the ASTM Order of Merit and was made a Fellow of the ASTM.

A more efficient system of taking data for industrial grade platinum resistance thermometers, using a digital voltmeter and constant current source instead of a high resistance bridge, was developed.

The documentation on the calibration of liquid-in-glass thermometers is being refined for publication.

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 - 0.5 K).

III.A. EPT-76: TEMPERATURE SCALE

As has been described in previous annual reports, the EPT-76 temperature scale has been realized by E. R. Pfeiffer. He has completely "wrung out" the system and is preparing an NBS Journal of Research article describing the system.

Calibrations on EPT-76 requested this FY were deferred to FY88 to allow E. Pfeiffer to devote full time to emergency preparation and testing of Zn and Sn freezing point cells urgently needed for the platinum resistance calibration laboratory; and for a comparison of NBS and IMGC silver freezing point cells.

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.

Because of time distractions (editing of ASC-86 Proceedings and High-Temp Gas Thermometry) there was no activity in the SRM 767a project during FY 87.

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 international temperature scale from 1 mK to 500mK by the CCT when the next scale is formulated. A brief position paper was submitted at the CCT meeting in June. The general outline of this paper, that of using two absolute thermometers (noise and nuclear orientation) to define the pressure-temperature curve of the melting curve of ^{3}He, was accepted by the CCT. Intercomparisons among national standards labs would be conducted by a round robin using special SRM 768 units. The NBS program adds to this the use of a pseudo-thermodynamic thermometer--the nearly ideal paramagnetism of cerium magnesium nitrate (CMN). Progress is the four thermometer-areas this year is given below.

1. SRM 768

Ten regular SRM 768 units were assembled, measured and prepared for customers. This will still leave a backlog of two for FY 88.

Since NBS is to be the hub of a round robin using SRM 768 to intercompare cryogenic temperature scales, three special SRM 768 units (each contained in shields of cryoperm-10 and Nb) were constructed. One has been tested twice, the others will be studied in FY 88.

2. CMN Thermometry

A CMN thermometer was designed and constructed last FY. This past year, an auxiliary gas handling system and a SQUID susceptibility bridge were built and tested by J. Colwell and W. Fogle. The complete system will be ready for testing in September 1987. A theoretical analysis of the expected response time and sensitivity of the CMN thermometer was conducted by W. E. Fogle.

3. ^{3}He Melting Curve Thermometry

As was reported last FY, two melting curve thermometers were tested. One performed very poorly (very unstable), while the other exhibited almost all the qualities needed (it was deficient on long-term stability). Therefore, this FY, a more robust device was tested in three thermal cycles. To its examiner's (J. Colwell) disappointment, it too exhibited instabilities. More rigorous tests were developed and applied to quantatively characterize the instabilities.

4. Noise Thermometry

The major advance this year was the demonstration (R. J. Soulen, D. Van Vechten, Phys. Rev., August 1987) that a <u>very</u> accurate, physics-based model applies to the measured <u>impedance</u> of the R-SQUID which forms the noise thermometer. The same model has been adapted to predictions of the noise of the same circuit, and an experimental study to verify this model is underway. Sufficient confidence in the model already justifies its comparisons to the nuclear orientation thermometer (see III.A.4 below).

5. Nuclear Orientation Thermometry

a. The computer based data acquisition system has been programmed for use with the ^{60}Co<u>Co</u>(sc) thermometer. It, along with programs written in DATAPLOT for the NBS-(CS)^2 system, have been used in a preliminary comparison experiment with the noise thermometer. Results in the temperature range from ~7 to ~23 mK show that the two thermometers disagree systematically by about 0.3%. Further measurements are planned to resolve this discrepancy. In addition, in two separate series of measurements the ^{60}Co<u>Co</u>(sc) thermometer reproduced the published value for the tungsten superconducting transition temperature to within ±0.1%; namely, +0.09 and

0.04%. However recent re-evaluation of the noise temperature data may make the agreement slightly worse.

b. A systematic series of measurements was conducted in order to determine the magnitudes of several temperature gradients between the nuclear orientation thermometer and the main thermometer platform (i.e., gradients between the thermometer and copper mount, along the copper rod, across the screw connection between the copper rod and copper platform). These results are very important for users of nuclear orientation thermometers, to the NBS program and to users of copper rods and joints for low temperature experiments (almost everyone in the business). The results are available as a contract report from W. Fogle.

c. The NATO supported collaborative [Dr. G. Eska (West Germany); Prof. B. G. Turrell (Vancouver, Canada); Dr. R. M. Mueller, (West Germany); and H. Marshak (NBS)] experiment to measure the A- transition in ^3He (one of the proposed fixed points for the melting curve) using nuclear orientation thermometers has been delayed due to the relocation of Dr. Eska to a professorship at Bayreuth University, Bayreuth, West Germany. He has obtained a new high powered $^3He/^4He$ dilution refrigerator for his laboratory and will be adding a large nuclear cooling stage to it in the very near future. It is expected that the measurements at the A-transition will be carried out on it in the next year. In the meantime we have added a small nuclear cooling stage to Prof. Turrell's dilution refrigerator in Canada in order to perform an NMR/ON measurement on $^{184}Re\underline{Ni}$. At the completion of these measurements we will be able to use it for absolute nuclear orientation thermometry in the temperature region of ~0.5 to ~5 mK.

d. 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 (sc) has again had a very productive year. In Berlin, we were able to perform a nuclear double resonance experiment on this system. This was the first successful double resonance measurement made on an oriented nuclear spin system. As pointed out in last year's report, the terbium single crystal system is very interesting in that, in addition to having a very large nuclear magnetic dipole interaction, it also has an extremely large electric quadrupole interaction. The effect of the latter is to split the single dipole resonance line into widely spaced subresonances. The lowest subresonance ν_2(transitions between the m_I = +3 and the m_I = +2 substates) was observed for the first time by us last year. Since at low temperatures only the lowest magnetic substate (m_I = +3) is appreciably populated, observing the second subresonance ν_2 (transitions between the m_I = +2 and the m_I = +1 substates) would be very difficult by standard Nuclear Magnetic Resonance on Oriented Nuclei (NMR/ON) techniques. However, by saturating the first subresonance (irradiating with rf of frequency ν_1) we were able to considerably enhance the population of the m_I = +2 substate. We then simultaneously irradiate with rf to obtain the value ν_2 of the second subresonance. By measuring both of these subresonance frequencies we were able to deduce precise values for both the dipole and quadrupole interactions in this system. The results of this nuclear double resonance experiment was submitted to Physical Review Letters for publication.

The above results along with magnetization measurements currently being conducted here at NBS enable this terbium single crystal system to be used for absolute nuclear orientation thermometry in the temperature range of 10-125 mK. In the following figure we show the sensitivity functions the ^{60}Co<u>Co</u>(sc), ^{166m}Ho<u>Ho</u>(sc) and the ^{160}Tb<u>Tb</u>(sc) nuclear orientation thermometers. These three nuclear orientation thermometers cover the region from ~2 to ~1000 mK. Whereas the ^{60}Co<u>Co</u>(sc) and ^{160}Tb<u>Tb</u>(sc) thermometer are absolute in that the energy separations of their hyperfine levels have been measured by NMR/ON, no NMR/ON measurement has yet been carried out on the ^{166m}Ho<u>Ho</u>(sc) thermometer. The energy separation of its hyperfine levels have been measured indirectly by calibrated resistance thermometers, thus it remains a secondary thermometer.

A paper entitled "^{160}Tb<u>Tb</u>(sc): A New Absolute Nuclear Orientation Thermometer for Use in High Magnetic Fields" will be presented at the XVIII International Low Temperature Conference in Japan.

e. In addition to the two collaborative efforts mentioned above, a third, and much smaller collaboration, is being carried out with a nuclear physics group at the Los Alamos National Laboratory (see publications).

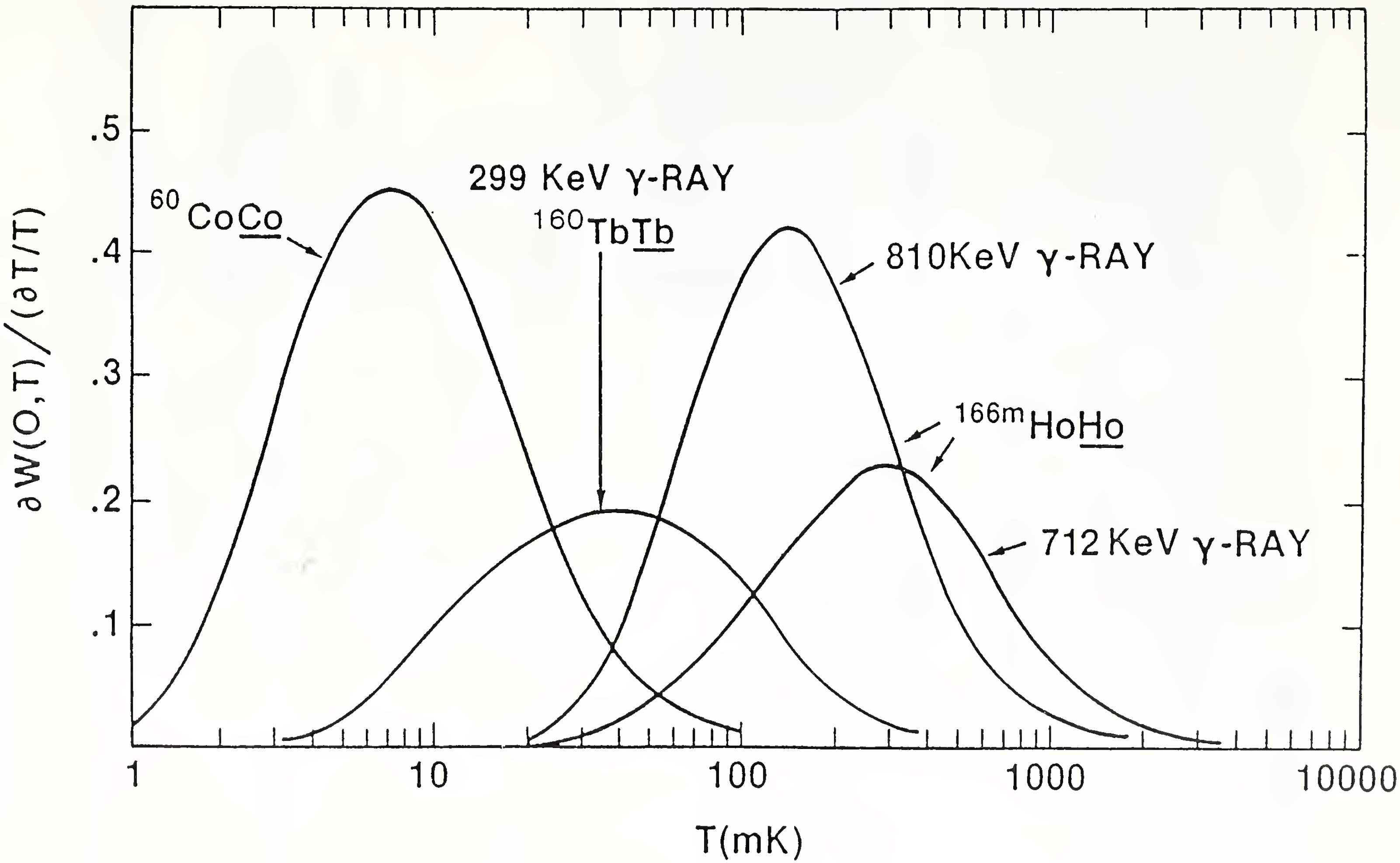


Figure 3. Sensitivity of three nuclear orientation (Tb, Co, Ho) thermometers versus temperature.

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.

Medical Temperature Fixed Points

Material	Tf (°C)	Status
Indium	156.635 ± 0.002	SRM 1971 100 cells tested.
Succinonitrile	58.0805 ± 0.0015	SRM 1970. 115 cells tested. RSI article published. NBS J. Res. paper published. SP 260-101 published.
Phenol	40.92	Under study.
n-Lauric acid	43.95	Under study.
n-Docosane	43.89	Under study.
Rubidium	39.303 ± 0.005	SRM 1969. Article published in TMCSI. SP 260-87 published
Ethylene carbonate	36.3238 ± 0.0004	Alternative to Rb. Paper published in Metrologia.
Gallium	29.772 ± 0.001	SRM 1968. Several papers published.

Specific accomplishments this FY include:

(1) There is a special (even critical) need for two fixed points bracketing the hyperthermia range used in cancer therapy. Those two points

should be at about 41 or 42 °C and 44 or 45 °C. Several materials have been selected as possible candidates for those temperatures, and small cells of phenol, n-lauric acid and n-docosane have been obtained for study. Their freezing/melting behavior has been investigated and, although all three of these materials look promising, n-lauric acid has been found to be much more difficult to purify than n-docosane. Consequently, we have chosen phenol and n-docosane as the materials for the two fixed points. More cells of phenol and n-docosane have been ordered for a proper investigation of their stability, reproducibility of their freezing-point temperature from freeze to freeze, and the dependence of the freezing-point temperature on impurities. The National Cancer Institute is now funding some of this work.

(2) The investigation of the melting/freezing behavior of high-purity indium in small Teflon cells conducted previously showed the feasibility of using this point (and realized in such small cells) as a temperature fixed point, and as an SRM. During FY 86, the NBS instrument shops constructed 100 cells appropriate for the indium SRM (SRM 1971). Those cells were filled with 99.9999+% pure indium, sealed under an atmosphere of dry argon, and 50 of them were tested for suitability to serve as SRM 1971 by about the end of September 1986. The remaining 50 cells were certified during the past year, a certificate written, and the SRM made available for purchase.

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 FY 1987:

Q-branch line broadening in hydrogenic molecules:

A manuscript has been prepared which presents our analysis of the J and collision partner dependence of the line broadening of the D_2 isotropic Q-branch for self-broadening, and with the collision partners H_2, He, Ar, and CH_4. This work, summarized briefly in last year's report, involves the use of an exponential gap law to describe the rotationally inelastic portion of the line width and the determination of the contribution of elastic vibrational dephasing (assumed independent of J) for the various collision partners. Recently, our collaborators at the Johns Hopkins University Applied Physics Lab, have verified our findings for the case of D_2:He. Their calculation, a first principle close-coupling calculation using an accurate ab initio intermolecular potential, results in line broadening coefficients within 5-10% of our measurements, and more importantly, very good agreement (10%) with our estimates of the contributions of rotational inelasticity and elastic vibrational dephasing. The importance of elastic vibrational dephasing in the hydrogenic systems, in particular for self-broadening, has only recently been realized. Dr. K. C. Smyth, NBS Center for Fire Research, collaborated in this work.

A manuscript describing our measurements and analysis of line broadening and shifting in the Q-branch of self-broadened HD also has been prepared. The very large contribution from rotationally inelastic collisions is analyzed by use of an exponential gap law. Comparisons can be made in the case of HD with direct measurements of rates of rotational energy transfer and with the results of other line broadening measurements. Very good consistency is found in these various comparisons under the assumption of a vibrational-state dependent rate for rotationally inelastic collisions. In this analysis we find a rate in the first-excited vibrational state which is approximately 30% larger than that in the ground state. We note that a similar degree of vibrational state dependence is found in the theoretical calculation, discussed above, on D_2:He. There is a large number of first principle calculations available for the HD:HD system. Our work, which agrees well with only one of these, should serve as a critical test of theory for this well-known, long-studied system. Prior experimental data were far too inaccurate to allow significant tests of theory and intercomparisons of line broadening values such as those discussed above. Dr. Smyth, Dr. A. D. May, U. of Toronto, and Dr. L. B. Petway, Howard U. collaborated in this work.

The study of the effects of simultaneous velocity and phase change upon collision has continued this year with an experiment on D_2:Ar up to ~34 atm. As described in last year's report, our measurements on D_2:D_2 revealed an additional weak-component in the Q-branch spectrum which 'collapsed' into the strong central peak at higher densities, i.e., ~15-20 amagat. This component was easily discernable in the Q-branch of pure D_2 only in the region 2.5-12 amagat. A two-line model was employed to fit the D_2 spectra which resulted in a correction, a 2-3% narrowing, of the strong- component in the spectra. This narrowed component extrapolated accurately to predict the high density (~20 amagat) single Lorentzian lineshapes. In an attempt to further understand the source of this extra component in the D_2 spectrum, we extended our study to the D_2:Ar system, in which the extra component is almost a factor of two more intense than that seen in pure D_2. The analysis of the experimental data is not yet complete; however, we have seen definite evidence of a nonlinear density dependence in the line broadening at densities above ~18 amagat. This nonlinearity, although small, i.e., of the order of 2%, can readily be extracted from our accurate line width determinations. The preliminary indications with respect to the extra component are that it is collapsed into the main peak at densities above ~11 amagat, and that the corrected central peak will extrapolate smoothly (nonlinearly with density) into the high density linewidths. The high density spectra have single Lorentzian line shapes to within our ability to measure them, i.e., down to the 1% of peak intensity level.

An experimental program to determine the effects of velocity and phase changing collisions on the Q-branch spectrum of H_2 has been initiated. Self- and foreign gas broadening (with Ar) has been studied at room T, and self-broadening measurements have been extended to 1000 K. These are the first high accuracy linewidth studies of H_2 above room temperature. In this work, we also are interested in deviations from conventional theories similar to those discovered in the case of D_2. No definite conclusions can be presented at this phase of the research. This work is part of our ARO contract.

<u>Application of exponential gap laws to predict Q-branch spectra:</u>

A manuscript has been prepared which presents our results and analysis of the J and temperature dependence of the Q-branch line broadening coefficients of pure CO. A modified exponential gap law for the state-to-state rates of collision-induced rotational energy transfer is shown to account for the J (to J = 38) and T dependence (to 1500 K). This law, when combined with a full relaxation matrix based theory for the Q-branch spectrum, gives reliable spectral predictions for the partially collapsed, 1 atm spectra up to 1500 K. This work, the experimental portion of which was conducted at the Combustion Research Facility at

Sandia National Labs in Livermore, CA, is the result of a collaboration with Drs. L. A. Rahn and R. E. Palmer and involved our summer student employee, Sharon Dohne.

An experimental study of the collapse of the CO Q-branch at high temperatures is currently in progress. This is a continuation of the collaboration with the Sandia staff under our ARO contract.

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_0, 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 87

A. Calibration Services

By the end of FY 87 we expect to calibrate 110 units for an income of $180 K, a 50% increase over last year.

B. New Primary Standard for the Gas Calibration Service

We expect to reduce the measurement uncertainty of our gas calibration service to 10 ppm by changing the primary standard from a controlled-clearance piston gage to manometry. The first experiments were conducted with the gas thermometer manometer which is capable of an uncertainty of 2 ppm over its range. Four carefully characterized piston gages, two made of tungsten carbide and two of steel, have been calibrated using the manometer with both helium and nitrogen at 3 pressures in the absolute mode. A piston gage measures the difference in pressure at each end of the piston. When the top of the piston experiences ambient atmospheric pressure, the gage is operating in the gage mode. For the absolute mode, the space at the top of the piston is evacuated.

These calibrations have been carried out three times: in 1983, 1984, and 1986-87. The data of 1983 and 1984 were contaminated by faulty equipment and by electrostatic forces generated within the piston gages. These problems have all been corrected. We believe the 1986-87 data to be valid. The two tungsten carbide gages are exceptionally well-behaved and are being used to calibrate the gages used in the calibration service. The repeatability and the independence of the area on the pressure for these two gages is very satisfactory. The standard deviation of A_0 from a constant value is 1.3 ppm for the worst case.

There is one issue to be resolved before we incorporate these results in the calibration service. These measurements were done in the absolute mode. The calibration service operates, however, in the gage mode. By cross-floating pairs of these gages we have noted relative changes in the apparent area between the gage and absolute modes as large as 23 ppm at one atmosphere using nitrogen. We believe the tungsten carbide gages are essentially free of the gage/absolute effect and that it is due primarily to imperfect geometry of the steel pistons. This hypothesis needs to be proven. Unfortunately, the gas thermometer manometer was not designed to operate in the gage mode and would not be useful for this purpose without extensive modifications. The study will be continued using the ultrasonic interferometer manometer (see Section VII) which is more amenable to gage operation. While its present accuracy does not match that of the gas thermometer manometer, we believe it has sufficient stability and sensitivity to resolve the gage/absolute question.

As part of our program to reduce our uncertainties, we have established a mass measurement capability up to a maximum of one kilogram. Preliminary data from a MAP with Division 523 indicate that our uncertainty in measuring piston gage weights will be less than 0.1 ppm.

C. Basic Research on Gas-Operated Gages

The gage/absolute effect mentioned in Section B is a function of the pressure, the gas, and the clearance between the piston and the cylinder. To explore the physics of this effect, we have built an apparatus to measure the change in gas density in the annular space between the piston and the cylinder as a function of the piston engagement length of an operating piston gage. We will use several gases in both the gage and absolute modes. The apparatus has been completed and demonstrated to work well. We expect to begin the detailed studies in the near future.

D. Distortion of Piston Gages at High Pressure

The key to correctly calculating cylinder distortion with pressure is to know the pressure in the annular space between the piston and the cylinder as a function of piston engagement length. We have shown earlier that this pressure profile can be calculated from the measured clearance between the piston and cylinder. As the measurements available from Division 731 are not adequate for our needs, we have developed our own capability to measure the changes of diameter as a function of length for both cylinder bores and pistons. The apparatus has nanometer resolution and better than 25 nanometer reproducibility. Figure 4 is a plot of the diameter of the bore of a piston gage cylinder as a function of its length. With this new capability, we will now be able to obtain the dimensional

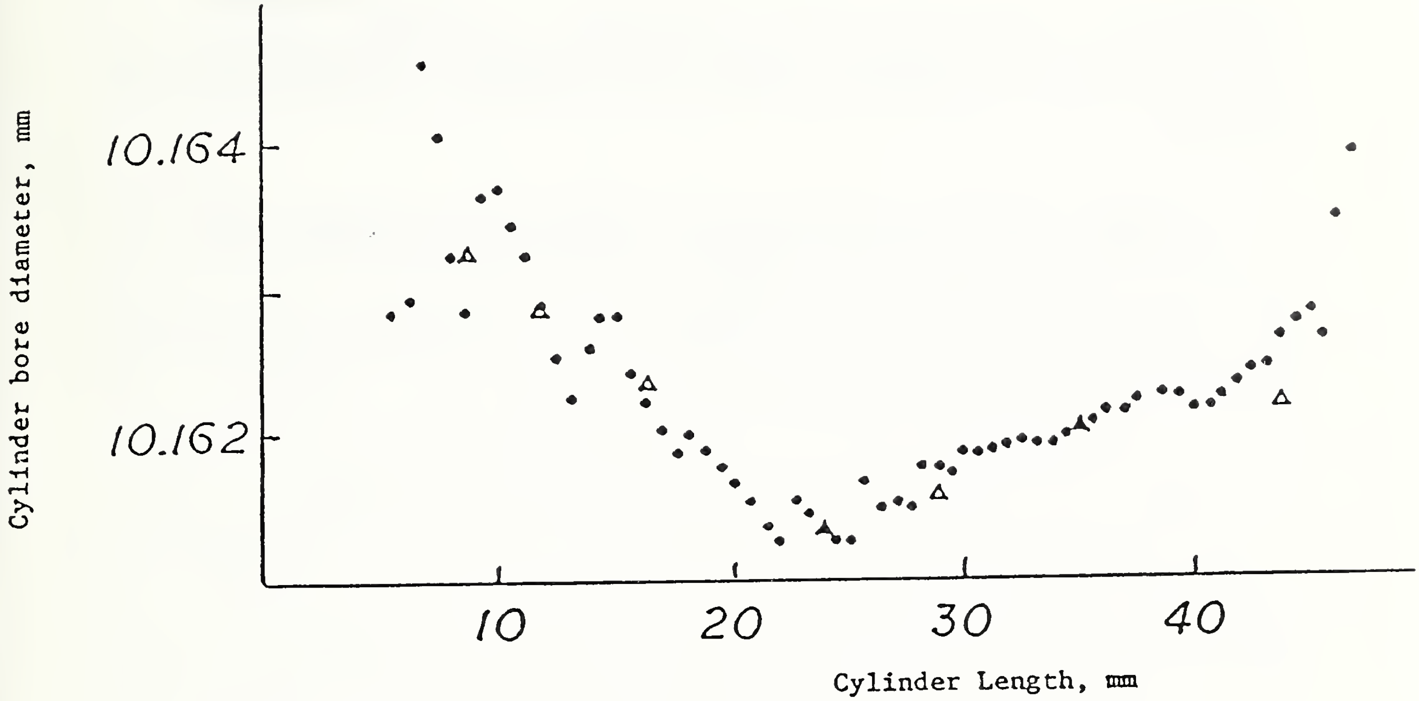


Figure 4. Measured cylinder bore diameter plotted as a function of cylinder length. The triangles represent measurements by Division 731.

data needed to test theoretical results with the extensive measurements we have made of cylinder distortion.

E. High Pressure Standards

To meet the needs of the increased calibration workload we have had to rob manpower from our high pressure program which has slowed our progress. The parts for the new 280 MPa standard are all available but the gage is yet to be tested. The new 700 MPa standard has been tested and works very well. More work is needed to complete the characterization. The InSb transducer has been demonstrated to have sufficient sensitivity to determine the cylinder distortion coefficient of a controlled-clearance piston gage at pressures as low as 70 MPa. It is expected to greatly expedite the characterization of controlled-clearance piston gages and to serve as a transfer standard in the 700 MPa pressure range.

F. Pressure Fixed Points

Pressure fixed points are valuable not only for laboratory intercomparison but also as an invariant against which standards can be compared as a function of time. Two pressure fixed points have been studied by Dr. Noel Bignell, a Guest Scientist from CSIRO, Sydney, Australia: the CO_2 vapor pressure at the temperature of the triple-point of water, about 5 MPa; and the ice Ih-ice III- water triple-point, about 200 MPa.

Purity of the CO_2 proved to be a major concern. The most consistent measurements were on samples prepared by ourselves by heating $NaHCO_3$ and passing the CO_2 through three separate drying systems.

The experimental work is now finished on both materials and the data are currently undergoing analysis.

VII. VACUUM AND LEAKS

(S. Dittmann, C. Ehrlich, A. Filippelli, R. Hyland, F Long, D. Martin and C. Tilford)

OVERVIEW

This group develops standards, addresses instrumentation and measurement problems, and provides services over 14 decades of pressure from 350 kPa to below 10^{-8} Pa, and four decades of flow (leaks) from 10^{-8} to 10^{-12} moles/sec. (Note: 1 atm = 15 psi = 100 kPa, 1 Torr = 133 Pa, and 1 mole/sec = 2 x 10^4 std cc/sec). This large range encompasses a great deal of diversity. State-of-the-art uncertainties range from a few ppm to factors of two or three. Instrumentation varies from the strictly mechanical and very simple piston gage to complex electronic mass analyzers. Applications include air transportation, food processing, nuclear materials handling and fabrication, and semiconductor processing. Reflecting this diversity, the activities of the group are divided into four areas: Manometry, High Vacuum, Ultra High Vacuum, and Leaks. These areas cooperate closely: Equipment and facilities are shared, standards in one area are supported by calibrations from another, and personnel may move from one area to another as needed. In particular, leak standards use both the techniques and equipment developed for high vacuum standards.

Richard Hyland is primarily responsible for manometry, although he spends a significant amount of time on leak standards. Sharrill Dittmann (formerly Wood) is responsible for High Vacuum, Albert Filippelli for Ultra High Vacuum, and Charles Ehrlich for Leaks. Donald Martin provides mechanical and technical support, Fred Long electronic support, and Charles Tilford overall coordination. Bruce Dove, who provided part time technical support, retired this winter. We have enjoyed the assistance of A. K. Gupta and D. R. Sharma, Guest Scientists from the National Physical Laboratory, India; Chris Sutton, a Guest Scientist from the Physics and Engineering Laboratory, New Zealand; and Rodney Ray, a summer student from Butler Community College.

The activities of the group are summarized below and detailed in the following "area reports."

More effort was placed in the manometry area than in previous years. The primary standard is the NBS-developed Ultrasonic Interferometer Manometer (UIM). A new design extending the range to 350 kPa (50 psi) was finished and evaluation begun. Several significant problems have been encountered but, as of this writing, the instrument works over its entire range and its low pressure performance is within a factor of two or three of the existing UIM. Use of the new speed of sound values and several changes have reduced the uncertainty for the present UIM to between 12 and 18 ppm, making it the most accurate pressure standard directly available to NBS calibration customers. Our confidence in this uncertainty has been strengthened by the agreement, to better than 1 ppm, of the recalibration of a gas-operated piston gage with a previous calibration by the UIM in 1983/84. A systematic effort is being made to understand several troublesome problems with gas-operated piston gages. This will include an evaluation of the dependence of piston gage effective areas on gas species in both the gage and absolute modes of operation. Comparisons with the piston gage standards of India and New Zealand will contribute to this effort. An experiment to measure the triple point pressure of argon and to use it as a check or transfer standard is being set up in collaboration with Chris Sutton.

The transition range (1 to 10^{-2} Pa) between the manometry and high vacuum standards has been and is a troublesome gap in our standards. This past year we have been able to make a preliminary comparison in this range of gages calibrated by our two different standards. These results are not optimum, being based on extrapolations of the calibrations, but do not indicate any significant differences between the standards.

The rapid rise in the number of high vacuum calibrations experienced in the last few years has leveled off, but the workload remains high. Construction of a new high vacuum calibration chamber has again been deferred because of uncertainty about an ultra high vacuum standard. Significant progress has been made in automating both the operation of the standard and data analysis. Satisfying agreement with vacuum standards at the other major national labs is evident in a recently completed international round-robin.

The Ultra High Vacuum program has had to face the "chicken and egg" problem of simultaneously developing primary standards and evaluating instrumentation. Several unexpected results were obtained in the initial evaluation of UHV ion gages but it became clear that these results are consistent with observations at several other laboratories. This work will continue along with an increased emphasis on residual gas analyzers. We now believe that the quickest way to obtain an operational UHV standard will be to obtain gage sensitivities by an extension of the technique used in the current high vacuum standard, and independently determine gage residual currents or "zero offsets." Towards this end, experiments are currently underway to evaluate the performance of the high vacuum standard between 10^{-6} and 10^{-8} Pa and to reduce the base pressure of the UHV chamber.

A significant effort has been required to get the new special test service for leaks operating in an efficient manner. A major part of this has been problems with the "standard" leaks submitted for testing, ranging from dirty artifacts to a generic design fault. Previous experience with new calibration services should have led us to expect this. Experiments during this past year have given us a much better understanding of the basic processes governing the behavior of helium diffusion leaks.

As our program has grown and is better known, the amount of time spent on outside contacts and services has steadily increased. Much of this benefits us as well as the user. Considerable time has been spent organizing three workshops this year on UHV gages, the spinning rotor gage, and leak measurements, but the two held so far have more than returned our efforts. Similarly, the increased time spent preparing and delivering talks has been compensated by a broadening of our experience and contacts. It is difficult to extend this corollary to calibration services. These clearly are of value to the user, they pay dearly for them. But they do take up increasing amounts of our professional staff time. This year we will bill about $75,000 for calibrations, about one staff year. This, and a nontrivial load of internal calibrations, are all performed by master and doctorate degreed staff. While the instrumentation and procedures tend to be complicated, much of it is becoming "routine" or automated to the point that significant professional staff time could be freed if calibration technical support were available.

VII.A. MANOMETRY

Introduction

The 160 kPa ultrasonic interferometer manometer (UIM) was developed to provide continuous pressure measurements over an absolute or differential pressure range from 1 to 1.5×10^5 Pa. Its design and performance, along with the capabilities of the calibration service, have been constantly upgraded. With the incorporation of the new speed of sound data, the UIM now provides calibrations with an absolute accuracy which is between 12 and 18 ppm, depending on the pressure, with a precision of 0.015 Pa.

Calibrations are routinely done for the aerospace, pharmaceutical, and semiconductor processing industries, as well as for various government standards laboratories.

The capabilities of the UIM make it invaluable as a research tool as well, and it is being used to calibrate transfer standards for an ongoing international laboratory intercomparison over the pressure range from 0.15 to 1500 Pa, evaluate the performance of gas operated piston gages, and measure the argon triple point.

FY 1987 Activities

Data reduction for the international intercomparison in the .15 to 1500 Pa pressure range is nearly complete. Preliminary results indicate acceptable levels of agreement between NBS, NPL-Teddington, CSIRO-Sydney, and PTB-Berlin, with a slight systematic offset from the latter.

The experiments to determine the effect of helium on the calibrations of differential quartz helix bourdon gage pressure transducers had been thought complete. However, based on the time constants associated with helium permeation leak artifacts, it may be necessary to wait longer times before any effects are seen, and one more set of experiments is planned.

The UIM was upgraded during the past year by the recalibration of its platinum resistance thermometers and the addition of a seventh thermometer. The software was modified to incorporate the new speed of sound values and eliminate an occasional problem with the ultrasonic data acquisition discovered during the speed of sound experiment. Other minor changes necessary to achieve the accuracies discussed in the introduction have been incorporated.

Work done in 1982, 83, and 84 suggested that the UIM might provide an alternative method for the calibration of low-range piston gages. Experiments during that period led to the determination of effective areas of one of the gages used routinely in the piston gage calibration service with a standard deviation of 1.4 ppm. After the upgrading of the error budget of the UIM and accounting for the new speed of sound data discussed in last year's report, another round of piston gage experiments has been initiated. The new average effective area for the same piston gage tested three years ago agrees with the old value to within 1 ppm, although the standard deviation has doubled. This experiment, although preliminary in nature, indicates excellent long term stability for the UIM and this particular piston gage. The results will also be part of an upgrade of the error analysis for the UIM.

The capacity to accurately calibrate piston gages will be used to compare piston gage calibrations in the pressure range from 10 to 160 kPa with NPL-New Dehli and DSIR-Wellington. These intercomparisons are underway.

A program has been initiated in conjunction with a guest scientist, C. Sutton of the DSIR-Wellington, to measure the triple point pressure of argon and develop portable triple point cells as check or reference pressure standards.

For-fee calibrations were done this year on 18 capacitance diaphragm gages. Calibrations also included the continued monitoring of a quartz bourdon tube gage which is used as a transfer standard for the calibration of altimeter setting indicators for FAA facilities. In addition, calibrations and preliminary evaluations of an air data systems calibration unit were done for the Navy Engineering Metrology Center. This exercise also served as training for the Navy personnel who will operate one of the 2.8 meter UIM's being constructed here at NBS.

The 2.8-meter (350 kPa) UIM's are the next extension of the UIM technology. One of the 2.8-meter UIM's has been assembled, and coupled to the new electronics. It has been demonstrated that there is adequate signal strength over its entire operational range. Work continues on the software development for its operation and evaluation of performance.

Several problems, including spurious ultrasonic signals, distorted transducers, and leaking seals, were identified during early testing of the

2.8-meter manometer. Modifications have been made to correct these problems in a 1-meter UIM being built for the Sandia Primary Standards Laboratory. Upon completion and successful testing of the 1-meter instrument, similar modifications will be made in the Navy's 2.8-meter UIM, as well as in a second 2.8-meter UIM which will remain at NBS.

FY 1988

In addition to the ongoing calibration work, the major projects for the coming year will be the completion and evaluation of one of the 2.8 meter manometers, the characterization of low-range gas-operated piston gages, and the determination of the argon triple point.

VII.B. UHV STANDARDS AND GAGING

The past year's efforts have been a continuation of the work started in the preceding year, and have again been concentrated on the following objectives:

(1) Evaluation of gages [total pressure ionization gages and residual gas analyzers (RGA)].

(2) Development of a primary UHV standard (pressures $< 10^{-6}$ Pa).

1. UHV Gaging

a. Residual Currents: To measure total pressure with an ionization gage, one needs to know the total ion current. However, in the UHV region the gage's residual (pressure-independent) current may be comparable to the ion current. Therefore, determination of the residual current is necessary for accurate UHV pressure measurements. Unfortunately, this parameter is often either unknown or only poorly known. We have employed two independent methods to determine the residual current in several types of UHV ionization gages including, an extractor gage and two modulated gages. The key results were: (i) residual currents varied from gage to gage by more than a factor of 10 among nominally identical gages and (ii) there was no evidence of hysteresis in any gage's response to pressure changes. This latter finding was somewhat unexpected for the measurements which were performed in H_2 (as well as H_e), since other workers have seen significant gas adsorption/desorption effects in ionization gages .

b. Ionization Gage Sensitivities: Ionization gage calibrations performed on the existing NBS primary HV standard have shown increasing scatter in the computed sensitivity of a gage as the pressure is reduced below about 10^{-6} Pa and, in some cases, the sensitivity appears to have a pressure dependence. However, at these pressures it is expected that the gage's sensitivity will be constant. It is not yet clear to what extent the apparent systematic changes are due to gage effects, or to low pressure errors in the standard. Two possibilities are: (a) electron stimulated desorption (ESD) of ions may be contributing significantly to the measured collector currents (although the results in 1.a. above indicate that this is not the case) and/or (b) the assumptions used in calculating the generated pressure may not be valid at the lowest pressures, in particular, the assumption that the turbomolecular pump speed is pressure independent.

A new set of experiments just underway (June 1987) is designed to evaluate the performance of UHV gages, set bounds on possible low pressure errors in the primary standard, and help determine the low flow errors of the flowmeter used for both the pressure standard and the leak standard.

c. UHV Gaging Workshop: An ultra-high vacuum gaging workshop, organized by the vacuum standards group at NBS, was held November 3 and 4, 1986, in Gaithersburg, Maryland. Internationally-recognized experts in the area of UHV gaging were among the 80 attendees at this workshop, which addressed 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 was on total pressure ionization gages. The presentations and personal exchanges at this meeting were invaluable in helping the NBS vacuum standards group acquire some perspective on the problem areas in UHV gaging. Further, it was gratifying to find that others' experiences with residual currents and sensitivity measurements were similar to ours.

d. Residual Gas Analyzers: The widespread and increasing use of residual gas analyzers (RGA) in science and industry has prompted us to investigate the possibility and practicality of calibrating such instruments. To this end, over the past 2.5 years we have acquired 8 electric quadrupole and 2 magnetic sector instruments. There is a continuing accumulation of data and experience as a result of daily use of these instruments in the course of both research and routine calibration work with other gages. In addition, in the spring of 1987 we carried out a series of 2-3 day duration experiments on the short and long term stability of these instruments. It is yet too early to draw conclusions about relative performance but it has already become clear that RGA's equipped with a secondary electron multiplier can exhibit rather long settling times in response to a pressure step. Longer term systematic studies of both stability and calibration procedures will begin in November 1987 with the arrival of a Hungarian Guest Scientist.

2. UHV Standard (pressure $< 10^{-6}$ Pa)

The areas of UHV gaging and UHV standards are not independent. Characterizing and understanding ionization gage behavior at pressures below about 10^{-8} Pa depends on the ability to obtain base pressures below 10^{-9} Pa, which is an order of magnitude below what is achieved in the present NBS standard. In our approach to developing a new UHV primary standard, we have (i) constructed a test chamber with the same material and basic design as the existing standard and (ii) concentrated our efforts on identifying and reducing the sources of the residual gas background (mostly

H_2) in the test chamber. The experiments planned or partially completed at the time of last report have been completed, as well as some additional experiments not then mentioned. Among these experiments, we mention the following:

a. <u>Extended (380 hour) High Temperature (450 °C) Baking</u>. This reduced the partial pressure of H_2 in the chamber by a factor of about 3 over that achieved with 250 °C bakes.

b. <u>Hydrogen Permeation</u>. Experiments with the diffusion of deuterium and heavy water through stainless steel, at both elevated temperatures and at room temperature, indicated that the influx of H_2 as a result of permeation of the vacuum chamber wall by hydrogen from atmospheric sources (H_2, H_2O, CH_4) is totally negligible at room temperature.

c. <u>Cooling (-20 °C) of Chamber</u>. This resulted in a H_2 pressure reduction of only about 20%, rather than the order of magnitude (or more) reduction expected, based upon the temperature dependence of the diffusion coefficient for hydrogen in stainless steel and assuming that hydrogen dissolved in the stainless steel is the only source of hydrogen. This experiment, together with the results of experiments a. and b. above, indicate that at the present time, the ultimate low pressure in the test chamber is limited principally by the pump. However, even if this source (pump) can be reduced to zero, it will still be necessary to reduce the wall diffusion component by at least a factor of 2, to obtain an overall factor of 10 reduction in the H_2 partial pressure. As a consequence, it now appears that further processing (vacuum furnace degassing) of the test chamber is needed in order to reach our goal or that a different material (aluminum) should be used.

d. <u>Magnetic Bearing Turbomolecular Pump (TMP)</u>. A new magnetic bearing TMP was substituted for the TMP previously used. The after-bake H_2 base pressure was found to be about a factor of 2 larger than that previously obtained with the other pump. This behavior is puzzling, because the H_2 compression ratio for the new pump is specified to be 50 times greater than that for the previously-used pump. Experiments with the new pump are continuing.

Our thinking on the subject of a primary UHV standard has evolved during the course of the above-described experiments. If it can be demonstrated that ionization gage sensitivity remains constant into the UHV region, a dynamic (orifice/flowmeter) system to generate known pressures $<10^{-8}$ Pa may not be necessary. It may then be sufficient to achieve base vacua low enough that residual currents can be determined directly. Then the gage's sensitivity could be determined at higher pressures, with the existing NBS primary standards.

Our plans for the coming year call for continued experimentation with other types of pumps on our test chamber, as well as very close examination of the existing HV standard at the low end (10^{-6} Pa) of its range.

Decisions about design and construction of a new UHV standard hinge on the results obtained in the above-described plan of investigation.

VII.C. HIGH VACUUM STANDARDS

The high vacuum standard is of the orifice-flow type and currently covers the range 10^{-2} to 10^{-6} Pa. Work this year has involved interactions with several standards laboratories from around the world, work at the upper and lower ends of the pressure standard, calibrations, and continuing involvement in education and training.

As an extension of the International Vacuum Congress held in Baltimore, MD, in November 1986, representatives of national standards laboratories from six countries and KFA in Julich, West Germany, met at an NBS-organized workshop to discuss the spinning rotor gauge (SRG) as a transfer standard.

NBS participated in an international round robin conducted under the auspices of BIPM with PTB, Berlin as the pilot laboratory. Four SRG's were calibrated in argon and hydrogen gas at pressures between 2×10^{-4} and 4×10^{-2} Pa. The initial report from PTB is that their before and after calibrations agreed to within $\pm 1\%$ and that there was satisfying agreement between the NBS results and all but one of the seven other standards laboratories. This is most rewarding after instabilities of the transfer standards compromised two previous comparisons. In addition, data were taken in nitrogen where most of the work at NBS is done. Two check standards were carried throughout the work and their calibrations were within 1% of prior values.

Spinning rotor gages calibrated at NBS are now in use at IMGC, Italy, and KSRI, Korea, and discussions have been held with NRC, Canada, to exchange SRG's. Two calibrated rotors and a calibrated ion gauge will be sent to NPL, India, this summer.

At higher pressures, four capacitance diaphragm gauges (CDG's) which had been calibrated against the ultrasonic interferometer manometer were compared against two SRG's which had been calibrated against the primary high vacuum standard. The intercomparison was carried out between 10^{-4} and 7 Pa, a region which includes the gap between the UIM and the high vacuum standard and, as such, represents an extrapolation for both types of gauges. After corrections were made for thermal transpiration in the CDG's and for gas viscosity in the SRG's, the readings agreed to within about 0.6%. Of particular interest was the apparent success of the SRG gas viscosity correction, which has been empirically determined by KFA, Julich and adopted by the manufacturers. Interest in developing vacuum standards to cover this range remains high.

Work has begun at pressures below 10^{-6} Pa to study both the behavior of the primary standard and the sensitivities of nude ion gauges of several types. This is discussed further in the ultra high vacuum section.

The high vacuum calibration load did not increase significantly for the first time since the service began in 1981. Thirty-one gauges were calibrated for fee, 20 SRG's and 11 ion gauges. More gauges are coming directly from manufacturers and many of our customers are industrial calibration laboratories so most calibrations reach many end users. We are receiving increasing numbers of inquiries from the semiconductor industry which had previously shown no apparent interest in gauge calibrations. Our growing body of historical data on the long-term performance of the SRG, both in our laboratory and after industrial use, has proven valuable to the vacuum metrology community.

Initial work has been accomplished toward automating data collection from the flowmeter that is an integral part of the standard. With the forthcoming installation of platinum resistance thermometers in the flowmeter, all of the data needed to calculate the pressure generated in the calibration chamber will be available to a computer. In addition, real-time analysis in now possible for certain vacuum gauges as a result of the automation.

Education activities continue to be important. Sixteen students attended the three-day, hands-on workshop on The Use of Spinning Rotor Gauges to Calibrate Ion Gauges. Twenty-two people attended an informal Spinning Rotor Gauge Users' Group in Baltimore, Md which was led by NBS personnel. Telephone consultations make up the balance of the educational activities.

VII.D. LEAK STANDARDS

With the introduction last year of a Special Test Service for helium permeation leak artifacts in the range 10^{-8} to 10^{-11} mol/s ($2x10^{-4}$ to $2x10^{-7}$ atm cc/s @ 0 °C), activities this year have focussed on providing this service in an effective and timely manner. Thus far nine leak artifacts have been received into the Special Test Service, and at least seven will have been evaluated and returned to the customer by the end of the fiscal year. This includes two artifacts in use at the Three Mile Island reactor (TMI). The Primary Leak Standard has been improved with a new manifold system that increases from two to six the number of artifacts that can simultaneously be mounted for evaluation, without the necessity of opening the vacuum system. This manifold, with dual pumping systems and a residual gas analyzer, provides the flexibility to measure flow rates from one artifact while performing additional experiments with another.

A more detailed investigation into the properties of the helium permeation artifact itself has yielded a much better understanding of the fundamental processes governing the flow rate, and of the proper ways in which to use these leaks. This has also resolved a discrepancy that exists in the recent literature concerning the functional dependence of flow rate on various parameters. A primary issue is the time response of the leak rate from an artifact to thermal fluctuations. On the one hand, it is well known that the leak rate from an artifact can take several days to stabilize when the leak reservoir is first filled with helium. On the other hand, leak rates from artifacts are known to stabilize much more quickly when subjected to discrete changes in temperature, even though the helium reservoir pressure changes accordingly. Our experiments support that part of the literature on the permeation of gases through vitreous glasses which asserts that it is the helium concentration gradient in the glass, and not the pressure gradient across the glass, that governs the flow rate.

The development and testing of a temperature-controlled leak artifact has shown considerable promise toward providing a stable artifact for both laboratory and field use. During observations made in the truck bay serving the two reactors at TMI, using uninsulated leak artifacts, it became clear that large thermal fluctuations in the truck bay could lead to serious misuse of the leak artifacts. Insulating the artifacts helps, but an artifact that is thermally regulated offers a greater degree of stability, and reduces the associated uncertainties. We have tested two different temperature controller designs, one commercial and the other developed at NBS. The NBS controller was found to give better regulation (10 mK vs. 200 mK) about a given temperature, however, both were found to yield approximately the same shift in artifact temperature for a fixed change in the temperature of the environment (0.3 K for an environmental change of 37 K, or 0.8%). After final laboratory evaluation at NBS, an artifact of this design will be sent to TMI for field testing.

The calibration schedule for the new special test service was badly delayed by instabilities in a number of leaks belonging to outside customers as well as NBS. After several months of testing the problem was traced to an improperly installed valve on the leaks which allowed helium to leak out during heating and cooling cycling. Since this could cause large errors with time the manufacturer was advised of the problem. He has modified his assembly procedure and repaired the offending leaks.

Studies are being planned to evaluate the uncertainties associated with using the Leak Comparator, in conjunction with leak artifacts that have been measured on the Primary Leak Standard, to perform the entire calibration of customer leaks.

A Standard Leak Calibration Workshop, to be held at NBS on Sept. 21-22 and co-sponsored with Sandia Laboratories, will provide a forum for sharing our findings with the user community, as well as learning about other new developments in this area. Besides talks directly related to leak calibration and design, the workshop will feature speakers from the nuclear transportation, electronics, refrigeration, and leak detector manufacturing industries. Representatives from nuclear and military contracting organizations, and national standards organizations, including the American Society of Testing and Materials, American Vacuum Society, American Society of Nondestructive Testing, American National Standards Institute and authors of MIL specs, will also present talks outlining their organization's activities.

INVITED TALKS

Temperature and Pressure Division (522)

G. W. Burns, "Thermocouple Calibrations at the NBS," ASTM Temperature Colloquium, Cincinnati, OH, May 13, 1987.

Sharrill Dittmann, "Where are the Challenges in Pressure Measurements," 33rd International Instrumentation Symposium, Las Vegas, NV, May 7, 1987.

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

Albert R. Filippelli, "A Comparison of Three Types of Commercial UHV Ionization Gages," AVS Florida Chapter, 16th Annual Symposium on Applied Vacuum Science and Technology, Clearwater Beach, FL, Feb. 4, 1987.

Albert R. Filippelli, "Sensitivity and Residual Currents for Several Commercial UHV Ionization Gauges," Workshop on UHV Gauging, Gaithersburg, MD, Nov. 3-4, 1986.

W. S. Hurst, "Broadening and Narrowing of Raman Q-branch Spectral Lines of Diatomic Molecules," Departmental Colloquium, Department of Physics, The Pennsylvania State University, University Park, PA, Oct. 9, 1986.

Richard W. Hyland "Leak Artifacts - Calibrations and Considerations," AVS New England Chapter (Annual symposium), Newton, MA, June 15, 1987.

B. W. Mangum, "Calibration, and the Associated Uncertainties, of Standard Platinum Resistance Thermometers at the NBS," ASTM E-20 Colloquium, Cincinnati, Ohio, May 13, 1987,

B. W. Mangum, "Standard Reference Materials for Use in Precision Thermometry," National Conference of Standards Laboratories' 1987 Workshop & Symposium, Denver, Colorado, July 15, 1987.

G. J. Rosasco, "The effects of velocity and phase changing collisions on the lineshape of Raman Q-branch transitions in D_2," Fall Meeting of the Atomic and Molecular Physics Division, Canadian Association of Physicists, Winnepeg, Manitoba, Canada, October 1986.

G. J. Rosasco, "The effects of velocity and phase changing collisions in the D_2 Q-branch spectrum," The Combustion Research Facility, Sandia National Laboratories, Livermore, CA, April 1987.

G. J. Rosasco, "Phase and velocity changing collisions studied via the D_2 Q-branch," The Johns Hopkins University Applied Physics Laboratory, Laurel, MD

J. F. Schooley, "Properties of Bulk Superconductors", NBS Seminar on High-Temperature Superconductivity, May 26, 1987.

R. J. Soulen, Jr., "Tunneling Effects in Superconductors," NBS Seminar on High-Temperature Superconductivity, May 26, 1987.

R. J. Soulen, Jr., "Recent Advances in Pressure and Temperature Measurements at NBS," Physikalisch-Technische Bundesanstalt, Braunschweig, West Germany, June 2, 1987.

R. J. Soulen, Jr. "Recent Advances in Pressure and Temperature Measurements at NBS," Phyusikalisch-Technische Bundesanstalt, Braunschweig, West Germany, June 17, 1987

R. J. Soulen, Jr. "Progress in Division Pressure and Temperature Standards," Navy CCG Planning Conference, Corona, CA, 1987.

Charles R. Tilford, "Vacuum Gages," Rocky Mountain Chapter of the American Vacuum Society, Boulder, CO, April 1, 1987.

Charles R. Tilford, "Fundamentals of Vacuum Gaging and Calibrations," Northern California Chapter of the American Vacuum Society, San Jose, CA, February 20, 1987.

Charles R. Tilford, "High Vacuum Gaging and Calibrations," Technical meeting of the New England Chapter of the American Vacuum Society, Bedford, MA, January 14, 1987.

PUBLICATIONS

Temperature and Pressure Division (522)

IN PRINT:

R. E. Edsinger, M. L. Reilly and J. F. Schooley, "Thermal Expansion of Platinum and Platinum-Rhodium Alloys," J. Res. NBS, 91, 333 Nov./Dec. (1987).

R. E. Edsinger and J. F. Schooley, "Gas thermometric determination of t (KTTS) vs t (IPTS-68) in the range 457°C to 660 °C," Paper No. CCT/87-4, International Bureau of Weights & Measures, June 1987.

C. D. **Ehrlich** "Present Status of the Leak Standards Program at the National Bureau of Standards," J. Vac. Sci. Technol. A, Vol. 5, 125 (Jan./Feb. 1987).

A. R. Filippelli, "Operation of a Bayard-Alpert Gauge in a Uniform 0-0.16 Tesla Magnetic Field," J. Vac. Sci. Technol. A5, March/April, 1987.

A. R. Filippelli, "Residual Currents in Several Commercial Ultrahigh Vacuum Bayard-Alpert Gauges," J. Vac. Sci. Technol., Sept./Oct. 1987.

G. T. **Furukawa**, "The Triple Point of Oxygen in Sealed Transportable Cells," J. Res. NBS (USA) 91, 255-275(1986).

J. D. Cox and **B. W. Mangum**, "Evaluation of the Triple Point of 1,3-Dioxolan-2-One," Metrologia, 23, 173-178 (1986/87).

B. W. Mangum, "Standard Reference Materials for Use in Precision Thermometry," Proc. NCSL 1987 Workshop & Symposium, 44-1 to 44-10 (1987).

H. Marshak, "Nuclear Orientation Thermometry," Chap. 16, Low Temperature Nuclear Orientation, eds. N.J. Stone and H. Postma (North-Holland, Amsterdam, 1986), p. 769-820.

H. Marshak, J. N. Knudson, et al., "Excitation of the Isobaric Analog State of ^{165}Ho by Pion Single Charge Exchange," Phys. Rev. C 35, 1382 (1987).

K. E. McCulloh, C. R. Tilford, C. D. Ehrlich and F. G. Long "Low-range Flowmeters for use with Vacuum and Leak Standards," J. Vac. Sci. Technol. A, Vol. 5, 376 May/Jun (1987).

P. H. E. Meijer, Mustafa Keskin, and Erik Bodegom, "A Simple Model for the Dynamics Towards Metastable States," J. Stat. Phy. 45, 215 (1986).

P. H. E. Meijer, P. Pecheur and G. Roussaint, "Electronic Structure of the Cd Vacancy in CdTe," Phys. Stat. Sol. (b), 140 155 (1987).

P. H. E. **Meijer** and Marek Napiorkowski, "The three-state lattice gas as model for binary gas-liquid systems," J. Chem. Phys. 86, 5771 (May 1987).

G. J. **Rosasco**, and **W. S. Hurst** "Dispersion of the electronic contribution to the third-order nonlinear susceptibility of H_2," J. Opt. Soc. Am. B 3, 1251 (1986).

J. F. Schooley, "1986 Applied Superconductivity Conference, September 28-October 3, 1986, Baltimore, MD," **R. J. Soulen, Jr.**, V. A. Bardos, M. A. Green, **J. F. Schooley**, Editors. IEEE Trans. Magn., MAG-23, No. 2, March 1987.

K. C. Smyth, **G. J. Rosasco**, and **W. S. Hurst**, "Measurement and rate law analysis of D_2 Q-branch line broadening coefficients for collisions with D_2, He, Ar, H_2, and CH_4," J. Chem. Phys. July 1987.

R. H. Ono, M. W. Cromar, R. L. Kautz, **R. J. Soulen**, **J. H. Colwell**, and **W. E. Fogle**, "Current-voltage characteristics of nanoampere Josephson Junctions," Proceedings of the Applied Superconductivity Conference, IEEE Trans. Magn., MAG-23, 1670 (1987).

R. J. Soulen, Jr., and Deborah Van Vechten, "Impedance of radio-frequency-biased resistive superconducting quantum interference devices," Phys. Rev. B 36, 3186 (1987).

APPROVED FOR PUBLICATION:

A. R. Filippelli, "Emission from Atomic Nitrogen Produced by Electron Impact on Nitrogen Molecules" (with D. L. A. Rall, F. A. Sharpton, S. Chung, C. C. Lin, and R. E. Murphy); accepted for publication in the Journal of Chemical Physics, Oct. 1987.

B. W. Mangum, "NBS Platinum Resistance Thermometer Calibration Service;" revised version completed and to be published as a supplement to Special Publication 250.

H. Marshak, W. D. Brewer, P. Roman and M. Bottcher, "^{160}TbTb(sc): A New Absolute Nuclear Orientation Thermometer for Use in High Magnetic Fields," Japanese J. Appl. Phys.

H. Marshak, W. D. Brewer, E. Klein, K. Freitag and P. Herzog, "Nuclear Double Resonance of ^{160}TbTb Oriented at Low Temperatures," Phys. Rev. Lett.

P. H. E. Meijer, Mustafa Keskin, and M. Napiorkowski, "The Influence of Electrical Field on Diffusion in Semiconductor Junctions," J. Appl Phys.

G. F. Molinar, J. C. Legras, **V. E. Bean**, V. H. Borovkov, J. Jager, A. Keprt, S. L. Lewis, R. Lewisch, Mobius, L. Rydstrom, J. G. Ulrich, S. Yamamoto, and S. Yi-Tang, "International Comparison of Pressure Measurements in a Liquid Medium from 20 to 100 MPa," Proceedings of the XIth Conference of the International Association for the Advancement of High Pressure Science and Technology, Kiev, USSR, 12-17 July 1987.

C. R. Tilford, Editor, Proceedings of the Ultra High Vacuum Gaging Workshop, J. Vac. Sci. Technol., Sept/Oct., 1987.

C. R. Tilford, "The Speed of Sound in a Mercury Ultrasonic Interferometer in Mercury," Metrologia, September 1987.

A. van Roggen and **P. H. E. Meijer**, "The Eddect of Electrode-Polymer Interfacial Layers on Polymer Conduction. Part 2: Device Summary," Proceedings of Conference on Molecular Electronic Devices, Crystal City, VA.

SEMINARS, WORKSHOPS, AND MEETINGS ORGANIZED OR CHAIRED

Temperature and Pressure Division (522)

Precision Thermometry Seminar, NBS, Gaithersburg, MD, October 20-24, 1986 A seminar which consists of integrated instruction in Platinum Resistance Thermometry, liquid-in-Glass Thermometry, Thermocouple Thermometry and Thermistor Thermometry which is given over a five-day period. Material covered includes the IPTS-68 (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 is split between lecture sessions and hands-on measurements in the laboratory.

Ultra-high Vacuum Gaging Workshop. The workshop was organized by members of the Vacuum Standards Group at NBS. It was held on November 3 and 4, 1986 at the Sheraton-Potomac Hotel, Gaithersburg, MD. Topics were UHV gauging needs in different areas of vacuum science and technology; past and present gaging research; performance of UHV gages; and UHV standards.

Workshop on the spinning rotor gage as a transfer standard, NBS, November 5, 1986.

Pressure Seminar, May 14 and 15, 1987.

Standard Leak Calibration Workshop, to be held September 21-22 at NBS, Gaithersburg, MD.

Use of the Spinning Rotor Gage to Calibrate Ion Gages, class given at NBS, February 25-27 and March 2-4, 1987.

ASTM E-20 Seminar on December 3, 1986. At this meeting, Dr. T. P. Wang of Thermo Electric, Inc. of Saddle Point, NJ gave a presentation on "Thermocouples for High Temperature Applications". (Mangum, Organizer and Chairman)

ASTM E20.06, New Thermometers and/or Techniques. On December 2, 1986. Mr. Philip Alderton of Instrulab, Inc. of Dayton, Ohio, presented a talk on and demonstration of Precision Resistance Bridges at this meeting. (Mangum, Organizer and Chairman)

ASTM E20.06, New Thermometers and/or Techniques. On May 12, 1987. Mrs. Carol Croarkin of the NBS presented a talk at this meeting. The talk was entitled "Derivation of Uncertainty Statements for Temperature Measurements". (Mangum, Organizer and Chairman)

ASTM E-20 Seminar on May 13, 1987. At this meeting, Dr. B. W. Mangum and Mr. George Burns of the NBS gave presentations on "Calibrations, and Their Associated Uncertainties, of Standard Platinum Resistance Thermometers and of Thermocouples at the NBS". (Mangum, Organizer and Chairman)

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, 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).

S. D. Dittmann (Wood), Chairman, AVS (American Vacuum Society) Subcommittee on Subcommittee on the Use of Spinning Rotor Gauges as Transfer Standards.

C. D. Ehrlich, Co-Chairman, AVS American Vacuum Society) Calibrated Leak Standards Subcommittee.

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

A. R. Filippelli, Member, (AVS) American Vacuum Society 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.

R. W. Hyland, Board of Directors, Vacuum Technology Division of AVS (American Vacuum Society).

R. W. Hyland, American Vacuum Society Subcommittee of Standards Committee on the Use of Capacitance Diaphragm Gages as Transfer Standards.

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 InstruGlass Fever Thermometers Thermometers; Working Group WG.03, Continuous Clinical Temperature Monitoring 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, Delegate, Consultative Committee on Thermometry of the International Committee on Weights and Measures (CIPM); 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.

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 E-21, 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.

C. R. Tilford, Member, Board of Directors, Vacuum Technology Division of the American Vacuum Society.

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

LENGTH AND MASS DIVISION

SUMMARY OF ACTIVITIES

FISCAL YEAR 1987

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. The Division also 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 concordance. 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 achieving a value for 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, continuing development of the laser controlled kilogram comparator, and development of the scanning tunneling microscope as a position sensor with sub-Angstrom resolution and as an optical heterodyne detector for use in laser frequency comparisons.

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 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 realizing and disseminating the length standard to industrial and scientific laboratories and 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. Formal contacts have also been made with Hungary and India 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 a new measurement of the ohm by means of the calculable capacitor in the NBS Electricity Division. This measurement is part of the continuing international effort by the electrical standards community to establish the quantized Hall effect as the primary standard of resistance. Last year 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. He has continued to assist John Shields in his efforts to upgrade the performance of the calculable capacitor.

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

The collaboration with Dr. William Lichten of Yale University on the measurement of the Rydberg constant by using crossed atomic and optical beams has been successfully completed and 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. An Extension of this work using radiation in the near infrared is now being planned.

PLANS FOR FY 88: The work of providing access to the length standard through the iodine stabilized laser will continue at approximately the same level as in FY 87. Plans are being made for a new 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. In this experiment a widely tunable waveguide CO_2 laser will be stabilized on a saturated absorption of osmium tetroxide and calibrated via the French optical frequency chain to obtain a higher accuracy length standard. This measurement should exhaust the opportunities for improving the Rydberg constant measurement with low atomic number atoms.

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 an 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 has redirected his efforts toward the development of a scanning tunneling microscope for length metrology with sub-Angstrom resolution.

PLANS FOR FY 88: 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.

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 kilogram comparator has been operating under servo control for over one year. It became clear during operation that several aspects of the controls needed to be improved. The hydraulic controls on the weight changer were completely redesigned. All electric relays were repackaged in a robust chassis and a greater variety of information is now displayed. The data acquisition is now semi-automatic: temperature, barometric pressure and balance readings are all taken by the computer; and the weight table is raised and lowered by computer control. Measurements on the Voland could be completely automated if the weight table could be rotated under computer control. A Cutkosky controller (a stepper-motor driver developed for the robotic weighing arm) has been constructed for this purpose and will be installed soon.

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 last year by Schoonover and Cutkosky to construct an 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 FY 88: 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 -- the recalibration of the U.S. national prototype kilograms, K20 and K4, and two stainless steel kilograms at BIPM -- has been completed and documented. Work is underway to calibrate a group of stainless steel check standards and working standards for the calibration service. A new set of quality control procedures will be 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 have been 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.

Now that our 1-kg mass comparator has a standard deviation of less than 0.0015 mg, it became clear that our usual cleaning method for stainless-steel kilograms was removing 0.005-0.010 mg on each application. While this is a small amount (less than the equivalent of one monolayer of metal), the fact that it appears to be monotonic rather than random has led us to search for a less aggressive cleaning method. A review of alternative methods has revealed several possibilities that are being studied.

When these studies are complete, 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.

PLANS FOR FY 88: The best cleaning method of those under study will be adopted and the quality control system will be put in place and documented. Special dust-free containers for the six stainless-steel kilograms will be constructed.

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 developed.

The special robotic arm has been constructed and programmed to automatically load and unload a commercial electronic balance according to a specified schedule. The present system will store 107 weights at a time on a temperature-regulated aluminum plate. Up to seven weights can be placed on the balance at one time as called for by the schedule, so that the usual weighing designs can be accommodated. Standard weighing designs performed on 5-2-2-1 and 5-3-2-1 weight sets indicate that the process standard deviations are comparable to those obtained using the present manual techniques. Work is now underway to reinstall the equipment on a pier in the mass calibration laboratory for final evaluation.

A paper describing the six-axis stepper motor driver used to control the robot arm has been submitted to the IEEE Transactions on Instrumentation and Measurement. An abstract of a paper describing the entire weighing system has been submitted to the Measurement Science Conference which will be held in January, 1988.

PLANS FOR FY 88: Research and testing will continue on all of these automated components until adequate performance has been demonstrated. They will then be adapted for use 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 been assembled and calibrated. It has now been successfully circulated to 9 participating laboratories in a round robin which included both state and industrial laboratories.

PLANS FOR FY 88: 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 have been 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 so that the customer's mass standards can be calibrated and certified in his own laboratory. The software for the extended package will be developed in FY 88.

F. Frequency Dependencies of Resistors

Requests for data on the frequency dependencies of resistors have been received from a number of sources, including the NBS Temperature and Pressure Division and the Sandia National Laboratories. Six selected 100-ohm resistors of commercial manufacture were compared with a 100 ohm coaxial resistor of NBS construction at various frequencies between dc and 400 Hz. The results are contained in a paper now undergoing editorial review. The resistors used in the test were provided by NBS and The Sandia Laboratories; the four bridges used were obtained from various sources within NBS. It is possible that the coaxial standard will not be usable for such testing very much longer, since the insulation used in its construction has greatly deteriorated.

G. New Measurement of the Gas Constant

The measurements of the ideal gas constant, R, have been completed. Richard Davis collaborated on the project led by M. Moldover of the Thermophysics Division. His job was to measure the interior volume of a 3 liter acoustic resonator with an uncertainty less than 1 ppm, if possible. He has succeeded in this. A draft report has been written which documents that the volume measurement contributed only 0.8 ppm to the error budget of R. The volume was determined three times over a period of six months. The range of values was less than 1 ppm of the nominal volume, making it one of the most precise measurements of its type ever reported. Davis' involvement in the project has now been completed.

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R. D. Cutkosky, "A Six-Channel Stepper Motor Controller for Use in Laboratory Instruments," to be published in IEEE Transactions on Instrumentation and Measurement.

R. D. Cutkosky, "Frequency Dependencies of Precision Resistors," to be published in Review of Scientific Instruments.

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R. M. Schoonover and J. E. Taylor, "An Investigation of a User Operated Mass Calibration Package," in progress.

INVITED TALKS

R. S. Davis, "Tracking the SI Kilogram," presented at NBS for the Government-Industry Data Exchange Program, April 27, 1987.

H. P. Layer, "Laser Length Metrology," presented at the NCSL Meeting in Denver, CO, July 15, 1987.

H. P. Layer, "Laser Length Metrology," presented at the Precision Measurements Association in Golden, CO, July 15, 1987

R. M. Schoonover, "Standards Lab Practice," presented at George Washington University, April 24, 1987.

TIME AND FREQUENCY DIVISION
FISCAL YEAR 1986

I. INTRODUCTION

The Time and Frequency Division, located in Boulder, 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, the speed of light being a defined constant. The Division played a major role in the measurement of the speed of light and the new realization of the meter. However, responsibility for maintaining the practical meter resides in the Length and Mass Division.

Section II of this report provides a separate, general discussion of some of the key issues facing the Division. The purpose of this discussion is to provide a background against which the work of the Groups in the Division can be understood. Following this, the work of the Division is presented along organizational lines as shown below. Since there is some overlap between the work of several Groups, certain tasks are referenced in more than one place.

Each of these sections begins with a short description of the general program and objectives of the Group along with a list of staff and guests in the Group. In an effort to relate the Division's work to it's mission, a set of objectives have been used. Any objective which is 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. Specific accomplishments and plans are listed under each objective.

<u>Objectives</u>

o Generate NBS time scales UTC(NBS) and TA(NBS).
o Maintain international time and frequency coordination.

- o Provide radio and satellite broadcast services.
- o Provide seminars and measurement services on a reimbursable basis.
- o Develop advanced methods for time transfer.
- o Establish the second and the meter for the International System.
- o Perform research and development on new primary frequency standards.
- o Perform basic studies in areas related to future frequency standards.
- o Develop metrology for precise time, frequency and length measurements.
- o Provide reference frequencies from the microwave to visible regions.
- o Measure far infrared frequencies of atoms and molecules.
- o Advise industry and government agencies on time and frequency metrology.

II. KEY ISSUES IN TIME AND FREQUENCY

General

The discussion below does not address the measurement technology and broad range of user services which are now adequately handled by the Division. Rather, it is aimed at defining where the Division is going or, in some cases, where it should be going.

Time Transfer

Satellite time transfer has become the method of choice for international time coordination with NBS playing a key role through development of the GPS Common-View Method. With this advance, time and frequency transfer is now limited by the performance of the primary standards themselves and the Division now uses the technique to support other applications (e.g., NASA Deep Space Network and studies of the Millisecond Pulsar). The Division is also working on two-way time transfer using commercial communication satellites, a method which should provide even higher-accuracy time transfer to support pending improvements in primary standards. Satellite time transfer has substantially altered the conduct of the Division operations and, in the future, it will play a larger role in the synchronization of major systems.

Primary Frequency Standards

Radiatively-cooled, trapped ions have been considered by many to be the best choice for future standards. The first demonstration of a Beryllium standard operating at an accuracy of one part in 10^{13} along with the development of a 'commercial' ion standard have bolstered that view. 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 very highest accuracy primary standards will most likely operate at frequencies in the optical region. This is due to the fact that, regardless of the clock frequency, the observation time most often determines the minimum linewidth and thus, the Q of the resonance increases directly with frequency. For this reason, the Ion Storage Group has been investigating an optical frequency standard based on mercury ions and it seems likely that they will demonstrate a prototype of such a device in the next few years. 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 where it could then be used as a time standard. The challenge is that of accurately relating an optical frequency to a microwave frequency. The Division has expertise in this area, but all would agree that this is a difficult thing to do routinely. Thus, it is important to initiate development of a simple, reliable chain (frequency division or multiplication) linking the microwave and optical regions. This could also provide for improvement of our realization of the meter and support optical frequency metrology which will be needed to support coherent optical communication systems.

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 stability and reliability of the ensemble. Research on time-scale algorithms should also continue, since this can contribute significantly to time-scale stability.

Broadcast Services

The advantages of satellite time transfer are discussed at the beginning of this section. It should be obvious that satellite broadcast of time and frequency signals 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 tracking information provided by operators of the GOES system. Communication satellites provide the potential for a very simple broadcast service with accuracy in the range of 100 ns to 1 μs. The Division and the National Research Council in Canada are both studying this concept and considering cooperation, since a single broadcast service might well serve both countries.

Discussions with the electrical power industry suggest the need for 1 μs synchronization of power networks. Deregulation of the communication industry poses synchronization problems at a similar level. The Division is interacting with the latter industry through their timing standards committee to support some collective resolution of the problems. A high-accuracy satellite service could be of value to both of these industries.

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 for such measurements in other regions of the electromagnetic spectrum. The Division is now working to develop and demonstrate phase-noise measurement systems in other important spectral regions. This effort is coordinated with the work in Division 723 on broadband-thermal-noise standards. The work naturally involves the development of stable reference oscillators and low-phase-noise multipliers, components which are important in the Division's work on primary standards and frequency synthesis.

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 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 two other projects: synchronization of clocks using two-way satellite time transfer, and timing for space-borne communications nodes. 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, Chief Eng.
A. R. Trevarton	D. Okayama

Convenient access to NBS standards of time and frequency is accomplished for the majority of users through 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 acquaint users with techniques for characterizing oscillators and distributing frequency and time signals. Examples of important applications of time and frequency services are given below.

Navigation

Celestial navigators need time to determine their precise location. An error of 2 s could cause a ship to miss its destination by about 1 km. 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 μs could produce the same 1 km 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 location and analysis of fast occurring events (faults), measurement of power flow, and the control of systems to minimize losses and avoid outages caused by exceeding stability limits.

Radio and TV stations need accurate frequency to broadcast signals at exactly their assigned frequencies. They need accurate time to set clocks so they can join the networks at the right instant. The aviation and aerospace industries need accurate time for aircraft traffic control systems and for synchronization at satellite and missile tracking stations.

The telecommunications industry needs time accurate to 1 μs and better to synchronize communication's nodes spread over wide geographical areas. Divestiture by AT&T along with the growth of other major carriers poses significant difficulty for synchronous transfer of calls through the interfaces between companies. Increasing data rates in the newer digital communication systems will further complicate system synchronization.

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 occur can be an important factor in determining the cause of a plane crash or equipment malfunction.

Geophysicists and seismologists studying lightning, earthquakes, weather, and other geophysical disturbances need time to synchronously and automatically obtain data from wide geographical areas and to label geophysical events. Other scientists use time for controlling the duration of physical and chemical processes while astronomers use time for labeling astronomical events, such as lunar occultations, eclipses, and pulses.

Science and Metrology

Manufacturers need time and frequency to calibrate counters, frequency meters and test equipment. Accurate spectra of molecules including information on pressure broadening are needed to accurately determine atmospheric concentrations of important pollutants. Laser frequency measurements provide accurate calibration frequencies for spectroscopists and for radio astronomy as well as the means for realization of the meter.

OBJECTIVE: Provide radio and satellite broadcast services.

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, 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 MHz for both stations and 20 MHz from WWV only. Accuracies within 1 ms 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 the capability of obtaining NBS time and audio frequency signals. The caller can receive a time signal, accurate to 30 ms 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-kHz low frequency receiver is required. WWVB's signal includes a binary coded system, needing special decoding equipment. The WWVB broadcast covers 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 have been relayed through the 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 permits automatic correction for variations in path delay resulting in time accuracy of 100 μs.

FY 1987 Plans and Accomplishments

Complete the survey of WWV, WWVB, WWVH and GOES users and document results.

Accomplishment - The survey is in progress and will continue until October, 1987. About 5000 responses were received as of August, 1987. Results are being tabulated in a dBase format and, following analysis of the results, a final report on the survey will be prepared.

Develop and implement staffing plans at Fort Collins and Hawaii that respond to anticipated retirements of both Chief Engineers.

Accomplishment - The Chief Engineer at WWVH, Chuck Trembath, retired on August 1, 1987. Noburu Hironaka, an engineer at WWVH, assumed the responsibilities of Chief Engineer on that date and a new electrical engineer was recruited to fill the vacancy created by the retirement. The Chief Engineer at WWV/WWVB is now eligible for retirement, but has decided to stay on for the foreseeable future. Arrangements made several years ago provide backup for his eventual retirement.

Conduct tests of electronic voice synthesis system for improved broadcast announcements.

Accomplishment - Voice synthesis equipment has been delivered to WWV by the National Weather Service, but the equipment manufacturer is still working on the required software and hardware interfacing. Testing will proceed as soon as the equipment is ready. Equipment costs have been covered by the Weather Service.

Develop 2nd-generation, more-automated software for GOES time code operations.

Accomplishment - The software is essentially complete except for one data acquisition/plotting module. Improvements will continue to be developed and implemented as appropriate.

Develop and implement an automatic tuning system for the standby WWVB antenna.

Accomplishment - The automatic tuning system is complete. Final testing and implementation will be completed shortly.

Maintain reliable operations from WWV, WWVB, WWVH, and the GOES satellites.

Accomplishment - Outages for all services continue to be minimal at levels varying from 0% (WWV) to about 0.1% (GOES) of total transmission time. Improved backup for the electrical power system for the GOES timing equipment has been developed and installed at Wallops Island, Virginia.

FY 1988 Plans

Procure and install new energy-efficient transmitters for WWV. This will include acceptance testing at the manufacturer's site and Fort Collins. The objective is to replace outdated equipment and to reduce energy costs. The savings should pay for the transmitters over the course of five years.

Prepare a final report on the findings of survey of users of services.

After the voice-synthesis equipment becomes operational, perform on-the-air tests of the equipment. Determine acceptability of broadcasts by users and, if successful, investigate options for acquiring additional systems for Fort Collins and Hawaii to replace outdated magnetic recording systems.

Maintain reliable broadcasts from WWV, WWVB, WWVH and the GOES satellites.

Develop documentation for and lead U.S. Study Group 7 (Time and Frequency Services) of CCIR. Head U.S. delegation to 1988 Interim Meetings of the International CCIR Study Group 7. Contribute NBS input to CCIR handbook on satellite timing methods and resources.

OBJECTIVE: Provide seminars and measurement services on a reimbursable basis.

Frequency Measurement Service

The frequency measurement service is automated, modest in cost, and provides traceability to NBS at a level of one part in 10^{12}. The service is based on common-view reception of low frequency signals from stations such as WWVB or Loran-C. This service provides the user with a data logger and a low frequency receiver which is appropriate to the particular location. A typical system contains a receiver, microcomputer, disc units and printer-plotter. The user provides a dedicated phone line and modem so that the system data can be compared with data recorded at NBS providing assurance that the users reference is accurate. To assist the user in getting the most out of this system, the Division provides training with the actual equipment.

Time and Frequency Bulletin

The Division continues distribution of it's Time and Frequency Bulletin to over 500 service users. The bulletin provides information on the performance of many useful references and notes events and service changes of interest to users. It was expanded to cover new services.

Seminars

The annual Division seminar provides industry and other agencies with information and training on the use of frequency standards. 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 1987 Plans and Accomplishments

Continue operation of the Frequency Measurement Service. Implement the automated training program so as to minimize staff hours spent on the service.

Accomplishment - Low turnover and good customer feedback indicate high customer satisfaction with this service. Service growth during the year was only modest since the Division decided to reduce promotion of the service in order to stabilize it near the current size (48 users).

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.

Accomplishment - This year's seminar, which was fully subscribed months in advance, was held off site at a local hotel. Many of the attendees were from the communications industry (AT&T, MCI, SPRINT, etc.). Guest lecturers from the communications industry and DOD provided special emphasis on timing for communications.

FY 1988 Plans

Continue operation of the Frequency Measurement Service.

Provide a comprehensive Time and Frequency Seminar (reimbursable). Develop an improved method for demonstrating time-domain and frequency-domain measurement systems to the large seminar audience.

OBJECTIVE: Develop advanced methods for time transfer.

The use of communications satellites for time transfer at all levels of performance appears to be widely accepted. In a recent annual report, the BIPM/BIH urged further development of the concepts. Much of this is due to improvements in the available technology and significant reduction in the cost of components and leased transceivers on satellites. 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 satellite. Additional tests have indicated that 20 ps comparisons are possible using the same techniques with higher transmission power levels. NBS, USNO and the NRC in Canada have informally agreed to develop a permanent time-transfer network to serve the three laboratories. All of the necessary equipment has been acquired and tests will begin next year.

FY 1987 Plans and Accomplishments

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.

Accomplishment - The NBS satellite earth station came into full operation early this year. Leased time through two commercial communications satellites was obtained for $35 per half hour. Subnanosecond precision was obtained in loop tests through these satellites. For a time-transfer network covering North America and Europe, INTELSAT has offered time on an Atlantic satellite for one year at no cost.

Begin operation of the two-way, time-transfer system on a limited basis with a few laboratories.

Accomplishment - Because of problems in bringing earth terminals into operation at USNO and NRC and because the INTELSAT satellite will not be available until mid 1988, the operation of the two-way-time-transfer system has been delayed by at least a year. The satellite delay is a result of problems with the Ariane launch rocket.

FY 1988 Plans

Perform two-way time comparisons between USNO, NRC and NBS using a domestic communications satellite.

Procure, assemble and license a mobile KU-band earth station for calibration of the two-way satellite facilities of NBS, USNO and NRC.

Begin trans-Atlantic time comparisons following availability of INTELSAT satellite (to be launched).

OBJECTIVE: Advise industry and government agencies on time and frequency metrology.

FY 1987 Plans and Accomplishments

Complete study of the synchronization of space-borne communications nodes.

Accomplishment - The study, identifying and evaluating technology relative to DOD needs for space communications and other applications, is complete. A timing architecture capable of supporting space communication systems was proposed. Using this architecture, timing sources and timing delivery to space platforms were examined.

Pending funding, implement a satellite tracking network and experimentally determine how best to generate the satellite ephemeris required to support a 0.1 μs time and frequency broadcast service.

Accomplishment - Without funding, progress on the project was minimal.

FY 1988 Plans

Pending funding, simulate time transfer to space platforms through use of two-way time transfer between earth stations.

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 timing centers 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 it's research. The Group has developed a coordination scheme based on common view of the Global Positioning System (GPS) satellites which is now the de facto coordination approach for the world.

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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 standards 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) and AT1 time scales are computed following each 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) with 1 ns accuracy at all times. Coordinating with the Bureau Internationale de L'Heure, UTC(NBS) is steered toward and kept within 1 μs of UTC. AT1 is a metrology tool, unsteered in time or frequency, and made to be as stable and uniform as possible.

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 periodic calibrations of the ensemble by the primary frequency standard, NBS-6.

FY 1987 Plans and Accomplishments

Finish remodeling of the clock room.

Accomplishment - All of the clock room equipment has been purchased, all of the critical clock room rearrangement has been completed and the recabling of the semi-rigid coaxial lines is proceeding in a systematic and orderly fashion -- having to be done while the time scales are in full operation. The public display window is complete.

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.

Accomplishment - Five poorly performing clocks, two belonging to NBS and three sent by USNO to NBS for this study have been aligned per the De Marchi procedure. Significant improvement was observed in all cases. One of the USNO clocks now performs as well as any commercial cesium standard ever tested by the Division.

Install and test backup measurement system for the time scale.

Accomplishment - The backup measurement system has been installed, and the tests were initiated in May, 1987. The testing will continue over the next several months as the cabling is carefully changed on the time-scale operating system so that the output is not perturbed.

Improve time-scale reference for the NBS Global Time Service.

Accomplishment - The new time-scale reference has been completed and tested. The final cabling of it into the system is near completion.

FY 1988 Plans

Test and document the performance of the NBS Time Scales in order to evaluate their performance for the most stringent of measurements, e.g. comparisons with the millisecond pulsar.

Complete the semi-rigid coaxial connections for both the back-up and the primary-measurement system and implement necessary software adaptations.

Contingent on the availability of funding, proceed with the acquisition of a new time-scale computer.

Train several Division staff on the De Marchi alignment techniques for commercial cesium standards.

OBJECTIVE: Maintain international time and frequency coordination.

A satellite-based, time-transfer system developed by the Division is now in operation. 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 and TAO in Tokyo, Japan; VSL in Delft, The Netherlands; NPL in England; NPL in Israel; CSIRO in Australia; TUG in Austria; USNO in Washington, D.C.; and NBS in Boulder. A computer-based, automatic-data-collection network acquires data from the receivers. This data is combined with 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 of better than 10 ns after one day of averaging. The Jet Propulsion Laboratory employs three receivers developed by NBS in the same mode to provide frequency calibrations at a few parts in 10^{14} between the sites of the NASA Deep Space Network. 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 generation of the International Atomic Time Scale (TAI).

FY 1987 Plans and Accomplishments

Transfer the software for handling GPS common-view data to the BIH.

Accomplishment - The NBS software has been successfully transferred to the BIH, and BIH staff now generate the schedule for international comparisons. In addition, BIH sent a staff member to NBS to acquire techniques for optimal time and frequency transfer using GPS.

Study methods for improving the accuracy of time transfer using the common-view technique.

Accomplishment - Using NBS developed software, several problems have been identified and solutions proposed for improving the accuracy of GPS time transfer by as much as an order of magnitude. In particular, it appears that two-frequency measurements can provide a simple means for more accurate determination of delay variations in the ionosphere.

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.

Accomplishment - Two NBS calibrated GPS receivers were sent to the BIH accompanied by a Division staff member. One receiver was then carried to each of the European national time centers. A joint report and paper analyzing the study revealed some problems, but verified that the accuracy of the GPS common-view technique is at the 10 ns level.

FY 1988 Plans

Cooperate with BIH, USNO and the Naval Research Laboratory on calibration and evaluation of GPS receivers for optimum time and frequency transfer.

Assist other national timing centers as appropriate with the use of GPS common-view time transfer.

Develop the hardware and software needed to implement major improvements in GPS common-view time transfer including evaluation of system biases.

Develop software to further streamline and automate international time comparisons with the goal of weekly estimates of the world time ensemble.

OBJECTIVE: Develop metrology for precise time, frequency and length measurements.

Techniques for Measurement of Frequency and Frequency Stability

The Division has been a world leader in the development and dissemination of the measures of frequency stability and their practical implementation. The Division developed the de facto international standard for practical specification of frequency stability and played a major role in the development and test of the dual-mixer concept for measuring time, frequency, and frequency stability providing for simple, precise (picosecond) measurement of the difference between state-of-the-art frequency standards. Work on the effects of phase noise on frequency multiplication provided an explanation for 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 low noise devices have many applications in precise measurement as well as in the development of new frequency standards such as the passive hydrogen maser, the stored ion standard, and cesium standards.

Techniques for Characterizing Noise in Clocks

Memory of the rate of the primary standard is stored in a time scale, an ensemble of commercial cesium standards. The clocks in the time scale don't have the accuracy of NBS-6, but they do have very good frequency stability. The stability of a clock ensemble can be improved by increasing the number of clocks, by improving the stability of individual clocks, by wisely utilizing the clocks available, or by a combination of these approaches. The Division has chosen to use a modest number of clocks ensuring sufficient reliability, redundancy and variety (to avoid systematics from a particular manufacturer), but then to characterize the clocks with enough care so that the algorithms which average the clocks make optimum use of the performance of individual members of the ensemble.

The algorithms which control the time scale have evolved to their current state through considerable work over a long period. UTC(NBS) is generated by an algorithm which can be traced back 20 years. In order to estimate the performance of this algorithm, several studies were conducted. Using Kalman filters, a method was developed 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 correct. A study was then made of the statistical significance of frequency drift and this yielded additional important insights. A second major development was a Kalman (or recursive) algorithm for estimating time from the ensemble of atomic clocks. 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). During this effort the earlier algorithm which generates UTC(NBS) was found to be very near optimum in its performance. Over the last year its stability was shown to be of the highest order as it was found to be the most stable reference for the characterization of the stability of the millisecond pulsar, PSR1937+21.

FY 1987 Plans and Accomplishments

Put environmental parameters into the time-scale data base and correlate the time scale performance with them.

Accomplishments - The hardware was installed and measurements have been taken for some time on various environmental parameters. The data was archived, but not on the time scale computer. This will be done when other higher priority work on the time scale is completed.

Assist others in the application of the time-series statistical methods to other areas of metrology.

Accomplishment - A major paper on this topic was published in the IEEE I&M Transactions. The Statistical Engineering Division has now initiated study of the ideas. Preliminary findings are good and they have developed interesting insights into this statistical concept.

FY 1988 Plans

Evaluate the NBS time scales and algorithms to ensure confidence in measurements such as comparisons with the millisecond pulsar.

Document the performance of the NBS algorithm for practical clock systems.

If funds and staff are available, continue study of the use of time-series-analysis techniques in other disciplines. A joint proposal with the Statistical Engineering Division on this subject was made to management.

OBJECTIVE: Provide seminars and measurement services on a reimbursable basis.

Global Time Service

The Division now offers a service, based upon an NBS designed receiver, which provides for highly precise time and frequency transfer to a users site. A receiver, located at the users facility, communicates data automatically to an NBS computer which stores the 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 the NBS computer through which he can access the results of the NBS analysis. Tests between receivers in Colorado, Canada, Germany, France, Spain, Wyoming, Louisiana, Washington, DC and California have demonstrated time comparisons with precisions of better than 10 ns 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.

Calibration of Atomic Standards

In conjunction with development of the time scale algorithms the Division has developed a time and frequency measurement system with exceptional performance. Clocks are now calibrated and characterized through comparisons with the ensemble clocks using the same measurement system which reads the ensemble clocks. This system is used as a reference for research within the Division as well as for reimbursable calibrations.

FY 1987 Plans and Accomplishments

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.

Accomplishment - NBS has a representative on the committee which is drafting a civilian-sector, interface control document to be incorporated in a more general DOD document on GPS use. The committee is considering solutions which would yield no degradation in accuracy of time transfer.

Improve the algorithm for estimation of the performance of remote clocks (accessed through GPS) to improve accuracy and stability assessments.

Accomplishment - This work is complete and the algorithm is now routinely used. The concepts have been shared with the BIH staff.

FY 1988 Plans

Expand the time scale measurement system to allow for additional input ports for clock calibrations.

Continue participation on GPS committee with the goal of minimizing the effects of GPS degradation on the transfer of time and frequency.

Develop and implement methods for eliminating or minimizing bias effects which have been identified in GPS measurements.

OBJECTIVE: Advise industry and government agencies on time and frequency metrology.

FY 1987 Plans and Accomplishments

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.

Accomplishment - A joint study conducted by USNO, NRL and NBS was completed and the results have been published. Through computer simulation, NBS demonstrated that time steering to 10 ns is achievable. Implementation of the proposed concept is proceeding in a cooperative effort. Several sources of system bias have been identified, but corrective measures must still be developed.

FY 1988 Plans

Continue to assist the Joint Program Office at Air Force Space Division on methods for GPS time steering.

Assist the Joint Program Office with consultation on proper methods for utilizing clock ensembles and combining algorithms to improve reliability and stability of the GPS reference systems.

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 was 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 other issues 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 measurement of phase-noise 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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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 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.

FY 1987 Plans and Accomplishments

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 between failure.

Accomplishment - Work on this program has been slowed by a lack of funding from the Naval Research Laboratory. The third maser is still three or months away from completion. However, the second maser was retrofitted with a new vacuum system to improve reliability and it should be back in service by December.

Continue to advise the staff of the cesium standard project on servo issues including actual circuit implementations.

Accomplishment - Consultation with this Group is substantial involving a number of servo design issues.

Explore new phase modulator concept theoretically and initiate experimental study if appropriate.

Accomplishment - Based on the shortcomings of the phase modulators used in NBS-6 and the small hydrogen masers, calculations on three different designs have been performed. These are all inherently more stable and have smaller distortions. The most promising of these should be easy to construct and involves very little manual adjustment. A prototype is being built in order to verify the concept.

Purchase a commercial version of the passive hydrogen maser to improve performance of the NBS ensemble.

Accomplishment - Purchase of this device was delayed because the manufacture wasn't quite ready to accept fixed price orders. They are just beginning full tests of the maser and expect to be able to accept orders in September 1987.

FY 1988 Plans

Through the Industrial Research Associate Program, test the performance and environmental sensitivity of the commercial passive hydrogen maser.

Pursuant to positive results in the above tests, purchase a commercial passive hydrogen maser for the time scale.

Continue to assist the cesium Group in the design of accurate servo systems for NBS-7. This will include the evaluation of new modulator(s).

OBJECTIVE: Provide seminars and measurement services on a 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 1987 Plans and Accomplishments

Modify the 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.

Accomplishment - The prototype system for this frequency range was built and tested. The system automatically finds phase quadrature as needed for accurate measurements. Full automation of the phase-lock-loop gain requires a custom microprocessor. The hardware is in hand and the software written, but the system is not yet fully integrated.

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.

Accomplishment - The prototype system was constructed and tested. The system automatically finds phase quadrature as needed for the measurement and the noise floor is very low. The custom microprocessor needed to interface the system with the computer controller is in hand and most of the code has been written for it.

Develop a low-noise reference signal at 10.6 GHz.

Accomplishment - The phase noise of the best available microwave sources has been reduced by 10 to 40 dB through use of a reference cavity in a frequency lock loop. This composite system will eventually by phase locked to a multiplied quartz oscillator system.

FY 1988 Plans

Complete automation of the 5 MHz to 1 GHz phase noise measurement system to include an automated calibration of the accuracy to approximately ±1 dB.

Complete automation of the 1 GHz to 26 GHz phase noise measurement system.

Assemble and test a 33 to 50 GHz phase-noise-measurement system with a 1 GHz bandwidth. The accuracy goal is ±1 dB to 30 MHz and ±2 dB to 1 GHz.

Build and test a multiplier system to lock the 10.6 GHz microwave oscillator to a quartz oscillator at 100 MHz. The 100 MHz oscillator will then be phased locked to a 5 or 10 MHz oscillator for normal analysis.

OBJECTIVE: Establish the second and meter for the International System.

FY 1987 Plans and Accomplishments

Conduct experimental tests of new method for low-noise synthesis to X band with funding from the Washington University and the Department of Defense.

Accomplishment - A very low noise divider system for dividing 100 MHz down to 10 and 5 MHz was developed. The noise is about 30 dB less than the best systems described in the literature. This will greatly simplify the synthesis problems. Two new technologies which appear capable of dividing 10 GHz down to 100 MHz were also identified. Arrangements were made to obtain sample devices for testing. In the meantime, development has started on a very low noise multiplier based on harmonics of 500 MHz tied to 100 MHz. This will be used for testing the dividers and perhaps for the final synthesis if, for some reason, the dividers are not suitable. The phase noise of an X-band source was improved 20 to 30 dB by frequency locking the source to a high-Q cavity in a servo loop with a bandwidth of 2 MHz. For Fourier frequencies between 20 kHz to 1 MHz from the carrier, the performance is probably the best ever achieved for a room temperature device.

OBJECTIVE: Advise industry and government agencies on time and frequency metrology.

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 $\approx 5\times10^{-15}$ at 1 day and $\approx 3\times10^{-15}$ at 8 days. At a level of resolution of $\pm\ 3\times10^{-16}$/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 on this program. This cooperation continues and the first passive hydrogen maser to be constructed in this collaboration 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.

Phase noise

With the initiation of new work on measurement and control of phase noise, the Division is providing significant consultation on the subject to science, industry and other government agencies. The Division has a clear opportunity to provide a solid basis for phase noise metrology.

FY 1987 Plans and Accomplishments

Continue collaboration with Industrial Research Associates and the Naval Research Laboratory on the passive hydrogen maser.

Accomplishment - Work in this area has been more consultation than collaboration, since the phase-noise program has dominated available resources. Consultation with industry has focussed on the electronics and discharge problems and that with NRL has covered oven problems.

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.

Accomplishment - (1) An invited paper on "Low Noise Frequency Synthesis" was presented at the Symposium on Frequency Control. This paper reviewed practical limitations of circuits as well as recent advances made at NBS. (2) Lectures on phase noise were prepared for a short course on frequency standards given in July. A variation of these lectures was given in September at a short course on noise in microwave and millimeter systems. (3) Consultation was provided to the Applied Physics Laboratory and the National Security Agency on new approaches for low-phase-noise microwave sources.

Additional Accomplishments

Accomplishment - A low noise amplifier with the best room-temperature noise power, $(2.5\times10^{-16}\ A)(1\times10^{-9} V) = 2.5\times10^{-25}$ W, was developed and a paper submitted for publication.

Accomplishment - A paper on concepts for compensated thermal enclosures was presented at the Symposium on Frequency Control.

FY 1988 Plans

Continue consultation with industry and governmental agencies on methods for measurement and control of phase noise.

VI. ATOMIC BEAM STANDARDS

This Group is responsible for operation of the current primary frequency standard, NBS-6 and the development 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.

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OBJECTIVE: Establish the second and meter for the International System.

Operation of 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 $7x10^{-15}$. 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 clocks that. 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 include greatly improved components to provide narrower resonance lines (25 Hz), the ability to reverse direction of the atomic beam (which allows errors due to asymmetries in the cavity to be diagnosed), and other features aiding analysis of performance. NBS-6 has an accuracy of $8x10^{-14}$; 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 1987 Plans and Accomplishments

Shift responsibility for future evaluations of NBS-6 to 1 group. Past practice involved rotation of this responsibility.
Accomplishment - Responsibility for evaluation of NBS-6 has now been assumed by the Atomic Beam Standards Group.

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.

Accomplishment - NBS-6 was upgraded (improved electronic systems and modified vacuum system) to minimize difficulties encountered in previous evaluations. This has allowed evaluation in greater depth, since beam reversals can be accomplished more rapidly. The result is that the Group is learning a great deal more both about the standard and the physics of cesium beams in general. In the longer term, a reduction in the quoted uncertainty of 8×10^{-14} may be possible, but for now, some previously undervaluated systematic errors are proving difficult to model. At the present, proving the historical evaluation uncertainty is difficult.

As staff time becomes available, recharge NBS-4 with cesium and bring it back into operation.

Accomplishment - Higher priority has been placed on the study of systematic errors in NBS-6 and the development of NBS-7 resulting in delay of this project.

FY 1988 Plans

Complete current evaluation of NBS-6.

Recharge NBS-4 with cesium and bring it back into operation.

Study potential reduction of the uncertainty specification on NBS-6 and determine the advisability (limited resources) of attacking this project.

OBJECTIVE: Perform research and development on new 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 $\sigma_y(\tau) < 7\times10^{-12}\tau^{-1/2}$.

A larger test bed for the optically pumped standard has been designed and the major components have been fabricated and assembled. This test bed will serve as the basis for NBS-7. The 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 1987 Plans and Accomplishments

Initiate development of advanced electronic servosystem to achieve 10^{-6} splitting of the cesium resonance.

Accomplishment - The modulator and demodulator/integrator are at the heart of the servo system. A modulator promising improved linearity has been designed tests are in progress. The demodulator/integrator was designed and is under construction. Line splitting of 10^{-6} still appears reasonable. The frequency multiplier and odd-to-even synthesizer have been fabricated and tested.

Develop practical laser systems for optical state selection and detection.

Accomplishment - A method for narrowing the linewidth and controlling the frequency of diode lasers was developed in collaboration with a guest worker from France. It is now clear that this technique provides spectrally pure radiation which does not substantially increase the atomic-beam noise above the shot-noise limit. The stabilized diode lasers will be available to meet the clock development schedule, but additional study of the use of optical fiber for coupling between the diode lasers and the clock is in progress. Normal diode lasers are so sensitive to optical feedback that this would not be considered. However, with less sensitivity to feedback, the stabilized lasers might be usable with fiber.

Complete construction of the test bed for NBS-7 and demonstrate preliminary operation (no error assessment).

Accomplishment - The design and fabrication of all of the major components of the beam tube are complete. Testing of the individual subsystems has been initiated and it is reasonable to expect that an atomic beam can be generated by the end of FY 1987.

Initiate experimental studies of light shift, cavity phase shift and Majorana transitions.

Accomplishment - The need for theoretical study of systematic effects along with procurement problems slowed the design and fabrication processes so that the beam tube was not assembled until the end of the fiscal year. This left no time for the experimental studies.

Initiate development of a computer-controlled system for automated evaluation and operation of the standard.

Accomplishment - The basic concept for the automation of the standard has been developed and the computer for controlling the system along with some interfacing has been purchased.

FY 1988 Plans

Complete integration of all of the clock subsystems.

Determine the signal-to-noise performance and stability for the various optical pumping schemes.

Initiate evaluation of the systematic uncertainties of the standard.

Initiate test of servo system concepts for locating the line center.

OBJECTIVE: Advise industry and government agencies on time and frequency metrology.

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. 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 from other government agencies. In addition, the Division has formed an Industrial Research Agreement with a manufacturer of cesium clocks. 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 1987 Plans and Accomplishments

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.

Accomplishment - The first engineering prototype clock has been fabricated. As with the scientific prototypes before it, scattered light at the windows is a problem. A second tube with improved windows should be completed shortly.

Complete design and tests of modified recirculating cesium oven.

Accomplishment - Life test on the simple recirculating ovens have shown no deterioration in beam intensity. Based on calculation of the integrated flux from one oven, it appears that the initial cesium charge is nearly expended. This suggests that the beam intensity remains stable to the end of the life of the oven.

Collaborate with De Marchi in completing tests of the Rabi-pulling model on commercial cesium standards and transfer information on this work to industry and relevant government laboratories.

Accomplishment - With the Rabi-pulling model as a guide, several poorly performing cesium standards were tuned to power-insensitive operating points and then reevaluated. In every case the improvement in stability was substantial. One standard now performs as well as any commercial standard ever evaluated by the Division. Several government agencies have shown great interest in the result, since it offers a cost-effective approach to improving the performance of systems in the field.

FY 1988 Plans

Continue collaboration with industry on the development of optically pumped cesium standards.

Complete fabrication and testing of the hybrid recirculating oven.

Contingent on funding, develop improved methods for optimal tuning of commercial frequency standards and study the application of third order servo systems as a means for completely eliminating Rabi-pulling effects.

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 study 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 primary standard. While the focus of the work is ion standards, the techniques are also applied to other problems of fundamental interest.

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OBJECTIVE: Perform research and development on new 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 developed 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. The measured stability was about equal to that of a commercial cesium clock. Frequency stability and accuracy performance can be improved in the future by using an ion with a higher hyperfine frequency.

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 S→D quadrupole transition in Hg^+ has been studied. The transition was observed for the first time in a miniature rf trap on a single Hg^+ ion. The present linewidth is limited by the laser bandwidth, but this transition has a fundamental Q of about 0.5×10^{15} (radiatively limited).

Trapped Ion-Cloud 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 many 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 mHz) and reduction of errors due to the second-order Doppler shift.

FY 1987 Plans and Accomplishments

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.

Accomplishment - Recoilless absorption (optical Mossbauer effect) and Doppler-effect-generated "phonon" sidebands of a single trapped ion have been observed. The recoilless line has a direct application for optical frequency standards. Cooling to the theoretical laser cooling limit of 1.7 mK was verified by comparing strengths of the sidebands of the carrier. The best resolution (limited by laser linewidth) obtained to date is 30 kHz at 1.07×10^{15} Hz.

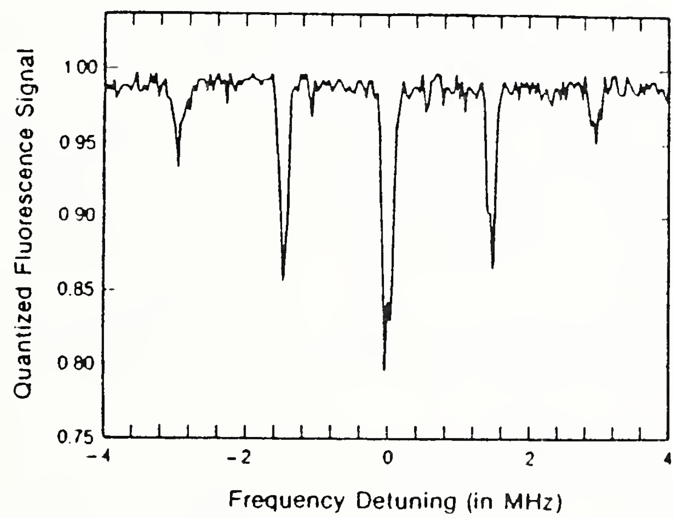

Figure 1. Quantized signal showing the electric-quadrupole-allowed $5d^{10}\ 6s\ ^2S_{1/2}$ ($m_J = -\frac{1}{2}$) - $5d^9\ 6s^2\ ^2D_{5/2}$ ($m_J = \frac{1}{2}$) transition in a single, laser-cooled $^{198}Hg^+$ ion. The horizontal axis is the relative detuning from line center in frequency units at 282 nm. The vertical axis is the probability that the fluorescence from the 6s $^2S_{1/2}$ - 6p $^2P_{1/2}$ first resonance transition, excited by laser radiation at 194 nm, is on. The recoilless absorption resonance (carrier) and the Doppler sidebands due to the residual secular motion of the laser cooled ion are clearly resolved.

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.

<u>Accomplishment</u> - The new trap has been fabricated and initial tests performed using $^9Be^+$ ions. With the increased magnetic field stability, the linewidths of the field-dependent transitions are observed to be more than two orders of magnitude narrower than previously obtained.

Careful theoretical analysis of limits to high-resolution spectroscopy and frequency standards will be undertaken and written up.

<u>Accomplishment</u> - The first draft of the paper is complete. It covers trade offs between signal-to-noise ratio (goes up with number of ions) and 2nd-order Doppler shift (also increases with number of ions).

<u>FY 1988 Plans</u>

Improve the spectral purity of the 282 nm source for the Hg^+ optical frequency standard. The basic approach is to frequency stabilize an existing laser to an ultra-stable, high-Q cavity.

Make first measurements of field-independent hyperfine transitions in $^9Be^+$ or $^{25}Mg^+$ with the new Penning trap in the superconducting magnet. The goal is an accuracy exceeding one part in 10^{13}.

OBJECTIVE: Perform basic studies in areas related to future 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.

<u>Search for Spatial Anisotropy</u>

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). As a test of the EEP the frequency of the $^9Be^+$ "clock" transition $(M_J = 1/2, M_I = -3/2) \rightarrow (M_J = 1/2, M_I = -1/2)$ has been compared to the frequency of a passive hydrogen maser to see if a correlation can be found with orientation in space. With a resolution better than 0.1 mHz, no variation was observed. These results decreased previous experimental limits by a factor of 300, but were superceded by work at the University of Washington. A projected gain of a factor of 1000 over previous measurements should be achievable using $^{25}Mg^+$ in the superconducting magnet. Such measurements are a fairly easy extension of searches for systematic frequency shifts in an ion frequency standard.

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 $^{9}Be^{+}$ 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 100. Calculations predict that at $\Gamma \simeq 2$, the pair correlation function should begin to show oscillations characteristic of a liquid, and at much larger values of Γ ($\Gamma \simeq 170$) 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 $\approx 2 \times 10^{7}/cm^{3}$ and temperatures of $\approx$ 10 mK produced values of $\Gamma \simeq 100$. 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 1987 Plans and Accomplishments

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.

Accomplishment - (1) The limit of absorption spectroscopy has been achieved by observing direct absorption by a single atomic particle. This was published in Optics Letters 12, 399 (1987). (2) Motional sidebands were observed (see Figure 1 under earlier accomplishment). (3) & (4) Work on sideband cooling and cooling to zeroth quantum level has been postponed. (Added Accomplishment) Quantum Jumps. Discrete fluorescence changes in a three-level, optical-pumping scheme on single Hg^{+} and Mg^{+} ions were observed and compared to theory. The results are shown in Figure 2. (Added Accomplishment) Quantum-Jump Spectroscopy. Lifetimes and branching ratios of a single, metastable Hg^{+} ion were measured by analyzing the statistics of quantum jumps. The only noise observed was the quantum noise of the ion.

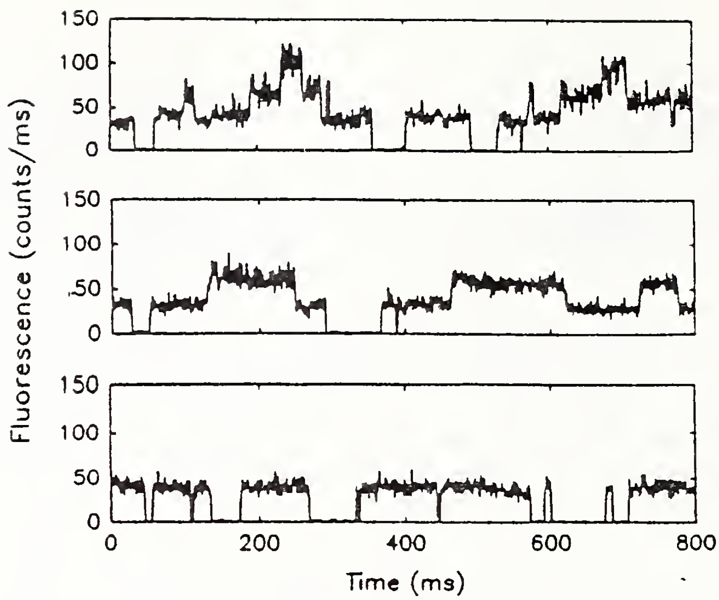

Figure 2. Fluorescence intensity as a function of time for samples of three ions (top trace), two ions (middle trace), and one ion (bottom trace) in an rf trap. The fluorescence changes suddenly each time a Hg^+ ion either makes a transition to a metastable D-state (step down) or back to the ground S-state from a D-state (step up). The integration time per point is 1 ms.

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.

<u>Accomplishment</u> - Mg^+ quantum jumps were examined theoretically (paper accepted for publication) and recently observed (paper in preparation). Stimulated Raman transitions were investigated theoretically, but the experiment has been postponed.

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.

<u>Accomplishment</u> - The effect has been shown to be masked by a hyperfine-induced, g_J-factor shift in third-order-perturbation theory (N. Fortson, U. of Washington). Therefore, this project has been temporarily shelved.

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.

<u>Accomplishment</u> - The apparatus for this experiment has been completed and initial tests are in progress. (Added accomplishment) An extensive study of the static properties of ion plasmas in three

experimental traps has been completed. Experimental studies of shear, cloud shape, aspect ratio vs. rotation, and temperature equilibrium were made and compared with theory. Results will be submitted to Physical Review A shortly.

FY 1988 Plans

Hg^+ Single Ions. (1) Initiate sideband cooling studies to reach the zeroth quantum level. (2) Complete studies of lifetime and branching ratios using quantum-jump spectroscopy. (3) Investigate the spectrum of pseudomolecules formed by two or more ions in a trap. (4) Develop narrower laser linewidth for higher resolution studies of quadrupole resonance.

Ion Plasmas. (1) Investigate Bragg scattering on $^9Be^+$ plasmas. (2) Look for order is plasmas by imaging plasmas onto a photon-counting imaging tube. A shell structure is predicted by theory. (3) Study ion plasmas in an rf trap with emphasis on reducing rf heating. (4) Investigate non-neutral plasmas using macroscopic (10 μm diameter) particles in an rf trap.

Synchrotron Frequency Divider. Assemble first test apparatus to isolate single electrons in a new superconducting-magnet apparatus.

VIII. LASER FREQUENCY SYNTHESIS

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 frequency and wavelength spectroscopic standards in the infrared and far infrared. Of particular note is the generation (synthesis) of tunable far infrared radiation (TuFIR) using either second-order or third-order mixing on the metal-insulator-metal, point-contact diode. The generated radiation completely covers the far infrared part of the spectrum. The Group continues to improve devices and concepts for frequency synthesis. This will prove to be especially valuable for stored ion standards in the visible part of the electromagnetic spectrum.

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OBJECTIVE: Provide reference frequencies from the microwave to visible regions.

Frequency References (Measured with Respect to the Cesium Standard)

The advances made by the Laser Frequency Synthesis Group in extending direct frequency measurements from the microwave to the visible portion of the spectrum are now being used to determine the frequencies of atomic and molecular transitions. These measurements are hundreds of times more accurate than the old wavelength measurements. The knowledge of the frequencies of selected species allows the spectroscopist, astronomer, or atmospheric scientist to calibrate spectrometers and receivers with appropriate atomic or molecular 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. The CO_2 laser which is stabilized to CO_2 itself furnishes the main frequency grid for all of the measurements and is widely used for reference purposes.

The far infrared (0.1 to 5 THz, 3 mm to 60 μm)

The frequencies of several hundred optically pumped lasers have been measured. Frequencies of > 800 lines were published this year in a review paper. Rotational frequencies of CO, HCl,HF, and HBr have been measured.

The Infrared Region (25 to 200 THz, 1.5 to 12 μm)

The frequencies of hundreds of lines of OCS, DBr, CO, CO_2, N_2O, and NO now furnish reference grids for this region. The methane line used to stabilized the He-Ne laser is especially noteworthy. Atlases and tables of reference frequencies covering selected infrared regions are available.

FY 1987 Plans and Accomplishments

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.

Accomplishment - The measurements were completed and the results published as NBS Technical Note 1308.

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.

Accomplishment - The measurements and analysis are complete and a paper describing the results is in preparation.

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.

Accomplishment - These measurements are in progress and should be completed shortly.

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.

Accomplishment - The priorities in the NASA-NBS Frequency Standards Program were reordered. This work was replaced by measurements of the B, C, D and E bands in OCS. A publication of the results is in preparation.

FY 1988 Plans

Measure the 1372 cm^{-1} hot-band of OCS leading to molecular constants and standard frequencies in the 520 and 2412 cm^{-1} region as well.

Measure frequencies of spectral lines near 1635 cm^{-1} in N_2O for use as standard reference frequencies.

Measure hot-band features in OCS near 1700 cm^{-1} OCS as standard references.

Make accurate measurements on H_2O in the far infrared so that "impurity" absorption at low pressure can be used to calibrate Fourier transform spectrometers.

OBJECTIVE: Establish the second and the meter for the International System.

Frequency Measurements Suitable for Realizing the Definition of the Meter

In 1982 the Comité Consultatif pour la Définition du Métre (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. 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 requires measurement of the absolute frequency of spectral lines in the visible region. To this end, the Division has performed two highly accurate frequency measurements of hyperfine transitions in molecular iodine used for laser stabilization.

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 (3.39 μm). 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 with respect to CH_4. 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.

Measurement of Frequency and Frequency Stability

Frequency metrology from the far infrared to the visible has been greatly stimulated by work in the Division. An extremely important aspect of this work was the first frequency measurement of the 3.39 μm line of CH_4 followed by the wavelength measurement of the line. The product is a value for the speed of light nearly 100 times more accurate than the previously accepted value. Coupled with frequency measurements of visible lines, this has led to 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 it reduces the number of frequency reference lines needed to 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. The Division has 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 spectrum. The MIM diode played a major roll in the frequency synthesis chain which connected the cesium clock to the visible I_2-stabilized lasers and hence provided the realization of the meter from the new definition.

The MIM diode has been used for the past 20 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. Six tenths of a microwatt of cw, tunable-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. Recently the HCl, CO, and HF spectra from 0.5 to 5.5 THz have been measured and these simple molecules now provide for excellent calibration standards in that frequency range.

FY 1987 Plans and Accomplishments

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.

Accomplishment - In collaboration with the Phase Noise Project, a highly stable microwave oscillator is under development. This will provide the low-end base for the chain. The first step in the chain will involve multiplication using a Schottky-barrier or MIM diode to about 0.5 THz. Several approaches can be taken with the higher frequency elements in the chain and further study is needed to select the best approach.

Continue the study of diode base materials and coatings for the tungsten whiskers in an effort to develop more efficient and more stable mixers.

Accomplishment - The current-voltage curves for tungsten whiskers on nickel, cobalt, and tin-telluride were studied and the results are being analyzed.

Initiate measurements of the spectral purity (phase noise) of the low-end components for a multiplier chain in collaboration with Fred Walls.

Accomplishment - A new system which locks a 10 GHz oscillator to a 5 MHz quartz oscillator has been assembled and testing is in progress. Initial results indicate a substantial reduction in phase noise.

FY 1988 Plans

Investigate the use of special high-frequency, Schottky diodes for frequency synthesis in the far infrared.

Using the best available mixer, attempt to synthesize ~0.5 THz from X band. This will be the first link in the new chain connecting the microwave to the optical region where the stored ion standard will operate.

OBJECTIVE: Measure far infrared frequencies of atoms and molecules.

High resolution spectroscopic measurements in the far infrared have been advanced significantly through development (at NBS) of two measurement techniques. These are used to make laboratory measurements, previously inaccessible, which have bearing on 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.

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 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.

FY 1987 Plans and Accomplishments

Search for the ions HeH^+, ArH^+ and H_2D+.

Accomplishment - New observations are difficult to plan. The ArH^+ ion was found and two unexpected finds were NeH^+ and N_2H^+ ions. The results are being analyzed and results will be published.

Measure the temperature dependance of the broadening coefficient for OH and HCl. Measure the broadening of HF produced by O_2 and N_2.

Accomplishment - The broadening coefficients for O_2 and HCl produced by O_2 and N_2 were measured.

Search for other molecules (frequency measurements and molecular constants) such as H_2O, H_2O_2, HO_2, HOCl and O_3.

Accomplishment - Using TuFIR spectroscopy, the HD, CH, and $H_2{}^{18}O$ molecules were found. Using LMR spectroscopy, a new molecular species, metastable CH ($^4\Sigma$) was identified, and LMR spectra of ^{13}CH and ^{13}CF were observed.

Finish work on the helium-cooled pre-filter detector.

Accomplishment - The work is in progress and will be finished shortly.

FY 1988 Plans

Continue improvements in TuFIR spectrometry and search for new species interesting to radio astronomers and atmospheric spectroscopists. Install a new photoconductive detector in the spectrometer to enhance sensitivity.

Build a higher power CO_2 laser to pump the FIR laser and install a beam splitter in the FIR laser.

Continue LMR spectroscopy of metastable molecular species to obtain new information on previously unknown species.

Search for the elusive H_3O^+, H_2D^+, and NH^+ molecular ions.

IX. GEOPHYSICAL MEASUREMENTS

This is a small program conducted in JILA by Time and Frequency Division staff. One of the projects involves construction and demonstration 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. These tiltmeters are also installed in a seismic zone in Southern California to investigate the utility of tilt measurements for earthquake prediction. A third program involves the use of GPS signals for geodesy. This is a joint effort involving 7 universities and funded by the National Science Foundation.

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- J. Levine, Project Leader
- J. A. Magyar
- A. Brewer (Res. Assistant - CU)
- B. Busby (Res. Assistant - CU, graduated 7/87)
- M. Holt (Res. Assistant - CU)
- K. Hurst (Res. Assistant - Columbia U.)
- C. Meertens (Res. Assistant - CU, graduated 5/87)
- C. Rocken (Res. Assistant - CU)
- A. Levchenko (Guest Worker - USSR)
- V. Sadofsky (Guest Worker - USSR)

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 appears that very accurate geodetic measurements can be accomplished. A major program in this area, funded by NSF, involves collaboration between a number of universities to utilize this concept. This NBS Group has assumed responsibility for hardware and software developments involving the GPS satellites and for some aspects of the initial data reduction and analysis.

FY 1987 Plans and Accomplishments

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.

Accomplishment - Several tests of the multiple-wavelength system were conducted over baselines ranging from a few meters in the laboratory to a 23 km baseline between Boulder and Erie. The laboratory tests were intended to evaluate the hardware and software in a controlled environment and to evaluate the magnitudes of systematic errors in the system. These tests showed that the hardware was stable and had systematic errors whose magnitudes were at a level of 1 mm or less. The field tests were conducted over baselines ranging from 900 m to 23820 m. These tests were intended to evaluate the stability of the dispersion and distance determinations in the presence of typical atmospheric turbulence and to compare the dispersion measurements with direct end-point measurements of the atmospheric parameters. All of the experiments were successful. Data was even taken during sunrise (when the sun shines almost directly into the telescope at the Western end-point) and during the day when turbulence due to thermal inhomogeneities is particularly severe. Measurements made during continuous 36-hour runs showed fluctuations in distance of a few mm or less, and the measured dispersion agreed well with simultaneous end-point measurements made by NOAA.

Initiate analysis of GPS/Iceland data to extract network baselines.

Accomplishment - A campaign to acquire data in Iceland was completed in July, and the reduction of the data was begun in early August. The data were analyzed in two modes. The first analysis was a simultaneous least-squares adjustment of the entire network of baselines using software developed in Berne and converted to run on our system. The second analysis used software developed by Texas Instruments and involved individual solutions for the 1600+ baselines using several VLBI stations as fixed reference points. The first solution achieved typical closure errors of less than 1 ppm, while the latter method showed uncertainties about an order of magnitude greater (or more in some cases). A preliminary summary of the results was presented at the Fall meeting of the American Geophysical Union, and a publication is in preparation.

FY 1988 Plans

Conduct longer baseline tests of the multiple wavelength system. Initial tests will focus on stability and reproducibility, so that an a-prior knowledge of the baseline length is not necessary. Subsequent measurements will be made over calibrated baselines. Install additional microwave hardware to complete the microwave measurement of the water vapor (the existing system is really only a 2.5 wavelength system).

Develop software to improve the analysis of GPS data. This will include incorporation of data obtained by water vapor radiometers. The data provides real-time measurement of the atmospheric-water-vapor correction. A radiometer, obtained from JPL, will be incorporated into the system.

Continue GPS data analysis for measurements at various sites including recent campaigns in Southern California in collaboration with MIT and measurements in Hawaii in collaboration with Peter Bender and others. The measurements are motivated by geophysical considerations. Measurements of several baselines near Boulder will also be made. This series of baselines ("The Colorado Triangle") is designed to test improvements in the analysis software and the importance of water-vapor corrections.

Geophysical Tilt Measurements

FY 1987 Plans and Accomplishments

Test usefulness of the tiltmeter as a short-period, surface-wave seismometer to improve resolution in tests of the model.

Accomplishment - Calibrations of various tiltmeter configurations were conducted using a specially designed test jig. This jig applies small tilts to the sensor and measures the impulse and step responses. The data were reduced to show the performance in both the time and frequency domains. A sensor was also installed in a borehole in Boulder and event-detection software was designed to sample the instrument whenever an earthquake was detected. While the measurements were successful, they showed that the response of the instrument in the seismic band is not sufficiently flat to permit use as a seismometer without significant data deconvolution using the measured impulse response. Analysis of the data from Yellowstone was also completed. The Yellowstone data will continue to used to evaluate the tiltmeters for earthquake prediction. The first phase of an investigation of the coherence between tiltmeters installed in Yellowstone and in Southern California is nearly complete.

FY 1988 Plans

Continue operation of several tiltmeters in Southern California and in Yellowstone National Park. Contingent on funding, install additional instruments at a site (Durmid Hill) that is deemed to have a significant probability for an earthquake in the near future. The NBS instruments have been incorporated into several regional networks to provide real-time comparisons of data from different instruments. The proposed instruments at Durmid Hill will be included in this network, and this data will be sent directly to the USGS central analysis system in Menlo Park.

NOTICE OF TALKS

D. W. Allan, "Process of Atomic Time Keeping and Time Coordination, National Physical Laboratory, Jerusalem, Israel, August 1987.

D. W. Allan, "Measuring the Stability of Precision Oscillators," and "Comparison of Remote Clocks Using GPS in Common-view," Tel Aviv University, August 1987.

D. A. Allan, "Global Timing via GPS Satellite in Common-view," and "Millisecond Pulsar Rivals Best Atomic Clock Stability," International Union of Radio Science (URSI), Tel Aviv, Israel, August 1987.

D. W. Allan, "Estimating the GPS Ephemeris Plus Propagation Errors and Their Effect on Time and Frequency Transfer," 41st Annual Symposium on Frequency Control, May 28, 1987.

D. W. Allan, "Millisecond Pulsar Rivals Best Atomic Clock Stability," 41st Annual Symposium on Frequency Control, May 27, 1987.

J. C. Bergquist, "Quantum Jumps in a Single Atom," University of Stanford, Stanford, CA, Dec. 8, 1986

J. C. Bergquist, "Quantum Jumps in a Single Atom," NOAA, Boulder, CO, Jan. 27, 1987.

J. C. Bergquist, "Single Atom Spectroscopy," International Quantum/Electronics Conf., Baltimore, MD., April 30, 1987.

J. J. Bollinger, "Liquid and Solid Plasmas," Gordon Conference on Atomic Physics, July 1987.

J. J. Bollinger, "Sympathetic Cooling of Positrons by Atomic Ions," Intense Positrons Beam Workshop, Idaho Falls, June 1987.

J. J. Bollinger, "Strongly Coupled Nonneutral Ion Plasmas," Conference on Atomic Processes in Plasmas," September, 1987.

K. E. Evenson,"Tunable Far Infrared Spectroscopy," Univ. of Tucson, March 1987.

K. M. Evenson, "The Last Measurement of the Speed of Light," University of Arkansas, Fayetteville, Ark., May 1, 1987.

K. M. Evenson, "Tunable Far Infrared Laser Spectroscopy," 11th International Conference on Submillimeter & IR Waves, Pisa, Italy, Oct. 21, 1986

D. W. Hanson, "Secure Military Communications Can Benefit from Accurate Time," MILCOM '86 Conference, Monterey, CA, Oct. 5-9, 1986.

D. W. Hanson, "Elements of Low-Cost, Operational Two-way Satellite Time Transfers," International Union of Radio Science (URSI), Tel Aviv, Israel, Aug. 26, 1987.

D. A. Howe, "Ku-Band Satellite Two-way Timing Using a Very Small Aperture Terminal (VSAT), 41st Annual Symposium on Frequency Control, May 28, 1987.

D. A. Howe, "Stability Measurements of Ku-band Spread Spectrum Two-way Time Transfer Equipment," 18th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, Dec. 3, 1986.

W. M. Itano, "The Observation of Quantum Jumps in Hg+," Eighth International Conference on Laser Spectroscopy," Are, Sweden, June 22, 1987.

W. M. Itano, "Review of High Precision Spectroscopy of Atomic Ions in Traps," Workshop and Symposium on the Physics of Stored and Trapped Particles, University of Stockholm, June 24, 1987.

J. Levine, "Applications of Geophysical Measurements to Relativity," Rocky Mt. Theoretical Physics Meeting, Laramie, Wyoming, Oct. 15, 1987.

D.B. Sullivan, "Activities and Plans of the Time and Frequency Division of the National Bureau of Standards," 18th Annual Precise Time and Time Interval (PTTI) Meeting, Dec. 3, 1986.

F. L. Walls, "Low Noise Frequency Synthesis," 41st Annual Symposium on Frequency Control, May 28, 1987.

F. L. Walls, "Analysis of High Performance Compensated Thermal Enclosure," 41st Annual Symposium on Frequency Control," 41st Annual Symposium on Frequency Control, May 29, 1987.

M. A. Weiss, "A Calibration of GPS Equipment at Timing Laboratories in Europe," 18th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, Dec. 3, 1986.

D. J. Wineland, "Single Ion Spectroscopy," New York APS Meeting, March 1987.

D. J. Wineland, "Cooling Limits in Traps," Symposium on the Physics of Stored and Trapped Particles, Sweden, June 1987.

D. J. Wineland, "Spectroscopy of Single Atoms," Boston DAMOP (APS) Annual Meeting, May 1987.

D. J. Wineland "Ion Traps for Large Storage Capacity," Workshop on Cooling, Condensation, and Storage of Hydrogen Cluster Ions Workshop, SRI, Jan. 1987.

D. J. Wineland, "Fundamental Limits to Spectroscopic Accuracy," Workshop on Fundamental Measurements on Optically Prepared Atoms, NBS, Gaithersburg, MD, Sept. 29-30, 1986.

PUBLICATIONS

D.W. Allan, "Millisecond Pulsar Rivals Best Atomic Clock Stability," 18th Precise Time and Time Interval Meeting (Washington, DC, 1986) pp. 453-466.

D.W. Allan, Characterization, "Optimum Estimation, and Time Prediction for Precision Clocks," 17th Precise Time and Time Interval Meeting (Washington, DC, 1986) pp. 45-67.

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J.M. Brown, J.E. Schubert, R.J. Saykally, and K.M. Evenson, "The Far-Infrared Laser Magnetic Resonance Spectrum of the CF Radical and Determination of Ground State Parameters," Journal of Molecular Spectroscopy 120, 421 (1986).

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R.E. Drullinger, J. Shirley, D.J. Glaze and L.W. Hollberg, "Progress Toward an Optically Pumped Cesium Beam Frequency Standard," 40th Annual Symposium on Frequency Control (Philadelphia, PA, 1986) pp. 428-431.

K.M. Evenson, D.A. Jennings, L.R. Zink, and K.R. Leopold, "Tunable Far Infrared Laser Spectroscopy," 11th International Conference on Infrared and Millimeter Waves (Pisa, Italy, 1986).

A. Hinz, J.S. Wells and A.G. Maki, "Heterodyne Measurements of Hot Bands and Isotopic Transitions of N_2O Near 7.8 μm," Z. Phys. D - Atoms, Molecules and Clusters 5, 351 (1987).

D.A. Howe, "Stability Measurements of Ku-Band Spread Spectrum Two-Way Time Transfer Equipment," 18th Precise Time and Time Interval Meeting (Washington, DC, 1986) pp. 437-451.

M. Inguscio, G. Moruzzi, K.M. Evenson, and D.A. Jennings, "A Review of Frequency Measurements of Optically Pumped Lasers from 0.1 to 8 THz," invited review in Journal of Applied Physics 60, R161 (1986).

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D.A. Jennings, R.E. Drullinger, K.M. Evenson, C.R. Pollock and J.S. Wells, "The Continuity of the Meter: The Redefinition of the Meter and the Speed of Visible Light," NBS Journal of Research 92, 11 (1987).

W.J. Klepczynski, H.F. Fliegel and D.W. Allan, "GPS Time Steering," 18th Precise Time and Time Interval Meeting (Washington, DC, 1986) pp. 237-250.

K.R. Leopold, "Far Infrared Laser Magnetic Resonance Detector of NH and ND ($a^1\Delta$)," J. Chem. Phys. 85, 324 (1986).

K.R. Leopold, L.R. Zink, K.M. Evenson, and D.A. Jennings, "Far Infrared Spectrum of Sodium Hydride," Journal of Molecular Spectroscopy 122, 150 (1987).

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R.J. Saykally, K.M. Evenson, D.A. Jennings, L.R. Zink, and A. Scalabrin, "New FIR Laser Lines and Frequency Measurements for Optically Pumped CD_3OH," International Journal of Millimeters and Infrared Waves 8, 653 (1987).

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M.A. Weiss and D.W. Allan, "Using Multiple Reference Stations to Separate the Variances of Noise Components in the Global Positioning System," 40th Annual Symposium on Frequency Control (philadelphia, PA, 1986) pp. 394-404.

D.J. Wineland and W.M. Itano, "Laser Cooling," Physics Today 40, 34 (1987).

D.J. Wineland, J.J. Bollinger, W.M. Itano, and J.D. Prestage, "Angular Momentum of Trapped Atomic Particles, Journal of the Optical Society of America B 2, 1721 (1987).

P. Zhao, W. Lichten, H.P. Layer and J.C. Bergquist, "Remeasurement of the Rydberg Constant," Phys. Rev. A 34, 5138 (1986).

P. Zhao, W. Lichten, H.P. Layer and J.C. Bergquist, "New Value for the Rydberg Constant from the Hydrogen Balmer-β Transition," Physical Review Letters 58, 1293 (1987).

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L.R. Zink, M. Vanek, J.S. Wells and A.G. Maki, "NO_2 Heterodyne Frequency Measurements with a Tunable Diode Laser, a CO Laser Transfer Oscillator and CO_2 Laser Standards," NBS Technical Note 1308 (1987).

L.R. Zink, J.S. Wells, and A.G. Maki, "Heterodyne Frequency Measurements on N_2O Near 1060 cm^{-1}, Journal of Molecular Spectroscopy 122, 426 (1987).

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D.W. Allan, "Should the Classical Variance Be Used as a Basic Measure in SI Standards Metrology?," submitted to 1986 Conference on Precision Electromagnetic Measurements.

B. Dahmani, L. Hollberg, and R.E. Drullinger, "Optical Frequency Stabilization of Semiconductor Lasers," submitted to Optics Letters.

David A. Howe, "Ku-Band Satellite Two-way Timing Using a Very Small Aperture Terminal (VSAT)," submitted to 41st Frequency Control Symposium and IEEE UFFC.

D.A. Howe, "Progress Toward One Nanosecond Two-Way Transfer Accuracy Using Ku-Band Geostationary Satellites," submitted to IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control.

R.G. Hulet and D.J. Wineland, "Quantum Jumps via Spontaneous Raman Scattering," submitted to Physical Review A.

M. Inguscio, L.R. Zink, K.M. Evenson and D. A. Jennings, "Sub-Doppler Tunable Far Infrared Spectroscopy," submitted to Optics Letters.

Wayne M. Itano, J. C. Bergquist, Randall G. Hulet and D. J. Wineland, "The Observation of Quantum Jumps in Hg^+," submitted to 8th International Conference on Laser Spectroscopy.

W.M. Itano and D.J. Wineland, "Laser Spectroscopy of Trapped Atomic Ions," submitted to Science Magazine.

Steven R. Jefferts and Fred L. Walls, "A Low Noise Cascode Amplifier," submitted to NBS Journal of Research.

I.G. Nolt, J.V. Radostitz, G. DiLonard, K.M. Evenson, D.A. Jennings, K.R. Leopold, M.D. Vanek, L.R. Zink, A. Hinz, and K.V. Chance, "Accurate Rotational Constants of CO, HCl, and HF: Spectral Standard for the 0.3 to 6 THz (10 to 200 cm^{-1} Region," submitted to Journal of Molecular Spectroscopy.

M. Schneider, A. Hinz, A. Groh, K.M. Evenson, and W. Urban, "CO Laser Optogalvanic Lamb-dip Stabilization from 5.0 to 6.3 μm on CO," submitted to Applied Physics B.

F.L. Walls, "Low Noise Frequency Synthesis," submitted to 41st Frequency Control Symposium (Philadelphia, 1987).

F.L. Walls, "Analysis of High Performance Compensated Thermal Enclosures," submitted to 41st Frequency Control Symposium (Philadelphia, 1987).

F.L. Walls, "Characteristics and Performance of Miniature NBS Passive Hydrogen Masers," submitted to 1986 Conference on Precision Electromagnetic Measurements.

F.L. Walls, "Errors in Servosystems Using Sinusoidal Frequency (Phase) Modulation," submitted to the IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control.

M.A. Weiss and D.W. Allan, "Precision Time and Frequency Transfer by Weighting and Smoothing of GPS Common View Data," submitted to 1986 Conference on Precision Electromagnetic Measurements.

D.J. Wineland, W.M. Itano, J.C. Bergquist and R.G. Hulet, "Laser Cooling Limits and Single Ion Spectroscopy," submitted to Physical Review A.

D.J. Wineland, "Ion Traps for Large Storage Capacity," submitted to the Proceedings of the Workshop on Cooling, Condensation, and Storage of Hydrogen Cluster Ions.

L.R. Zink and M. Mizushima, "Pure Rotational Far Infrared Transitions of $^{16}O_2$ in Its Electronic and Vibrational Ground State," submitted to the Journal of Molecular Spectroscopy.

L.R. Zink, K.M. Evenson, D.A. Jennings, G. Moruzzi, and M. Inguscio, "Direct Frequency Measurement of the K=6 Asymmetry Splittings in CH_3OH," submitted to the Journal of Molecular Spectroscopy.

SEMINARS ORGANIZED

NBS Time and Frequency Seminar, July 21-23, 1987, Boulder, Colorado.

SPECIAL REPORTS

J. L. Jespersen and D. W. Hanson, "Space Communications Timing, to be published as RADC Report.

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, 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 Measurement 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 1987

OVERVIEW

The Joint Institute for Laboratory Astrophysics[1] (JILA) continues to grow and thrive:

- Although Carl Lineberger's term as Chairman of JILA came to an end on December 31, his efforts on behalf of JILA and the success of the new building continue unsparingly. He is succeeded by Gordon Dunn, who brings to the position eight years of experience as Chief of the Quantum Physics Division.

- Construction of the new JILA building should be complete by January 1988. The building will provide an additional 16,000 square feet of desperately needed office and laboratory space. The National Science Foundation and the Department of Education are each providing $500 K toward its cost.

- JILA is pleased to welcome two new Fellow Adjoints, Douglas O. Gough and Eldon Ferguson. Gough is a theoretical astrophysicist at the Institute of Astronomy, University of Cambridge. His research is in astrophysical fluid dynamics with special emphasis on helioseismology. Ferguson is a chemical physicist at the Université de Paris - Sud. His main interests are in ion chemistry, atmospheric processes and interstellar chemistry. Together with Neal F. Lane, Michael J. Seaton, Stephen J. Smith and Richard N.Zare, they bring the number of Fellow Adjoints to six.

- Stephen R. Leone has received a John S. Guggenheim Fellowship for his research in chemical dynamics. He plans to use his Fellowship to study three areas of physics likely to affect chemical physics in the years ahead.

- David J. Nesbitt has received an Alfred P. Sloan Fellowship for unrestricted use in research of his choice, directed in particular toward starting innovative projects.

- JILA has proposed that NSF provide partial support for a JILA Center for Theoretical Atomic, Molecular and Optical Physics.

- During the past year, Quantum Physics Division scientists have:

    - Developed laser stabilization techniques to produce laser linewidth of 50 millihertz with a frequency predictability better than 100 millihertz for more than 1 minute.

    - Found that the relativistic precession rate for the lunar orbit, as determined from lunar laser ranging data, agrees to 10% accuracy with the rate calculated in 1916 by DeSitter from general relativity.

- Determined that there is no differential free-fall acceleration down to 5 parts in 10^{10} between U_{238} and Cu, thereby establishing better experimental limits on any possible Fifth Force over the range 0.2 km to 10^4 km.

- Discovered an exact solution to the saddle point equations for the Stark ionization of hydrogenic ions in states with non-zero angular momentum.

- Developed a technique to map the surface structure of rapidly rotating stars using high spectral resolution profiles of emission lines.

- Partially resolved a serious discrepancy between calculations and measurements, both by JILA scientists, for electron impact excitation of the simple lithium-like ion of beryllium.

- Demonstrated the dominance of, and measured for the first time, the effective cross sections for the excitation of Ar atoms and N_2 molecules by fast neutrals in electrical discharges at very high electric field to gas density ratios.

- Measured atom-atom energy-transfer cross sections differentially with respect to scattering angle.

- Provided the first demonstration of the existence of multiple, stable conformations (i.e., geometrical isomerism) in hydrogen bonded molecular complexes.

- Measured for the first time Ba^* velocity distributions in a well-characterized electric drift field, showing that contrary to theoretical prediction, spreading in the transverse direction at low field strengths is similar to that in the parallel direction.

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[1]Through the Quantum Physics Division, 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 as the last section in this report.

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 a priori 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. A key new technology being developed in Hall's lab arises out of a collaboration with Professor T. W. Hänsch, formerly of Stanford University. 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 to provide effective frequency/phase correction of the laser field *after the laser has produced its output*. The present effort is to integrate this concept with the controller of a commercially-available stabilized dye laser system. 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.

The next major challenge is to develop refined methods of tuning/guiding/offsetting the laser's frequency 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 ($\Delta\nu \leq 100$ kHz). They have filed for patent coverage on this system, called the "rf Sigmameter", which is also attracting commercial interest. The basic idea is that a Michelson interferometer can be configured with two inputs so that optical *frequency* changes are manifested as changes in the *phase* of a locally-generated rf waveform. With the powerful methods of electronic phase-locked circuitry, it is possible to develop an optimal signal for guiding the tunable laser. The attractive feature of this concept is that scanning errors are *non-accumulating*, so that enormous frequency scans can be accomplished without nonlinearity and distortion. For modest scans (± 3.5 GHz) of still higher accuracy, for example scanning over the (potentially) Hz-wide absorption of Hg^+ in an ion trap, optical heterodyne phase/frequency locking techniques can be used as demonstrated in earlier work at JILA.

An interesting application of the JILA 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 to obtain higher resolution. 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 10s to 100s of milliseconds, bringing the prospect for Hz-level resolution.

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 onto 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 scientists in Hall's group 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, they 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. The increased space and improved environmental control planned for the new JILA addition will certainly help these laser stability experiments to approach their goal of reaching the fundamental limits.

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 2.5 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.

Laser Gravitational-Wave Observations in Space - **P. L. Bender and J. E. Faller**

Funding to the University of Colorado is continuing under the NASA Innovative Research Program to support 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 a cluster of 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 some years.

As discussed earlier, studies of expected gravitational wave signals due to binary star systems have been carried out by D. Hils, R. F. Webbink (former JILA Visiting Fellow) and Bender. 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 roughly 10^{-5} 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.

On the basis of the studies on sources of gravitational waves, it has been concluded that additional efforts should be made to improve the gravitational wave sensitivity at frequencies near 1 Hz. As a result of developments in Nd Yag lasers pumped by laser diode arrays, it now appears that transmitted laser powers of up to about 3 W can be used to reduce the shot noise limitations, and shortening of the interferometer length to about 10^{5} km probably is desirable. The resulting shot noise limit to the sensitivity would be roughly 3×10^{-21} $Hz^{-0.5}$. These questions will be explored further by R. T. Stebbins and Hils (University of Colorado), along with Bender and Faller.

Mercury Orbiter Relativity Satellite - **P. L.** Bender

M. A. Vincent and Bender have investigated the accuracy with which the orbit of a small relativity satellite around Mercury could be determined from high-accuracy tracking data from the Earth. The most accurate results have been obtained by considering only tracking periods when the solar radiation hitting the satellite is not eclipsed by Mercury. Doppler tracking data with 1×10^{-14} accuracy and range data with 3 cm accuracy were assumed for 40 carefully chosen 8-hour periods, and 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.

A possible conceptual design for the relativity satellite also has been studied. Roughly 0.5 W of transmitted power at X-band and 0.2 W at K-band would be required with a 30-cm diameter antenna. The total spacecraft power needed during ranging is about 10 W. The thermal control problems are not serious because of the 2500 km altitude. The total spacecraft mass would be 50 kg or less, so it could be included as a small part of a possible future mission to Mercury.

Optical Imaging Interferometry in Space - P. L. Bender and J. E. Faller

Some preliminary work on a specific concept for an intermediate imaging interferometer in space has been carried out by Stebbins, Bender and Faller. The basic idea is to use roughly 15-meter long sections of graphite-epoxy truss structure or other low-expansion material for the basic interferometer structure. Three such sections could be used in a Y-shaped configuration, with about 15 afocal telescopes located along the axis. The light from each telescope interferes with that from each of the other telescopes to give an optical image. Careful thermal design would make the distortion rate for the interferometer relatively small. Laser measurements from two control blocks located on a mast perpendicular to the plane of the Y would be used to monitor the overall distortion and provide corrections for the optical paths with 10^{-2} wavelength stability over a typical observing time of roughly two hours. The laser measurement system is similar to that planned for the POINTS (Precision Optical Interferometry in Space) astrometric interferometer being developed by R. D. Reasenberg and others at the Harvard/Smithsonian Center for Astrophysics.

With 50-cm diameter telescopes, the aperture coverage would be dilute. However, quite high magnitude sources could still be observed with good spectral resolution. The spatial resolution would be nearly an order of magnitude better than for the Hubble Space Telescope at the shortest wavelengths observable with the interferometer.

High Accuracy Atomic Mass Measurements - G. H. Dunn

Dunn is making a major change in the direction of his program to measure atomic masses to ultra-high precision - a part in 10^{10} and better. The goal is to use Penning ion trap technology, with which he has some 15 years experience, to explore important physical phenomena: atomic and nuclear binding energies, excitation energies of highly ionized species, nuclear and molecular isomer binding energies, neutrino mass, and masses of superpositions of states. These measurements bear on determinations of the fundamental constants and Avagadro's number in particular.

This program will use a Penning hyperbolic cell in a highly uniform magnetic field. A superconducting solenoid with fields up to 7 Tesla, uniform to better than 2×10^{-9} over a 3 mm sphere, and stable to better than 5×10^{-9}/hr for over 100 hr will be delivered soon. Superconducting flux trap rings near the trap should produce stability to better than 10^{-9}. Cyclotron resonances of single ions will be detected and the frequency measured. Special cool GAS FET amplifiers are being developed for detection of the high-frequency fempto-amp size currents involved. Dunn expects that the next year will be spent in design and construction, and that the project will yield results within 2 - 3 years.

Dunn is collaborating on this project with F. Walls of the Time and Frequency Division, and he consults frequently with D. Wineland of the same Division. He is assisted by a graduate student, S. Jefferts.

GEOPHYSICAL MEASUREMENT METHODS

Gravity Gradiometer - J. E. Faller

Faller and M. McHugh have constructed a fluid-float Eötvös experiment using Cu and Pb as the test masses to test the suggestion of a new "Fifth Force" over the 1 - 10 meter range. This target-of-opportunity experiment has resulted in the temporary suspension of their gravity gradiometer float studies. But as these two experiments are complimentary in terms of possible error sources and experimental limits of precision, they are also making progress with gradiometer studies.

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 (DMA) (both assigned to work in JILA) have completed the construction of six absolute gravimeters. These 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. All measurements were transferred to the same site using an ensemble of relative gravimeters. During the past year, Faller has analyzed his results and determined a transferred value for Serves Point A5. His value differs from the average value by 1.2 μgal and from the average obtained by rejecting three "outlying" measurements by 0.3 μgal!

The JILA, the Canadian, the West German, the National Geographic DMA/NGS, the Austrian and the Finnish instruments all appear to be working well. During this past year, Niebauer, McHugh and Faller used the dropping chambers from two of the JILA absolute instruments, together with, first the Finnish and later the DMA/NGS dropping chambers, to carry out a Galilean test of the Fifth Force hypothesis using U_{238} and Cu as the free-falling dropped masses. They measured no differential acceleration down to 5 parts in 10^{10}, thereby establishing better experimental limits on any possible Fifth Force over the range 0.2 km to 10^4 km.

Water Vapor Calibrator Measurement - P. L. Bender

S. J. Walter and Bender are working under NASA funding to develop a microwave-optical system to improve the accuracy of the correction to microwave distance measurements due to 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 altitude would serve to determine the microwave distance correction. 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 have been constructed. 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. The accuracy goal for the calibrator is 2 to 5 mm.

GPS Measurements in the Hawaiian Islands - P. L. Bender

Signals from the Global Positioning System (GPS) satellites have been used during the period 28 March - 12 April, 1987, to measure the distances between sites on Kauai, Oahu and Maui in the Hawaiian Islands. The main scientific goal was to obtain a direct measurement of the vector distance between the satellite laser ranging station on Maui and the NASA Very Long Baseline Interferometry station on Kauai. These stations are both used in measurements of the motion of the Pacific Plate with respect to the North American Plate, the Australian Plate, and other plates.

Geodetic Precession Rate from Lunar Laser Ranging Data - **P. L. Bender**

Studies with B. Bertotti (University of Pavia, Italy) and I. Cuifolini (University of Texas) have shown that present lunar laser ranging data provide the first experimental demonstration of the famous Geodetic Precession effect calculated by DeSitter in 1916 on the basis of general relativity. The actual geodetic precession rate for lunar perigee agrees with the rate calculated from general relativity to 10% accuracy.

The method used in the analysis was to calculate analytically the expected change in the lunar range as a function of time if a different geodetic precession rate had been used in the computer calculations of the lunar orbit, and then to show that such a change could not be absorbed by changing any of the other parameters or starting conditions in the problem. Basically, the motion of lunar perigee with respect to the Sun can be determined with an accuracy of better than 2 milliarcseconds per year because the solar perturbations of the lunar orbit cause roughly 1% changes in the Earth-Moon distance. The motion of the Earth with respect to the planetary dynamical frame (i.e., the non-rotating frame determined from planetary motions) is known to higher accuracy from the Viking Lander tracking data. In addition, the planetary dynamical frame was found not to rotate with respect to extragalactic radio sources at the 3 milliarcsecond per year level by comparing Earth rotation results from lunar laser ranging and from Very Long Baseline Interferometry (VLBI).

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 are carrying out a detailed analysis of the line spectra of 16 hot stars they observed at Kitt Peak National Observatory to 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. Seven stars have now been analyzed, and work on the remaining nine is now well underway. The results for Zeta Puppis appear to settle a long-standing uncertainty of about 40%. Also, the method of determining temperatures of hot stars from measured energy distributions has been shown to be utterly unreliable; many temperatures in the literature could be in error by 25% or more.

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 Professor 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.

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. The method uses purely spectroscopic data and contains no calibration or empirical correlations. It can be tested definitively in the next few years when distances to some "nearby" hot stars will be measured accurately by satellite observations using trigonometrical methods. Meanwhile, Hummer is testing the method by analyzing spectra of stars for which distances are known independently.

Equation of State - D. G. Hummer

Hummer, in collaboration with D. Mihalas (Visiting Fellow), has been working for the past three 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 given a treatment of this problem that accounts for the oscillatory nature of the plasma microfield, which appears now to be the dominant mechanism. This work is supported by experiment.

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. This calculation includes the effects of electron collisions, which become crucial as the electron density increases. Hummer and Storey 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 infrared astronomy within the next few years. The calculation of the corresponding results for the hydrogenic ions of C, N, and O is now complete.

Hummer and L. Smith (University 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 determination of distances to remote galaxies is one of the most important astronomical measurement problems and one of the primary goals of the Space Telescope. Such distances would yield the Hubble constant and perhaps even the value of the deceleration parameter. Supernovae are prime candidates for this purpose, as they are both bright and fairly well understood. One method 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. Two or more observations well separated in time then yield the distance from the ratio of the change in expansion velocity to the change in angular diameter. But realistic models of supernovae atmospheres are needed to extract this information from the observations. Abbott has computed models that give continuum fluxes with many of the features of Supernova 1987a, and a computer code to calculate the corresponding line spectra is well advanced.

Free-Free Opacity - **D. G. Hummer**

Although the free-free cross section for hydrogenic ions can be expressed exactly in terms of certain hypergeometric functions, the numerical evaluation of these quantities poses an extremely difficult computational problem. Hummer has developed a method of evaluating the thermally-averaged free-free absorption coefficient that is at least an order of magnitude more accurate than previously available computer codes and is probably two orders of magnitude faster.

Radiative-Collisional Switching in Non-LTE Calculations - **D. G. Hummer**

The equations describing the level populations in an optically thick gas, combined with the equations of radiative transfer, are notoriously non-linear. For 20 years they have been solved by a multi-dimensional form of the Newton-Raphson method. But in many interesting cases this procedures fails to converge. Hummer and his student Voels recently encountered a severe form of this problem in attempting to model the atmospheres of hot, helium-rich stars. When the atmosphere was assumed to be in LTE, the equations converged; when the radiative rates dominated (non-LTE), they blew up. Hummer was able to show that by multiplying the radiative rates by a parameter that was initially small and allowed to increase as the iterations proceeded, he could obtain solutions for arbitrary helium abundances. This simple technique, which essentially defines a series of intermediate problems for the iteration process to follow, is extremely valuable for the whole field of low-density gas-radiation investigations.

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 obtained results on stars cooler than had previously been possible to measure; they have also developed an analysis technique to take into account for the first time the saturation of optically thick absorption lines.

These measurements 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 spatial coverage. Three additional conclusions may be drawn from these measurements and the field parameters in somewhat warmer stars. First, the field strength is determined by hydrodynamic processes in the photosphere and not by dynamo field creation processes in the stellar interior. Second, stars with energetic or widespread magnetic-related phenomena have fields that cover nearly the whole star, indicating a high rate of field production in the stellar interior. Third, the fraction of the stellar surface covered by magnetic fields depends on the stellar rotation, as would be expected if fields were amplified by the dynamo process.

Planning for Future Space Observatories to Obtain Ultraviolet and X-Ray Astrophysical Data - J. L. Linsky

Linsky is participating in the detailed planning of several astronomical missions. The most immediate is the Hubble Space Telescope to be launched in 1989/90. 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. 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), now being designed to replace the HRS five years after launch. This instrument will have high spatial imaging capability as well as high spectral resolution over the extended spectral range 110-1100 nm.

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 of stars and galaxies in the mid-1990's. Linsky's specific interest is 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 proposed far ultraviolet spectroscopic explorer satellite called LYMAN. This satellite would contain a grazing incidence telescope and spectrograph to cover the 10 - 200 nm spectral range at both low and high spectral resolution.

Microwave Measurements of Stars - **J. L. Linsky**

Linsky and S. Drake (Goddard Space Flight Center) have several projects underway to study microwave emission from stars. They have now 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 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 leaving the star. Drake and Linsky have now extended this program to study the mass loss from the coolest M giant stars, many of which are SiO maser emitters. They have also completed an extensive survey of microwave emission from close binary stars and from binary systems containing white dwarf companions and strongly enhanced heavy metal abundances.

Linsky and postdoctoral research associate J. Bookbinder have begun a large survey of microwave emission from the coronae of low mass flaring stars called M dwarfs. 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 in the chromosphere, transition region and corona. The 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.

Doppler Imaging of Active Regions on the Surfaces of Stars - **J. L. Linsky**

Linsky and his Ph.D. thesis student, J. Neff, are obtaining maps of the surface structure of stars using a technique they developed 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, information essential for modelling their atmospheres.

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.

The structure and evolution of flares in the solar transition region ($10^4 \leq T_e \leq 10^5$) is much less well understood than in either the lower chromosphere or the corona. It is in this region that the 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), have derived time sequences of He I and He II resonance line intensities at several sites within the flare of 15 June 1973 from observations obtained with the Naval Research Laboratory's slitless spectroheliograph on Skylab. The data were compared with predictions of six model flare atmospheres based on two values for the heating rate and three for the flux of photoionizing coronal X-rays. The inferred soft X-ray flux is 40 - 400 times that in the quiet Sun. Throughout the range of conditions in the flare kernels, the He II Lα line is found to be formed by collisional excitation, thereby contributing to the local cooling of the plasma at temperatures above 6×10^4 K. For the higher Lyman lines, the primary process at several sites is photoionization and 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 Porter 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.

All pre- and post-repair ultraviolet data with sufficient time resolution have now been analyzed to compare the behavior of the rapid brightenings in different active regions and to relate it to available measures of activity and magnetic characteristics. Solar-Geophysical Data Reports from NOAA, Hα flare reports and GOES satellite X-ray data provide the primary measures of activity. These sources are supplemented by Hα movies from Big Bear to check for any unreported subflare activity. Magnetograms from Kitt Peak National Observatory have been examined when available for the days of the SMM observations.

Together these data show that the observed bright sites tend to fall on magnetic neutral lines between two regions of opposite polarity within active regions, a characteristic they share with members of the flare family. Older active regions that are decreasing in size and producing few flares tend to show little or no intensity variations for many consecutive orbits. Such brightenings as are observed are typically less than 50% in amplitude over the background level. The more active regions appear to show brightenings of substantially higher amplitude and frequency, some sites bubbling almost continuously with fluctuations lasting 40 to 60 s.

The distribution of brightening events with amplitude is now reasonable, for the frequent, short-lived events seen here complement the less frequent UV impulsive events, involving say fourfold increases in brightness, studied variously with Skylab, OSO-8 and SMM. Clearly a broad spectrum of events is present, and our observations reveal that the threshold for the brightenings that can be detected is much lower in amplitude, and the variations much more rapid, than previously supposed.

ATOMIC AND MOLECULAR PHYSICS

Electron-Molecule Interactions - D. W. Norcross

This theoretical program is devoted to large scale computational studies of bound and continuum states of electrons interacting with simple molecules. The reaction process can take several forms and have a variety of products, e.g., rotational and vibrational excitation of the molecule, capture of the electron to form a molecular negative ion, or dissociation of the molecule into other atomic and molecular fragments. The effort is primarily developmental -- 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 apply to studies of many practical and fundamental processes, e.g., laser modeling, physics of the interstellar medium, and in studies of chemical reaction dynamics.

Production work in the recent past has included detailed calculations of cross sections for vibrationally elastic scattering of electrons by HF, HCL, CO and (linear) HCN; for ro-vibrational excitation of HF and HCL 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.

Due to the presence of sharp threshold structures in vibrational excitation of polar and many nonpolar molecules, an accurate computational treatment of this process demands complete and rigorous inclusion of the effects of nuclear dynamics in the theoretical formalism. To this end the partial-wave coupled scattering code has been generalized to further allow for the coupling of a manifold of lower vibrational states, while still incorporating reliable treatments of the tricky exchange interaction and the complicated correlation and polarization forces. Preliminary calculations of the 0-1 vibrational excitation cross section in HF, within Sigma symmetry, show good agreement with experimental results. Production runs for H_2, an important and oft-studied molecule for which the best current theoretical and experimental results are in serious disagreement, are in progress.

An improved package for the calculation of asymptotic solutions of scattering equations has been completed and successfully married to the molecular scattering code. This will permit the first practical and realistic calculations of the binding energies of weakly bound and diffuse molecular negative ion states, and perhaps also highly excited states of neutral molecules. The richest prize will be new results for the lowest bound states of HF^-, HCl^-, and HCN^-. This will finally uncover the full spectrum of the infinite number of bound sates 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 function of internuclear distance.

<u>Electron Impact Excitation of Atoms and Atomic Ions</u> - D. W. Norcross

This group is pursuing several fundamental and applied problems in the theory and computational physics of electron impact excitation. Excitation by electron impact is a primary source of energy transfer and radiation emission in both fusion and astrophysical plasmas. The needs for a vast amount of data for these processes, for both modeling and diagnostic purposes, are well documented, and the impossibility of generating all the necessary data by measurements is almost universally, if reluctantly, accepted. Since theory must be relied upon to provide the bulk of the data, it must be tested against measurements for carefully selected special cases. These cases, in turn, must be designed either to test or stretch particular aspects of the theory (e.g., transitions near thresholds, involving excited states, resonances, or state-selected projectiles or targets), or to check out particular novel experimental techniques under development (e.g., photometric calibration, recoiling- and merged-beam techniques, and angular distribution measurements).

A systematic series of calculations has been completed for Be^+. It has now been shown that neither an elaborate multi-configuration expansion for the electron-core interaction, nor an exhaustive treatment of virtual excitation into the continuum, has any significant impact. While the long-standing discrepancy in the polarization of the fluorescence radiation associated with this excitation has been resolved (ancient theoretical formalism was found to be in error), a stubborn 18% difference with Dunn's high precision measurements for the total cross section remains. In anticipation of new measurements, the latest series of calculations is being extended to provide a comprehensive set of differential as well as total cross sections.

Detailed calculations for ions in the sodium isoelectronic sequence have been initiated with work on the doubly-charged ion Al^{++}. Using the scattering code in a mode with all channels closed, binding energies have been computed for many of the low-lying bound states of Al^+, for which inclusion of polarization leads to much improved predictions of the ionization energies.

A project on electron-impact excitation of magnesium-like ions has also been completed. Rate coefficients have been calculated for S V, Ar VII, Ca XIII, Fe XV and Ni XVII for 120 transitions in each ion. The results are tabulated on a $\log_{10}$ grid at 15 temperatures extending over three orders of magnitude, a format suitable for various plasma applications. In anticipation of future scattering calculations, atomic structure calculations for boron isoelectronic sequence ions are in progress with emphasis on the C II eigenfunction expansion (which is the most demanding of all the ions in the sequence).

A collaboration with one of JILA's Visiting Fellows is being pursued, leading toward the development of a relativistic version of the IMPACT close-coupling code for electron-ion scattering. Toward this end a series of calculations on the ions of the heavier alkaline earths (Ca^+, Ba^+, and perhaps Sr^+), that will provide non-relativistic benchmark results, has been initiated.

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 associates P. Arcuni and M. Harris, and graduate students K. Gibble, 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 underway. 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 , M_s , and θ. Excellent signals and accurate threshold-region partial cross sections with respect to M and M_s have been obtained. Measurements of the θ dependence are in progress. These measurements test theories in the critical threshold region with orders of magnitude more detail than has previously been available.

Differential inelastic atom-atom energy-transfer collisions ($A^* + B \rightarrow A + B^*$) are being measured in a crossed-beam apparatus. Such measurements critically test understanding of the interactions and collisions. Gallagher and his colleagues use supersonic metal-atom beams with well-defined velocities and detect the energy transfer from one optically excited beam (A^*) to the other by laser induced fluorescence from the final state (B^*). The recoil Doppler shift in the B^* absorption spectrum can be analyzed to yield the differential cross sections with respect to scattering angle. They have now completed the first measurements in which A and B are both Na atoms, and are now analyzing these data. Based on the excellent signals and results here, mixed-alkali collision experiments such as Na-K are now being set up.

Another experiment measures total atom-atom collision 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 ultimately to a highly excited and ionized vapor.

<u>Silane Neutral Chemistry</u> - A. C. Gallagher

The quality and utility of hydrogenated amorphous silicon (a-Si:H) film photovoltaics have increased every year since their initial production in 1976. Efficiencies of 10% are now routinely achieved compared with crystal silicon cell efficiencies that are now about 20%. 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. It is also being developed in many companies for area display and reading. 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 worked on the surface chemistry in these discharges as well as on disilane and germane discharges. Along with modeling of the surface reactions, based on observations of molecules in the discharges, they have studied the radical reaction probabilities with the growing a-Si:H surface. Models for the gas and surface processes are developed and compared with all the observations.

A New Method for Electron-Ion Collision Measurements - **G. H. Dunn**

It has long been recognized that a new method must be found for measuring cross sections for electron-impact excitation of ions. The bulk of the measurements to date have used crossed beams and a fluorescence detection technique. Only four measurements have been done for ions of charge greater than one. A few measurements have been made of relative differential cross sections for excitation of singly charged ions over a narrow range of angle and energy. A new method is required to understand excitation of multiply charged ions and the role of resonances, as well as to study indirect processes in ionization of ions (excitation-autoionization, resonant-excitation-double-ionization, etc.).

Dunn, C. Timmer, and other students and post-docs have developed a new method to meet this need. Trochoidal merger-demerger analyzers are used to merge an electron and ion beam and to disperse inelastically scattered (or ejected) electrons from excitation (or ionization). The dispersed electrons are detected on position-sensitive detectors. One thus has detection efficiencies approaching unity compared with efficiencies of the order 10^{-4} or less in fluorescence or normal scattered electron configurations.

The new method promises to be useful primarily at energies near threshold for excitation. The apparatus has been built, fully assembled, and testing is in progress. Both electron and ion beams have been successfully put through the apparatus, measurement electronics and software have been tested, and measurements should be forthcoming in the near future. The apparatus will be moved to Oak Ridge National Laboratory (ORNL) for work on multiply charged ions after work at JILA on one or two singly charged ions is complete.

In other work on electron ion collisions, the group continued its close collaboration with ORNL, and participated in measurements of ionization of highly charged iron ions. Total cross sections were measured in crossed beams for the electron impact single ionization of Fe^{11+}, Fe^{13+}, and Fe^{15+}. In all cases, the indirect process of excitation-autoionization proved to be either comparable to or much larger than direct ionization. No real evidence was found for the resonant-excitation double autoionization mechanism.

Kinetics of Metastable H_2 and N_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 using H_2, and high power gas lasers using N_2.

A. B. Wedding (CU) and Phelps have extended measurements of the collisional destruction of $H_2(c^3\Pi_u)$ metastables to include the measurement of collisional coupling between the $c^3\Pi_u$ state and the $a^3\Sigma_g$ state. They find that the probability of metastable destruction by this process is small compared to the total destructions probability of essentially unity.

Wedding and Phelps are using the technique of laser absorption following perturbation of the density by a second laser to measure the destruction rate coefficient for the $a''^1\Sigma_g$ metastable state of N_2. This state has recently been proposed as the energy storage reservoir responsible for the onset of instabilities in high power CO_2-N_2 lasers. Initial results show that the destruction rate coefficient is about an order of magnitude smaller than for the H_2 metastables investigated previously.

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. The analyses of the spatial distribution of emission from steady-state, low current discharges led to the hypothesis that the optically forbidden states of N_2 molecules and Ar atoms are being excited as the result of collisions of fast neutrals with the gas molecules. In the case of Ar the ionization produced in such collisions was sufficient to produce an ion avalanche. The fast Ar atoms are produced in charge transfer collisions of Ar^+ with the gas atoms and have average energies of about 100 eV at the higher E/n.

D. A. Scott (CU on CSIRO fellowship) and Phelps have completed measurements of the time dependence of the light emission from Ar 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 electron excitation. As yet incomplete analyses of the waveforms indicate that the excitation of the 811 nm emission is produced by fast atoms. On the other hand, the 750 nm emission is primarily the result of electron excitation.

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. Their principal concern has been with the modeling of electron motion in the very high E/n experiment described above.

Collaboration with NBS/Gaithersburg - A. V. Phelps

The exchange visits of Phelps to NBS/Gaithersburg were continued during April and May of 1987. 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 as N_2, CO_2, O_2, Ar and Ne. This work is 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, reported at appropriate engineering meetings, and prepared for publication.

Collaboration with Overseas Scientists - A. V. Phelps

During FY 87 two collaborative projects were conducted involving overseas scientists. Work with K. Tachibana (Kyoto University and former CU postdoc) was completed on the excitation of Ne metastables by electrons under swarm conditions. The experiments had been carried out by Tachibana and Phelps at JILA and the data analysis was done at JILA and at Kyoto.

Phelps initiated a project in collaboration with G. N. Haddad (CSIRO, Australia) to demonstrate the sensitivity of electron swarm experiment and analyses for N_2 to the cross sections for rotational excitation at electron energies near 0.1 eV. Phelps made approximate calculations at JILA, which were confirmed by Haddad's exact calculations at CSIRO. These analyses also demonstrated that recently proposed and recommended theoretical cross sections are in error by at least a factor of two at electron temperatures of importance in ionospheric models.

JILA ATOMIC COLLISION CROSS SECTION DATA CENTER - J. W. Gallagher

The JILA Data Center under the direction of J. W. 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 1987 Accomplishments

1. *Absolute Cross Sections for Molecular Photoabsorption, Partial Photoionization, and Ionic Photofragmentation Processes.* J. W. Gallagher, C. E. Brion, J. A. R. Samson, and P. W. Langhoff

This review discusses methods of measurement and calculation, and compares cross sections for photoabsorption below the ionization threshold, partial channel photoionization cross sections and asymmetry parameters, and dissociative photoionization cross sections for 21 molecules.

2. *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

In collisional excitation, the alignment and orientation of the target charge cloud are represented by either four or five "natural parameters". Four such parameters are used in the fully coherent case exemplified by helium; five are used in the incoherent cases both with conservation of atomic reflection symmetry, as exemplified by atomic hydrogen, and without conservation of atomic reflection symmetry, as exemplified by the rare gases. This review presents an extensive discussion of the physical meaning of this parametric representation for each case and a comprehensive compilation of measured and calculated data for electron collisions with atomic targets and for ion-atom collisions with similar configurations.

3. *Rate Data for Inelastic Collision Processes in the Diatomic Halogen Molecules. 1986 Supplement.* J. I. Steinfeld

This report updates a compilation published in 1984.

Work in Progress

1. *Collisions of Electrons with Atoms and Molecules. Atomic Data for Fusion, Vol. II.* A collaboration with Oak Ridge National Laboratory

2. *Review of Electron Impact Optical Excitation Functions for Atoms and Atomic Ions.* D. W. O. Heddle

3. *Orientation and Alignment Parameters in Atomic Collisions. Part II. Quasimolecular Excitation.* N. O. Andersen, J. W. Gallagher, and I. V. Hertel

4. A collaboration was started with R. J. Van Brunt of NBS, Gaithersburg, who has developed procedures for checking the consistency between dielectric strength data for gas mixtures and available information on electron transport and electron collision cross sections for the mixture constituents. Large-scale application of this method requires computer access to a wide variety of data; to meet this need, plans have been made for Van Brunt to access the Atomic Collision Data Base. To complement this

effort, swarm data will be added to the data base.

The Atomic Collisions Data Base

Conversion from the IMF to the CDCS data base management system has been completed. A tape of the cross sectional data resident in the Data Base was sent to the International Atomic Energy Agency for incorporation into their data base. In FY 1988, an interactive retrieval program will be refined for general (public) use. Major expansion of the Data Base content in connection with some of the planned projects is expected in 1988.

FY 1988 Plans

An evaluated compilation of cross sections for electron-molecule collision processes is planned in collaboration with Michael A. Morrison of the University of Oklahoma, Norman, and R. J. Crompton of the Australian National University, Canberra. In preparation, identification and collection of pertinent papers and some data collection will begin in FY 1988.

S. J. Smith will be updating the Data Center's Multiphoton Bibliography (NBS Publ. LP-92 + Suppl. 1-4) series for 1983-1987 inclusive, preparing a report commenting on the general quality of available information relative to projected needs, and identifying needs for refinement and extension of experimental programs. The Data Center will provide support for this project with a literature search, acquisition of pertinent articles, preparation of an indexed bibliographic file, and preparation of the final bibliography.

CHEMICAL PHYSICS

Ultra-low Temperature Ion-Molecule Reactions - G. H. Dunn

The Penning trap used for measuring and studying ion-molecule reactions near 10 K has been revised to allow for the "creation" of a substantially larger initial ion sample and for direct variation of the temperature over the range 7 K to 100 K. In this revised trap ortho- and para-hydrogen can be introduced and used separately. Dunn and graduate student M. Schauer are making changes and testing the apparatus.

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 a variety of complexes, including ArHF, HFN_2, $HFCO_2$, $(HF)_2$, HFN_2O, HFH_2, $(CO_2)_2$. Many different vibrational states in each complex have been elucidated, which permits study of intermolecular potentials and coordinates far from the equilibrium geometry. Some key observations resulting from these studies are: 1) Depending sensitively on the nature of the vibration, internally excited complexes can be extremely metastable even with up to 40 times the energy to dissociate; 2) In loosely bound complexes, large amplitude quantum motion leads to extensive vibrational averaging of observable quantities (such as molecular rotational constant) and hence a high dependence on particular ro-vibrational quantum state; 3) Isomers in molecular complexes can exist, and exhibit two different, stable structures with completely different and assignable spectra; 4) Particularly in systems containing H_2, tunnelling effects from weak multiple minima in the potential can be observed and analyzed by virtue of spectral doublings resolvable in our apparatus. These studies are raising new and challenging theoretical questions about the nature of full 3-dimensional solutions of the multibody Schrödinger equation in molecular systems near the dissociation limit.

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. The first phase of the experiment has recently been successful and is resulting in Doppler lineshape velocity profiles of subliming HF thin films. 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. Some recent results to come out of these experiments are: 1) Even in relatively stiff molecules such as cyclopropane, we observe a J dependent rotationally induced mixing of vibrational levels above $J = 6$ due to internal Coriolis interactions; 2) In larger systems such as isobutane, vibrational mode mixing at the CH stretch level is already so extensive that discrete ro-vibrational structure is washed out even at the < 8 K jet temperature.

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. This experiment has just recently become fully operational. We now have developed methods for single frequency scanning the F-center under computer and servo loop control, as well as capturing transient IR signals for later analysis.

A new experiment is presently being built for diode laser probing of molecular species in supersonic jets. The diode laser will permit extension of our earlier efforts to a much wider region of the IR spectrum. In particular, we will be able to look at clusters containing the strong IR chromophores NO, N_2O, CO_2, CO, SO_2, and OCS. At present we are building up the vacuum system and expansion device, as well as gaining experience in stabilizing and scanning single frequency diode lasers. The first molecular effort will be towards characterizing $(NO)_2$ in the region near 5 microns. This system is of fundamental interest since pioneering picosecond experiments at NBS Gaithersburg have indicated predissociation lifetimes that depend sensitively on internal vibrational state.

<u>Photofragmentation Dynamics</u> - S. R. Leone

Photodissociation processes of molecules are providing some of the most detailed results of state-resolved chemical dynamics in recent years. These photofragment processes are particularly important because they are similar to the latter half of a collision, which in principle could represent a chemical transformation. While many groups have explored the use of laser-induced fluorescence to probe the states of diatomic fragments, few laboratories have considered the possibilities of detecting infrared emission, which can ultimately be extended to more complex polyatomic fragments.

R. Fletcher, E. Woodbridge, and Leone have completed a major new apparatus to study photodissociatation dynamics using time-resolved Fourier transform infrared (FTIR) emission spectroscopy. The method has now been shown to be highly successful in obtaining rotationally resolved product state information on the HF diatomic from the photolysis of 1,1-CH_2CFCl and the CCH radical fragment from dissociation of acetylene.

By another technique, W. Hess, J. Smedley, and Leone have been studying the atomic fragments of small molecule photodissociation. This technique, invented in these laboratories, uses a tunable diode laser or an F-center laser to probe by laser gain and absorption the accurate quantum yields of atomic electronic states. Two new problems have recently been investigated: the yield of spin orbit excited atoms of Br^* from bromine molecules and the yield of excited I^* atoms from ICN. In the photodissociation of bromine, the contributions of several molecular electronic states were mapped in detail by measuring the yield of excited Br^* atoms. This allowed the first clear assignment of the intensity of the A state continuum in the Br_2 absorption spectrum. In ICN, an accurate study of the yields of I^* provided a direct confirmation that previous data were erroneous for this molecule and allowed a reanalysis of the electronic bands in the absorption spectrum and a unification of all existing data.

Ion-Molecule Collision Dynamics - S. R. Leone

Several extremely exciting breakthroughs have been made this year to increase the powerful repertoire of methods to study ion dynamics.

A single mode dye laser technique has been used to study ion velocity distributions for the first time in a well-characterized electric drift field region, work carried out by R. Dressler, H. Meyer, V. Bierbaum, A. Langford, and Leone. The Ba^+ ion was drifted in a He buffer gas of a flowing afterglow apparatus, and the velocity distributions were recorded by scanning the single mode dye laser and detecting laser-induced fluorescence. The measurements obtained several fundamentally new pieces of information. In addition to measuring the drift velocity as a function of field strength (and hence the mobility) the temperatures (i.e., spreading of the ion velocity distribution) both parallel and transverse to the electric field were obtained for the first time. According to theory, for a heavy ion in a light buffer, the spreading in the parallel direction should be significantly greater than in the transverse direction. At low field strengths, they have been observed to be the same. These results open up a tremendous number of new possibilities to detect ion velocity distributions optically under well-characterized conditions and to compare the measurements to theory and provide refinements to the theoretical analyses.

A pulsed laser has been used by the same researchers to probe the alignment of N_2^+ ions drifted in He. The alignment comes about because of the anisotropy of the potential of interaction between the ions and the buffer gas. The measurements show a substantial alignment effect, which has been quantified as a function of field strength. In addition, theoretical work has been carried out to characterize how to measure alignment parameters under conditions of saturated laser-induced fluorescence. Another theoretical treatment has been developed to relate calculated cross sections for m_J changing collisions to the magnitudes of the observed alignment effects. Since the alignment will undoubtedly affect the mobility, new measurements are in progress to study simultaneously the alignment and velocity distributions of individual rotational states of the CO^+ ion.

A discovery about a Penning ionization process has been made by D. Sonnenfroh (NRC postdoctoral fellow) and Leone. Using a novel apparatus in which metastable states of Ne are reacted with rotationally cold N_2 molecules, a higher level of rotational detail has been revealed about the Penning process. The rotational distributions within each vibrational level show strong bimodality when the nitrogen is initially cooled to 8 K. At room temperature, this modest bimodality is not observable. The two rotational distributions are accounted for by the fact that the potential surface for the Penning ionization has two regions of electron transfer, caused by a change in the gradient of the repulsive potential as a function of distance of approach. New investigations are underway to calculate the accurate potentials that give rise to this fine detail in the reaction dynamics.

Energy Transfer - S. R. Leone

Energy transfer processes are important in a wide variety of environments, including laser and discharge media, interstellar space, and the upper atmosphere. The most exciting results in this area (notwithstanding the energy transfer work involved in the Ba^+ velocity distributions and the N_2^+ alignment mentioned above) have been in the study of alignment effects on electronic energy transfer of Ca and Sr atoms. In new experiments, W. Bussert and Leone have been able to measure several energy transfer processes as a function of alignment both in the forward and reverse directions. Thus, for the first time, the symmetries of both states involved in the electronic curve crossing have been determined. Experiments have also explored collisions with molecules. Although many of the molecular collision partners display little or no alignment effects, several molecules show strong effects, including H_2 and CO_2. Finally, a series of studies was made to investigate the alignment effects when two or more energy transfer channels are available. Surprising selective effects are observed, for example, in one case where the parallel alignment is preferred to form one product state and the perpendicular alignment is required to form another.

Surface Dynamics - S. R. Leone

K. Carleton, B. Bourguignon, and Leone have initiated a program in surface scattering dynamics and the growth of semiconductors. This project involves the use of lasers as tools for determining the participation of individual vibrational and electronic states of the gas phase species in the epitaxial kinetics and dynamics of surface semiconductor growth. The first work involves the growth of GaAs semiconductors on silicon single crystals. Measurements have been made using laser induced fluorescence detection of Ga atoms as they scatter and desorb from a Si(100) crystal to determine the binding energy of Ga atoms on the silicon surface. The results show a high binding energy (2.9 eV), which is similar to the energy of binding of As atoms on Si.

Leone and his colleagues have succeeded in probing the dynamics of the two different spin orbit states in the Ga, and have derived a model of the two-state desorption kinetics to explain the results. Structural studies using low energy electron diffraction show that the Ga forms ordered overlayers on Si up to coverages of one monolayer, most likely forming two bonds to the silicon surface and one Ga-Ga dimer bond. Structures for the Ga overlayers have been postulated. Finally, the dynamic measurements reveal that the Ga atoms have mobility in only one dimension on the silicon surface. The results have important implications for the industrial considerations of the growth of GaAs on silicon. For example, the binding energy considerations show that both Ga and As have equal propensity to bind to the clean silicon surface, thus explaining the difficulties previous researchers had with the growth of antiphase domains.

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(submitted and in press)

*R. Bilham, 'Southern San Andreas fault geometry and fault-zone deformation: Implications for earthquake prediction in the Coachella Valley, California,' presented at the National Earthquake Prediction and Evaluation Council, to appear in *U.S. Geological Survey Report.*

*E. Bohm-Vitense, 'Analysis of the transition layer and corona of Procyon,' *Astrophys. J.* (submitted).

*E. Bohm-Vitense, 'Analysis of the solar transition layer and corona,' *Astrophys. J.* (submitted).

A. Brown, 'Radio emission from pre-main sequence stars in Corona Australis,' *Astrophys. J.* (Letters) (submitted).

W. Bussert and S. R. Leone, 'Orbital alignment effects in the Ca(4s5p $^1P_1$) to Ca(4s5p ^3P_J) electronic energy transfer with molecular collision partners,' *Chem. Phys. Lett.* (in press).

W. Bussert, D. Neuschafer and S. R. Leone, 'The effect of orbital alignment on the forward and reverse electronic energy transfer Ca(4s5p $^1P_1$) + M $\leftrightarrow$ Ca(4s5p ^3P_J) + M with rare gases,' *J. Chem. Phys.* (in press).

W. Bussert and S. R. Leone, 'State-specific orbital alignment effects in electronic energy transfer: Sr(5s6p $^1P_1$) + M $\rightarrow$ Sr(5s6p ^3P_J, 4d5p $^3F_4$, $^3F_3$) + M,' *Chem. Phys. Lett.* (in press).

J.-P. Caillault and (D. J. Helfand), 'The Einstein soft X-ray survey of the Pleiades,' (Student Prize Lecture) Astron. Soc. New York (in press).

J.-P. Caillault and (S. Zoonematkermani), 'The Einstein survey of the young stars in the Orion nebula,' *Adv. Space Res.* (COSPAR) (in press).

K. L. Carleton and S. R. Leone, 'Laser probing of gallium atom interactions with silicon (100) surfaces,' *J. Vac. Sci. Technol. B* (in press).

*S.-I Chu, 'Multiphoton processes in intense laser fields,' in *Proceedings, Workshop on Atomic Spectroscopy and its Related Dynamical Properties* (Instit. of Atomic and Molecular Science and National Tsing-Hua University in Taiwan, R.O.C., June 23-25, 1984, in press).

(G. S. Agarwal), C. V. Kunasz and J. Cooper, 'Fluctuation induced Hanle resonances in phase conjugation,' *Phys. Rev. A* (submitted).

L. M. Cousins and S. R. Leone, 'T-V energy transfer and chemical reactions of laser-produced hot H and D atoms,' *Radiochim. Acta* (Proceedings, Hot Atom Symposium, Mt. Fuji, Japan, May 1987) (in press).

*(R. L. Waterland), J. B. Delos and M. L. Du, 'Excited states of an atom in collinear electric and magnetic fields,' *Phys. Rev. Lett.* (submitted).

*J. B. Delos, (R. L. Waterland) and M. L. Du, 'Semiclassical interpretation of eigenvectors for excited atoms in external fields,' *Phys. Rev. A* (submitted).

R. A. Dressler, H. Meyer and S. R. Leone, 'Laser probing of the rotational alignment of N_2^+ drifted in helium,' *J. Chem. Phys.* (submitted).

R. A. Dressler, H. Meyer, A. O. Langford, V. M. Bierbaum and S. R. Leone, 'Direct observation of Ba^+ velocity distributions in a drift tube using single-frequency laser-induced fluorescence,' *J. Chem. Phys.* (submitted).

G. H. Dunn, 'Resonances in electron-ion collisions,' in *Proceedings of the VI National Workshop on Atomic and Molecular Physics*, Varanasi, India, December 8-13, 1986 (World Scientific, Singapore, in press).

S. E. Barlow and G. H. Dunn, 'The effects of isotopic substitution on abstraction reactions of ammonia ions with hydrogen at very low temperatures,' *Int. J. Mass Spectrom. Ion Proc.* (in press).

*P. C. Engelking, 'On van der Waals stabilization of bubbles,' *Phys. Rev. Lett.* (submitted).

J. E. Faller and (A. Sakuma), 'Ballistic methods of measuring 'g' -- the direct free fall and the symmetrical rise and fall methods compared,' *Metrologia* (submitted).

A. Gallagher, 'Doppler-free lineshapes,' in *Proceedings, 8th International Conference on Spectral Line Shapes* (in press).

A. Gallagher, 'Laser spectroscopy of inelastic collisions,' in *Proceedings, First Symposium on Laser Spectroscopy*, Pecs, Hungary, August 1986 (in press).

A. Gallagher, 'Surface reactions in silane discharges,' in *Proceedings of the XIII International Symposium on the Physics of Ionized Gases*, Sibenik, Yugoslavia, September 1986 (in press).

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PUBLICATIIONS

Quantum Physics Division (525)

(submitted and in press)

Deposition,' *Int. J. Solar Energy* (submitted).

A. Gallagher, 'Neutral radical deposition from silane discharges,' *J. Appl. Phys.* (submitted).

(J. G. Porter), K. B.Gebbie and (L. J. November), 'Helium resonance lines in solar flare of 15 June 1973,' *Solar Physics* (submitted).

*(M. S. Pindzola) and D. C. Griffin, 'Double auger processes in the electron-impact ionization of lithium-like ions,' *Phys. Rev. A* (submitted).

*(M. S. Pindzola), D. C. Griffin and (C. Bottcher), 'Theoretical calculations of indirect processes in electron-impact ionization of atomic ions,' *Comments At. Mol. Phys.* (submitted).

*D. C. Griffin (M. S. Pindzola and C. Bottcher), 'Distorted-wave calculations of the electron-impact ionization of highly ionized Na-like ions,' *Phys. Rev. A* (submitted).

J. L. Hall, D. Hils, C. Salomon, and J.-M. Chartier, 'Towards the ultimate laser resolution,' in *Proceedings, Eighth International Conference on Laser Spectroscopy* (in press).

M. Harris, J. F. Kelly and A. Gallagher, 'Observation of three-body collisional transfer between atomic levels,' *Phys. Rev. A* (in press).

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Quantum Physics Division (525)

(submitted and in press)

continuum opacity,' *Astron. Astrophys.* (submitted).

(P. J. Storey) and D. G. Hummer, 'Recombination-line intensities for hydrogenic ions. II. Case B calculations for C VI, N VII and O VIII,' *Monthly Notices Roy. Astron. Soc.* (submitted).

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*(L. P. Presnyakov) and R. K. Janev, 'Excitation and ionization processes in electron-multiply charged ion collisions,' in *Proceedings, Vinis Symposium* (in press).

B. M. Jelenkovic and A. V. Phelps, 'Excitation of N_2 in dc electrical discharges at very high E/n,' *Phys. Rev. A* (submitted).

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P. T. Keyser, 'Forces on the Thieberger accelerometer,' *Phys. Rev. Lett.* (submitted).

*J. G. Kirk and P. Schneider, 'Cosmic ray acceleration at relativistic shocks,' in *Proceedings, Third George Mason Fall Workshop on Astrophysics, Supermassive Black Holes* (in press).

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*M. Sikora, J. G. Kirk, M. C. Begelman and P. Schneider, 'Electron injection by relativistic protons in active galactic nuclei,' *Astrophys. J. (Letters)* (in press).

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Quantum Physics Division (525)

(submitted and in press)

*P. Schneider and J. Kirk, 'Fermi acceleration at shocks with arbitrary velocity profile,' *Astrophys. J. (Letters)* (submitted).

L. J. Kovalenko and S. R. Leone, 'Innovative laser techniques in chemical kinetics: A pedagogical survey,' *J. Chem. Ed.* (submitted).

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J. Levine, 'Automatically running an indirect command file at some future time,' *RSX Multi-Tasker* (submitted).

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(B. E. Woodgate, A. Boggess, T. R. Gull, S. R. Heap, V. L. Krueger, S. P. Maran, R. W. Melcher, F. J. Rebar, H. D. Vitagliano, R. F. Green, S. C. Wolff, J. B. Hutchings, E. B. Jenkins), J. L. Linsky, (H. W. Moos, F. Roesler, R. A. Shine, J. G. Timothy, D. E. Wiestrop, M. Bottema and W. Meyer), 'Second generation spectrograph for the Hubble Space Telescope,' in *Proc., Society of Photo-Instrumentation Engineers* (in press).

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Quantum Physics Division (525)

(submitted and in press)

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*(W. Dappen), D. Mihalas, D. G. Hummer and (B. W. Mihalas), 'The equation of state for stellar envelopes. III. Thermodynamic quantities,' *Astrophys. J.* (submitted).

J. Mitroy, 'Coulomb phase effects in electron-ion scattering,' *Phys. Rev. Lett.* (in press).

*(S. Sapers, V. Vaida) and R. Naaman, 'Photodissociation of CH_3I clusters probed by multiphoton ionization,' *J. Chem. Phys.* (submitted).

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*(S. Cohen), R. Naaman and (J. Sagiv), 'Rotational state-resolved translational energy distributions of NO scattered from organized amphiphilic monolayers,' *J. Chem. Phys.* (submitted).

*(D. J. Donaldson, V. Vaida) and R. Naaman, 'Ultraviolet absorption determination of intramolecular predissociation dynamics in $(CH_3I)_2$ and $(CD_3I)_2$,' *J. Phys. Chem.* (submitted).

(F. M. Walter), J. E. Neff, (D. M. Gibson), J. L. Linsky, (M. Rodono, D. E. Gary and C. J. Butler), 'Rotational modulation and flares in RS Canum Venaticorum and BY Draconis systems. IV. The spatially resolved chromosphere of AR Lacertae,' *Astron. Astrophys.* (in press).

D. J. Nesbitt, 'Slit jet IR absorption spectroscopy of molecular complexes,' in *Structure and Dynamics of Weakly Bound Molecular Complexes* (Reidel, in press).

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Quantum Physics Division (525)

(submitted and in press)

*W.-T. Ni, 'Quantum-mechanical measurement noise in a Michelson interferometer using general squeezed-state light sources,' *Chinese J. Phys.* (in press).

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A. V. Phelps, 'Excitation and ionization coefficients,' in *Proceedings of the Fifth International Symposium on Gaseous Dielectrics* (Pergamon, in press).

(K. Tachibana) and A. V. Phelps, 'Excitation of the $1s^5$ and $1s^4$ levels of neon by low energy electrons,' *Phys. Rev. A* (in press).

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A. V. Phelps, B. M. Jelenkovic and (L. C. Pitchford), 'Simplified models of electron excitation and ionization at very high E/n,' *Phys. Rev. A* (submitted).

A. K. Pradhan, 'Opacity project: Astrophysical and fusion application,' in *Colloquium on Atomic Spectra and Oscillator Strengths for Astrophysics and Fusion Research*, Physica Scripta (in press).

D. Belic and A. K. Pradhan, 'Dielectric recombination,' *Comments At. Mol. Phys.* (submitted).

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A. J. S. Hamilton, W. D. Vacca, and A. K. Pradhan, 'Analysis of the spectrum of the type V supernova SN 1986J,' in *SNRs and Their Interaction with ISM*, *IAU Symposium 101* (Reidel, in press).

*N. F. Ramsey, 'Quantum mechanics and precision measurements,' *IEEE Trans. Instrum. Meas. IM-36* (in press).

*N. F. Ramsey, 'Time and the physical universe,' in *Council of Scholars* (Library of Congress, in press).

*N. F. Ramsey, 'The electric dipole moment of the neutron,' in *Proceedings*, *Stored Particle Conference*, Physica Scripta (submitted).

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Quantum Physics Division (525)

(submitted and in press)

*N. F. Ramsey, 'Precise measurement of time,' *American Scientist* (submitted).

S. H. Saar, 'Improved methods for the measurement and analysis of stellar magnetic fields,' *Astrophys. J.* (in press).

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*(Y. Kawai), H. Saio and (K. Nomoto), 'Steady state models of white dwarfs accreting helium or carbon/oxygen-rich matter,' *Astrophys. J.* (submitted).

*C. L. Sarazin, 'A simple cooling flow model for x-ray coronae around elliptical galaxies,' in *Proceedings of the Greenbank Workshop on Gaseous Haloes around Galaxies* (in press).

*C. L. Sarazin, 'Mass distributions in elliptical galaxies at large radii,' in *IAU Colloquium 127* (Reidel, in press).

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C. J. Schrijver and (J. Cote), 'The relation between the Ca II K line-core flux density and the magnetic flux density on the Sun,' in *Proceedings, Fifth Cambridge Workshop on Cool Stars, Stellar Atmospheres and the Sun* (in press).

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D. M. Sonnenfroh and S. R. Leone, 'Bimodal rotational distributions of N_2^+ produced in the thermal energy Penning ionization of N_2 by $Ne^*(^3P_2)$,' *Int.*

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Quantum Physics Division (525)

(submitted and in press)

J. Mass Spectrom. Ion Proc. (in press).

*(W. M. Sparks), S. Starrfield and (J. W. Truran), 'Nova outburst modeling and its application to the recurrent nova phenomena,' in *Proceedings, Workshop on the 1985 Outburst of RS Ophiuchi* (in press).

*S. Starrfield and (W. M. Sparks), 'A review of the classical nova outburst,' in *Proceedings, Workshop on Cataclysmic Variables*, Bamberg, Germany, June 1986 (in press).

*S. Starrfield, 'A theoretical and observational review of results on nova explosions occurring on ONeMg white dwarfs,' in *Proceedings, Paris Conference on New Directions in Nucleosynthesis*, held at the Institut d'Astrophysique, July 7-11, 1986 (in press).

*S. Starrfield, 'Using nonradial pulsations to determine the envelope composition of very evolved stars,' in *Proceedings, Paris Conference on New Directions in Nucleosynthesis*, held at the Institut d'Astrophysique, July 7-11, 1986 (in press).

*(E. M. Sion), S. Starrfield, (M. E. Van Steenberg, W. M. Sparks, E. P. Ney, J. W. Truran and R. E. Williams), 'A high resolution observation of the line of sight to Nova V693 CrA 1981,' *Astron. J.* (submitted).

*(A. N. Cox), S. Starrfield, (R. B. Kidman) and W. D. Pesnell, 'Pulsations of white dwarf stars with thick hydrogen or helium surface layers,' *Astrophys. J.* (submitted).

*S. Starrfield, 'A review of the ultraviolet studies of galactic novae,' in *New Insights in Astrophysics, 8 Years of Ultraviolet Astronomy with IUE* (ESA SP-263, 1986), pp. 239-245.

R. Stebbins and (P. R. Goode), 'Waves in the solar photosphere,' *Solar Phys.* (submitted).

R. T. Stebbins, P. L. Bender and J. E. Faller, 'Proposed studies of a 30 meter imaging interferometer concept,' in *Proceedings of the ESA Workshop on Optical Interferometry*, Granada, Spain (in press).
D. S. Belic, R. A. Falk, C. Timmer, G. H. Dunn, 'Absolute cross section measurements for electron impact ionization of Al^+, Cd^+ and Hg^+,' *Phys. Rev. A* (in press).

*(V. M. Baev, K.-J. Boller, A. Weiler) and P. E. Toschek, 'Detection of spectrally narrow light emission by laser intra-cavity spectroscopy,' *Opt.*

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Quantum Physics Division (525)

(submitted and in press)

Commun. (submitted).

*P. S. Toschek and (V. M. Baev), 'One is not enough: Intra-cavity spectroscopy with multi-mode lasers,' in *Arthur L. Schawlow -- Lasers, Spectroscopy and Ideas* (Springer-Verlag, in press).

*(F. Dorsch), S. Geltman and P. E. Toschek, 'Laser-induced collisional energy transfer in thermal collisions of lithium and strontium,' *Phys. Rev. A* (submitted).

O. Vilhu and (F. M. Walter), 'Chromospheric-coronal activity at saturated levels,' *Astrophys. J.* (in press).

O. Vilhu, (B. Gustafsson and B. Edvardsson), 'Spectroscopy of the rapidly rotating K-star HD 36705,' *Astrophys. J.* (in press).

O. Vilhu and J. L. Linsky, 'Detection of X-ray emission from the young low-mass star Rossiter 137B,' *Publ. Astron. Soc. Pacific* (in press).

*R. F. Webbink, 'Late stages of close binary systems -- clues to common envelope evolution,' in *Critical Observations vs. Physical Models for Close Binary Systems, Proceedings of the Beijing Colloquium on Close Binary Systems*, 7-13 November 1985 (K.-C. Leung and D.-S. Zhai, Eds., Gordon and Breach, New York, in press).

*(P. A. Teng, F. D. Lewis) and E. Weitz, 'Infrared laser induced homogeneous catalysis of olefin isomerization,' *J. Am. Chem. Soc.* (submitted).

N. C. Wong and J. 730
L. Hall, 'A high resolution measurement of water vapor overtone absorption in the visible by frequency modulation spectroscopy,' *J. Opt. Soc. Am. B* (submitted).

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 strong 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.
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.
Norman Ramsey	Department of Physics Lyman Laboratory of Physics Harvard University Cambridge, MA	Precision measurements, atomic and molecular physics.

1986-1987 VISITING FELLOWS

Quantum Physics Division (525)

Visiting Fellow	Home Institution	Area of Work
Hideyuki Saio	Department of Astronomy Faculty of Science University of Tokyo Tokyo, Japan	Stability and evolution of stars.

1987-1988 VISITING FELLOWS

Quantum Physics Division (525)

Visiting Fellow	Home Institution	Area of Work
David C. Clary	University Chemical Laboratory Cambridge University Cambridge, United Kingdom	Theory of molecular collision in processes in the gas phase.
James M. Farrar	Department of Chemistry University of Rochester Rochester, NY	Low energy ion-neutral interactions, crossed beam studies of reactive collisions.
Jack Feinberg	Department of Physics University of Southern California Los Angeles, CA	Optical computing; interactions of light with matter.
Juhan Frank	Max Planck Institut für Astrophysik Garching, West Germany	Accretion in active galactic nuclei and binary systems.
Ivan Hubeny	Astronomical Institute Czechoslovak Academy of Sciences Ondrejov, Czechoslovakia	Stellar atmospheres, atomic processes, line scattering, numerical simulations.
Wm. Lowell Morgan	Lawrence Livermore National Laboratory Livermore, CA	Computer simulation of atomic and molecular processes, gas-surface interactions.
Per Ake Nordlund	Copenhagen University Observatory Copenhagen, Denmark	Dynamics of the solar atmosphere.
Artur Stolz	School of Surveying University of New South Wales Kensington, Australia	Global positioning system and laser ranging.

1987-1988 VISITING FELLOWS

Quantum Physics Division (525)

Visiting Fellow	Home Institution	Area of Work
John Weiner	Department of Chemistry University of Maryland College Park, MD	Inelastic collision dynamics in simple systems.
Peter Zoller	Institute for Theoretical Physics University of Innsbruck Innsbruck, Austria	Interaction of laser light with atoms, multiphoton processes, laser physics, quantum optics, electron correlation effects.

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

P. S. Conti	H.J.G.L.M. Lamers Space Research Laboratory Utrecht, The Netherlands
J. Cooper	Girish Agarwal Hyderabad, India Dan Wells Waikato, New Zealand
G. H. Dunn	Eldon Ferguson CNRS (Centre Nationale de Recherches Scientifiques) Orsay, France Alfred Muller Justus-Liebig-Universität Giessen Strahlenzentrum Institut für Kernphysik Giessen, West Germany
A. C. Gallagher	J. Kelly University of Idaho Moscow, ID
J. W. Gallagher **Data Center**	Nils Andersen Institute of Physics University of Aarhus Aarhus, Denmark R. Van Brunt National Bureau of Standards Gaithersburg, MD
K. B. Gebbie	Francoise Bely-Dubau Observatoire de Nice France

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

Gebbie (cont.)	Alan Gabriel Laboratoire de Physique Stellar et Planétaire du C.N.R.S. Verriéres-le-Buisson France
J. Hall	Y. Krause Albuquerque, NM
	Motoichi Ohtsu Tokyo Institute of Technology Yokohama, Japan
	Brian Petley National Physical Laboratory Teddington, England
	Fujio & Kazuko Shimizu Universities of Tokyo and of Electro-Communications Tokyo, Japan
	Dan Walls Waikato, New Zealand
	F. Winterberg University of Nevada Reno, NV
	Professor Yao Tiarjin, Peoples Republic of China
S. R. Leone	Pavel Rosmus Fachbereich Chemie der J. W. Goethe-Universität Frankfurt am Main West Germany
J. Levine	V. Levshenko and A. Sadofsky Institute of the Physics of the Earth Moscow, USSR (Visit under Soviet - U.S. exchange)

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

J. L. Linsky	Kjell Eriksson Upsalla Observatory Upsalla, Sweden
	Juhani Huovelin Observatory and Astrophysics Laboratory University of Helsinki Helsinki, Finland
	Don Lamb Department of Astronomy University of Chicago Chicago, IL
	Osmi Vilhu University of Helsinki Helsinki, Finland
R. A. McCray	Shih-I Chu University of Kansas Lawrence, KS
	Timothy Kallman High Energy Astrophysics NASA-Goddard Space Flight Center Greenbelt, MD
	Randy Ross Holy Cross College Worcester, MA
	Peter G. Sutherland Department of Physics McMaster University Hamilton, Ontario, Canada
	Hai Shou Yang Astrophysics Division Geophysics Department Peking University Beijing, Peoples Republic of China

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE (Other than Visiting Fellows)

Quantum Physics Division (525)

McCray (cont.)	Qu Qin Yue President, Nanjing University Nanjing, Peoples Republic of China
D. J. Nesbitt	Ted Lindeman Department of Chemistry Colorado College Colorado Springs, CO
D. W. Norcross	Michael Fink University of Notre Dame Notre Dame, IN
	Michael Morrison Department of Physics University of Oklahoma Norman, OK
	Ken Taylor Department of Applied Mathematics Royal Holloway & Bedford New College Egham, Surrey England
S. J. Smith	Daniel S. Elliott School of Electrical Engineering Purdue University West Lafayette, IN
	Mei Ying Hou Institute of Physics Chinese Academy of Science Beijing, Peoples Republic of China
	Gerd Leuchs Max-Planck Institute für Quantenoptik Garching, West Germany
J. Toomre	Kumar Chitre Tata Institute for Fundamental Research Bombay, India

SCIENTISTS WORKING AT JILA ON SABBATICAL OR OTHER LEAVE
(Other than Visiting Fellows)

Quantum Physics Division (525)

Toomre (cont.)

Douglas Gough
Institute of Astronomy
University of Cambridge
United Kingdom

Edgar Knoblock
Department of Physics
University of California
Berkeley, CA

Michael Proctor
Department of Applied Mathematics & Theoretical Physics
University of Cambridge
United Kingdom

Nigel Weiss
Department of Applied Mathematics & Theoretical Physics
University of Cambridge
United Kingdom

Jean-Paul Zahn
Observatory of Pic du Midi
Toulouse, France

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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."

Fifth Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, University of Colorado, Boulder, Colorado, July 8-11, 1987. J. L. Linsky was Chairman of the Scientific Organizing Committee.

Eighth Workshop on the Vacuum Ultraviolet Radiometric Calibration of Space Experiments, JILA, Boulder, Colorado, March 18-19, 1987. J. L. Linsky was Chairman of the Scientific Organizing Committee.

The Fourth International Conference on Multiphoton Processes, JILA/University of Colorado, Boulder, Colorado, July 13-17, 1987. S. J. Smith, Conference Chairman.

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

JILA Colloquia

Charles Shank (AT&T Bell Laboratories) - Spectroscopy with Femtosecond Optical Pulses, October 7, 1986.

Norman Ramsey (JILA Visiting Fellow, Harvard University) - Experiments on Time Reversal Symmetry and Parity, October 21, 1986.

Peter Toennies (Max-Planck Institute für Stromungsforschung) - November 4, 1986.

Klaus-Peter Dinse (JILA Visiting Fellow, Institut für Physik, University of Dortmund) - High Resolution Spectroscopy With Optical Noise Excitation, November 18, 1986.

Roger Miller (University of North Carolina) - Infrared Spectroscopy and Vibrational Predissociation of Weakly Bound van der Waals Molecules, December 2, 1986.

Yong-Ki Kim (NBS, Gaithersburg) - Relativistic Effects in Electron-Atom Collisions, December 16, 1986.

Walther Johnson (Notre Dame) - Many Body Perturbation Theory Calculations of PNC Amplitudes for Heavy Atoms, January 27, 1987.

Tom Gallagher (University of Virginia) - February 10, 1987.

Y. R. Shen (University of California, Berkeley) - Nonlinear Optics Probing of Adsorbates at Interfaces, February 24, 1987.

Ron Naaman (JILA Visiting Fellow, Weizmann Institute of Science) - Reactions of Clusters--and Inside Clusters, March 10, 1987.

Robert W. Field (Massachusetts Institute of Technology) - Two Digit Theory for Eight Digit Spectra: Finding the Periodic Table in Molecular Spectra, April 21, 1987.

Daniel Kleppner (Wolfe Professor of Phyics, MIT) - Eigenstates of Chaos, May 5, 1987 (E. U. Condon Lecture).

John Kirk (Max Planck Institut für Physik und Astrophysik, Munich) - Particle Acceleration at Shocks: From the Solar Wind to Active Galactic Nuclei, May 12, 1987.

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

Joint JILA/Astrophysics, Planetary and Astronomical Sciences Colloquia

John Hillier (Harvard-Smithsonian Center for Astrophysics) - The Winds From Wolf-Rayet Stars, October 6, 1986.

Joseph Silk (University of California, Berkeley) - A Biased View of Galaxy Formation, November 3, 1986.

Margaret Geller (Harvard-Smithsonian Center for Astrophysics) - Bubble, Bubble, Toil and Trouble: The Foamy Structure of the Universe, November 10, 1986.

David Eichler (University of Maryland) - Collisionless Shocks and the Origin of Cosmic Rays, November 17, 1986.

Carl Pennypacker (Lawrence Berkeley Laboratory) - Recent Results From the Berkeley Automated Supernova Search, November 24, 1986.

Steven Kawaler (Yale University) - Dancing Down the Road to the Stellar Graveyard, December 1, 1986.

Robert Reasenberg (Harvard-Smithsonian Center for Astrophysics) - POINTS: Astrophysics and Light Deflection with 5 Microarc Second Accuracy, December 3, 1986 (with Physics Department).

Jacqueline Van Gorkom (National Radio Astronomy Observatory) - H I Imaging of Radio Galaxies, December 8, 1986.

Hedeyuki Saio (JILA Visiting Fellow, University of Tokyo) - Pulsations in Luminous Helium Stars, February 3, 1987.

Anne Cowley (Arizona State University) - The Nature of the Low-Mass X-Ray Binaries, April 13, 1987.

Alexei Filippenko (University of California, Berkeley) - Evidence for Low-Luminosity Seyfert Nuclei in Nearby Galaxies, April 28, 1987.

John Kirk (JILA Visiting Fellow, Max Planck Institut für Physik und Astrophysik, Munich) - Particle Acceleration at Shocks: From the Solar Wind to Active Galactic Nuclei, May 12, 1987.

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

Special JILA Seminars

H. A. Gebbie (Imperial College London) - Water Polymers in the Atmosphere, October 28, 1986.

Tom Wickham-Jones (University of Colorado) - Studies of Vibrational Energy Transfer of Small Molecules, November 12, 1986.

Dan Walls (University of Waikato, New Zealand) - Progress and Ideas About Squeezed Light, December 19, 1986.

Joachim Krause (University of New Mexico) - The Correlated Emission Laser Problem: Mode-locking or Real Sub-Schawlow-Townes Linewidths?, January 8, 1987.

John Delos (JILA Visiting Fellow, College of William and Mary) - Collisions of Negative Ions with Atoms, January 13, 1987.

John Delos (JILA Visiting Fellow, College of William and Mary) - Rotational Coupling in Ion-Atom Collisions, March 4, 1987.

Joel Bregman (NRAO) - Models for Cooling Flows in Clusters of Galaxies, March 4, 1987.

F. Winterberg (Desert Research Institute) - Possible Experimental Test of Einstein Theory of Relativity Against the Lorentz-Poincaré Ether Theory of Relativity, April 9, 1987.

Henk Spruit (Max-Planck Institut für Astrophysik, Garching, West Germany) - Stationary Shock Waves in Accretion Disks, April 16, 1987.

Peter Martin (MIT) - Momentum Transfer to Atoms Moving Along a Standing Wave, May 13, 1987.

Cool Stars Seminars

Loris Magnani (University of Maryland) - Kinematical Structure of the High Latitude Molecular Clouds, October 1, 1986.

John Stocke (University of Colorado) - Jets From Young Stars: L1551/IRS-5, October 8, 1986.

Karel Schrijver (JILA) - Emission From the Outer Atmosphere of a Star Like the Sun: A Construction Kit, October 15, 1986.

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

Cool Stars Seminars (cont.)

Osmi Vilhu (Helsinki University, Helsinki, Finland) - EXOSAT and EINSTEIN Archive Study of Cool Rapid Rotators: VW Cephei and HE 36705, November 19, 1986.

Steve Saar (JILA) - Correlated IUE and Magnetic Field Observations of Xi Bootis A, December 19, 1986.

David Muchmore (Heidelberg University, Heidelberg, West Germany) - Molecular Cooling and Gas Dynamics in Stellar Atmospheres, January 14, 1987.

Ken Carpenter (Goddard Space Flight Center) - The Latest Information on Red Giant Winds: Alpha Orionis and Its Friends, March 17, 1987.

Herman Marshall (Space Sciences Lab, UC Berkeley) - Uses and Abuses of the EUVE, March 24, 1987.

Steve Saar (JILA) and **Karel Schrijver** (JILA) - Relations Between Radiative and Magnetic Fluxes for the Sun and Stars, at Last, April 1, 1987.

Tom Ayres (University of Colorado) - The Chilling Truth About the Solar Chromosphere, April 7, 1987.

Guenter Wiedemann (Goddard Space Flight Center) - Five Micron Observations of CO in Stars, April 7, 1987.

J. Huovelin (Helsinki University, Helsinki, Finland) - Mysteries of HD199178, May 5, 1987.

J. L. Linsky (JILA) - Requirements for Theoretical Models of Outflows, May 20, 1987.

Chemical Physics Colloquia

William P. Reinhardt (University of Pennsylvania) - Spectra of Atoms In External Fields, October 3, 1986.

Marshall D. Newton (Brookhaven National Laboratory) - Kinetics of Electron Transfer Between Transition Metal Complexes: An Ab-initio Perspective, October 10, 1986.

Edward F. Green (Brown University) - The Interaction of Alkali Atoms with Silicon Surfaces: Equilibrium and Dynamics, October 17, 1986.

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

Chemical Physics Colloquia (cont.)

Robert C. Dunbar (Case Western Reserve University) - Photochemistry and Relaxation in Gas Phase Ions, October 24, 1986.

J. Barrie Peel (La Trobe University) - Photoelectron Spectroscopy of Molecular Dimers and Clusters, November 7, 1986.

R. Bruce Weisman (Rice University) - Direct Studies of Azoalkane Photodissociation Using Time Resolved CARS Spectroscopy, November 14, 1986.

Chris W. Patterson (Los Alamos Scientific Laboratory) - Adiabatic Switching and Quantum Chaos, November 21, 1986.

R. Benny Gerber (University of Tel-Aviv) - Energy Levels and Dynamics of Highly Excited Vibrational States, December 12, 1986.

Paul Houston (Cornell University) - Correlated Chemistry -- The Legacy of Johann Christian Doppler, February 13, 1987.

James L. Skinner (Columbia University) - Energy and Electron Transfer in Disordered Crystals: Quantum Percolation, February 20, 1987.

Wayne Hess (JILA) - I* Quantum Yields By Diode Laser Gain vs. Absorption Spectroscopy, February 25, 1987.

James L. Farrar (University of Rochester) - Reactive Scattering From Multiple Minimum Potentials, February 27, 1987.

Edward S. Yeung (Iowa State University) - Laser-Based Spectroscopic Probes and Their Applications in Physical and Analytical Chemistry, March 13, 1987.

Richard B. Hall (Exxon) - Laser Probes of Surface Reaction Kinetics, April 10, 1987.

Allan Laslette Smith (Drexel University) - Spectroscopy and Thermochemistry of Sulfur Allotropes, April 17, 1987.

C. R. Brundle (IBM, Almaden, California) - XPS Studies, in Conjunction with Other Techniques of Reactions at Well-Defined Metal Surfaces, April 24, 1987.

SEMINARS AND COLLOQUIA

Quantum Physics Division (525)

Chemical Physics After Dark Seminars

Peter Toschek (JILA Visiting Fellow, Universität Hamburg) - Intracavity Laser Absorption Spectroscopy, October 8, 1986.

Julian Coutts (JILA) - Excimer Lasers and Why They Don't Work as Well as You'd Like Them, October 22, 1986.

John Smedley (JILA) - Collisional Release of Br_2 , October 29, 1986.

H. C. W. Beijerinck (Eindhoven University, The Netherlands) - Polarization Effects in Collision-Induced Intramultiplet Mixing for Nee**, November 5, 1986.

Zeev Vager (Weizmann Institute, Israel) - Molecular Structure Determination by the Coulomb Explosion Technique, November 12, 1986.

Chris Lovejoy (JILA) Spectroscopy of van der Waals Molecules in a Slit Supersonic Expansion, December 3, 1986.

Bruce Koel (CIRES) - Chemistry of Nitrogen Dioxide on Metal Surfaces, December 10, 1986.

Jamie Donaldson (JILA) - State Resolved Studies of Dissociative Systems, December 17, 1986.

Bruce Wedding (JILA) - Tales From Down Under or Concentration Gradient Influences on Electron Transport in Gases Under a Uniform Electric Field, January 14, 1987.

Hrvoje Petek (Institute for Molecular Science, Japan) - Quantum State Dependence of Singlet-Triplet Mixing and Collision Induced Intersystem Crossing in Singlet + Triplet CH_2 - February 11, 1987.

Sean Moran (University of Colorado) - Photoelectron Spectroscopy of Sulfur-Containing Anions, February 18, 1987.

Wayne Hess (JILA) - I* Quantum Yields By Diode Laser Gain vs. Absorption Spectroscopy, February 25, 1987.

Kermit Murray (JILA) - Spectroscopy and Autodetachment Dynamics of PtN^-, March 11, 1987.

Chemical Physics After Dark Seminars (cont.)

Ron Naaman (JILA Visiting Fellow, Weizmann Institute of Science) - The Physics of Surfaces Covered With Organized Organic Monolayers, April 1, 1987.

Nancy Levinger (JILA) - Photofragmentation and Photoabsorption of Large AR_n+ Clusters, April 22, 1987.

David Nelson (Harvard University) - Molecular Beam Electric Resonance Studies of Ammonia Dimer, April 29, 1987.

Kenn Arnett (JILA) - Depolarization of Resonance Fluorescence With Finite Bandwidth Lasers, May 6, 1987.

INVITED TALKS

Quantum Physics Division (525)

P. L. Bender, "Laser Gravitational-Wave Antennas in Space," Workshop on Gravitational Wave Physics and Astronomy, MIT, Cambridge, Massachusetts, November 10, 1986.

P. L. Bender, "Sources and Sensitivities for Laser Gravitational-Wave Observations in Space at Hz to Micro-Hz Frequencies," Physics Department Colloquium, University of Colorado, Boulder, Colorado, February 4, 1987.

G. H. Dunn, "A Tuneable Atomic Reaction: Dielectronic Recombination," 9th Conference on the Application of Accelerators in Research & Industry, North Texas University, Denton, Texas, November 11, 1986.

G. H. Dunn, "A Tuneable Atomic Reaction: Dielectronic Recombination," Tata Institute of Fundamental Research, Bombay, India, December 1, 1986.

G. H. Dunn, "Dielectronic Recombination," Physical Research Laboratory, Ahmedabad, India, December 3, 1986.

G. H. Dunn, "Resonances in Electron-Ion Collisions," VI National Workshop on Atomic and Molecular Physics, Banaras Hindu University, Varanasi, India, December 10, 1986.

G. H. Dunn, "Electron-Ion Excitation: Past and Future (?)," Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, Cambridge, Massachusetts, May 22, 1987.

J. E. Faller, "The Physics of Basketball: An Introduction to Scientific Thinking," Physics Department, Lake Forest College, Chicago, Illinois, November 20, 1986.

J. E. Faller, "The New Roles of Gravity in Physics," Physics Department, Lake Forest College, Chicago, Illinois, November 21, 1986.

A. C. Gallagher, "Partial Cross Sections for Na 3S-3P Excitation by Electrons," Gaseous Electronics Conference, Madison, Wisconsin, October 9, 1986.

A. C. Gallagher, "Electronic Energy-Transfer Processes in the Alkali and Alkaline-Earth Metal Vapors," AFOSR Molecular Dynamics Conference, Cambridge, Massachusetts, October 15, 1986.

A. C. Gallagher, "Gas and Surface Mechanisms Leading to a SI:H Films," 1987 Materials Research Society, Palo Alto, California, January 26, 1987.

A. C. Gallagher, "Surface Reactions on Amorphous Silicon Films," American Physical Society Conference, New York, New York, March 19, 1987.

INVITED TALKS

Quantum Physics Division (525)

A. C. Gallagher, "Two-Photon Doppler-Free Line Shapes," International Quantum Electronics Conference, Baltimore, Maryland, April 30, 1987.

A. C. Gallagher, "Optical Diagnostics of Electron-Atom Collisions," DOE-Fundamental Interactions Branch Conference, Cambridge, Massachusetts, May 22, 1987.

A. C. Gallagher, "A New Approach to Fully Differential Electron Excitation Cross Sections," International Symposium on Polarization and Correlation in Electronic and Atomic Collisions, Belfast, Ireland, July 30, 1987.

J. L. Hall, "Measurement of Axial Velocity Distribution of Laser-Cooled Atomic Beam," Optical Society of America, Seattle, Washington, October 22, 1986.

J. L. Hall, "High Performance Laser Frequency Stabilization Using an External Electro-Optic Phase Shifter," Optical Society of America, Seattle, Washington, October 24, 1986.

J. L. Hall, "Stable Lasers: Progress and Applications," Canadian National Research Council, Ottawa, Ontario, Canada, December 10, 1986.

J. L. Hall, "Phase-Stable Lasers: Progress and Applications," University of Arizona, Tucson, Arizona, January 22, 1987.

J. L. Hall, "Noise Reduction in the Relative Phase of Two Lasers," International Conference on Quantum Electronics, Baltimore, Maryland, April 28, 1987.

J. L. Hall, "Progress Toward Phase-Stable Lasers," International Conference on Quantum Electronics, Baltimore, Maryland, April 29, 1987.

J. L. Hall, "Toward The Ultimate Laser Spectroscopy," Geoffrey Frew Lecture, Australian National Conference on Lasers, Surfers' Paradise, Queensland, Australia, May 1987.

J. L. Hall, "Toward The Ultimate Laser Resolution," Eighth International Conference on Laser Spectroscopy, EICHOLS, Are, Sweden, June 23, 1987.

S. R. Leone, "Laser Probing of Chemical Reaction Dynamics," Institute for Space and Astronautical Research, Tokyo, Japan, October 1986.

S. R. Leone, "Laser Studies of Molecular Photochemistry," Department of Pure and Applied Science, University of Tokyo, Japan, October 1986.

S. R. Leone, "Recent Advances in Laser Chemistry," Institute for Physical

Chemistry Research, Tokyo, Japan, October 1986.

S. R. **Leone**, "Laser Probing of Chemical Reaction Dynamics," University of Tokyo, Hongo, Chemistry Department, Japan, October 1986.

S. R. **Leone**, "Laser Studies of Photofragmentation and Free Radical Kinetics," Tohoku University, Sendai, Japan, October 1986.

S. R. **Leone**, "Laser Probing of Chemical Reaction Dynamics," Tokyo Institute of Technology, Tokyo, Japan, October 1986.

S. R. **Leone**, "Laser Studies of Molecular Kinetics," University Electro Communications, Institute for Laser Science, Tokyo, Japan, October 1986.

S. R. **Leone**, "Laser and Infrared Probing of the Thermal Energy Ion Molecule Reactions," Nagoya Meeting - Symposium on New Techniques in Reaction Dynamics, Japan, October 1986.

S. R. **Leone**, "Laser Gain vs. Absorption Probing in the Infrared," Hirota Group Meeting, Institute for Molecular Science, Okazaki, Japan, October 1986.

S. R. **Leone**, "Laser Probing of Chemical Reaction Dynamics," Institute for Molecular Science, Okazaki, Japan, October 1986.

S. R. **Leone**, "Laser Probing of Chemical Reaction Dynamics," Keio University, Yokohama, Japan, October 1986.

S. R. **Leone**, "Laser Studies of Molecular Photofragmentation and Free Radical Kinetics," Tsukuba Science City, Environmental Laboratory, Japan, November 1986.

S. R. **Leone**, "Time Resolved FTIR and Laser Studies of Surface Interactions," Department of Pure and Applied Sciences, University of Tokyo, November 1986.

S. R. **Leone**, "Laser Probing of Chemical Reaction Dynamics," Kyushu University, Kyushu, Japan, November 1986.

S. R. **Leone**, "Laser Studies of Molecular Photofragmentation and Free Radical Kinetics," Symposium on Photochemistry, Osaka, Japan, November 1986.

S. R. **Leone**, "Laser Studies of Surface Deposition: Ga on Si," Hitachi Central Laboratory, Tokyo, Japan, November 1986.
S. R. **Leone**, "Product State Analysis of Chemical Reaction Dynamics,"

INVITED TALKS

Quantum Physics Division (525)

Chemistry Department Colloquium, Washington University, St. Louis, Missouri, December 9, 1986.

S. R. Leone, "Laser Probing of State-Selected Dynamics in the Gas Phase and on Surfaces," University of California, Santa Barbara, California, April 1987.

S. R. Leone, "Laser Probing of State-Selected Dynamics," University of Tokyo, Japan, May 27, 1987.

S. R. Leone, "T-V Energy Transfer and Chemical Reactions of Laser Produced Hot H and D Atoms," XIII International Symposium on Hot Atom Chemistry, Mt. Fugi, Japan, May 1987.

S. R. Leone, "Alignment Effects in Atomic and Molecular Energy Transfer," Xth Conference on Molecular Energy Transfer, Emmetten, Switzerland, August 27, 1987.

S. R. Leone, "Alignment Effects in Electronic Energy Transfer and Reactive Events," NATO Advanced Research Workshop, "Selectivity in Chemical Reactions," Bowness-on-Windemere, United Kingdom, September 9, 1987.

S. R. Leone, "Laser Probing of Product State Distributions in Thermal Energy Ion-Molecule Reactions," Faraday Discussion No. 84, "Dynamics of Elementary Gas Phase Reactions," Birmingham, United Kingdom, September 15, 1987.

J. L. Linsky, "Recent Progress in Understanding Phenomena in Cool Star Atmospheres Using High Resolution Spectroscopy and Monitoring Techniques," 169th Meeting of the American Astronomical Society, Pasadena, California, January 7, 1987.

J. L. Linsky, "Stellar Magnetic Fields and Microwave Radiation: The Solar-Stellar Connection," Naval Research Laboratory, Washington, D. C., January 29, 1987.

J. L. Linsky, "Stellar Surface Structure and Magnetic Fields," Physics Department, NM Institute of Mining and Technology, Socorro, New Mexico, February 17, 1987.

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. March 20, 1987.

J. L. Linsky, "Stellar Surface Structure: Spots and Active Regions on RS

INVITED TALKS

Quantum Physics Division (525)

CVn Binaries and Flare Stars," Infrared Astronomy Group (IRAM), Université Scientifique et Medicale, Grenoble, France, April 24, 1987.

J. L. Linsky, "Requirements for Theoretical Models of Outflows," Second Torino Workshop on Mass Outflows from Stars and Galactic Nuclei, Turin, Italy, May 8, 1987.

J. L. Linsky, "Recent Advances in the Measurement of Stellar Magnetic Fields," Uppsala Observatory, Uppsala, Sweden, May 11, 1987.

J. L. Linsky, "Stellar Surface Structure as Revealed By Doppler Imaging and Rotational Modulation Studies of RS CVn Binaries and Flare Stars," Uppsala Observatory, Uppsala, Sweden, May 1987.

D. J. Nesbitt, "High Resolution, Direct Absorption Laser Spectroscopy in Supersonic Jet Expansions: Vibrational Dynamics of Molecular Clusters," University of Utah, Department of Chemistry, Salt Lake City, Utah, February 2, 1987.

D. J. Nesbitt, "Extreme Vibration-Rotation Coupling in Floppy Molecules," Telluride Summer Research Institute, Telluride, Colorado, June 22-27, 1987.

D. J. Nesbitt, "IR Spectroscopy of Molecular Clusters," Telluride Summer Research Institute, Telluride, Colorado, June 22-27, 1987.

D. J. Nesbitt, "Direct Absorption IR van der Waals Spectroscopy in Slit Supersonic Jets: Molecular Pinballs, Hinges, and Helicopters," 1987 Conference on the Dynamics of Molecular Collisions, Wheeling, West Virginia, July 17, 1987.

D. J. Nesbitt, "Rovibrational Dynamics of Bimolecular Clusters via IR Laser Absorption Spectroscopy in Slit Supersonic Jets," Faraday Discussions of the Royal Society, Birmingham, United Kingdom, September 22-24, 1987.

D. W. Norcross, "Theory of Electron-Molecule Collisions," 40th Annual Gaseous Electronics Conference, Georgia Institute of Technology, Atlanta, Georgia, October 13, 1987.

A. V. Phelps, "Excitation and Ionization Coefficients, 5th International Symposium on Gaseous Dielectrics, Knoxville, Tennessee, May 4, 1987.

A. V. Phelps, "Discharges at Extremely High E/n and Low Currents," International Conference on Phenomena in Ionized Gases, University of Swansea, Swansea, United Kingdom, July 13, 1987.

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, Technical Working Group on Imaging Interferometry in Space, NASA.

P. L. Bender, Editorial Board Member, Il Nuovo Cimento.

P. L. Bender, Member, Geostationary Platform Earth 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, Executive Committee, Division of Electron and Atomic Physics, American Physical Society.

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.

G. H. Dunn, Chairman, Political Advisory Committee, Division of Electron and Atomic Physics, American Physical Society.

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 WorldWide 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.

J. E. Faller, Member, Directing Board of IGC (International Gravity

Commission).

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, Chairman, 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, AMO 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.

S. R. Leone, Chairman, Division of Chemical Physics, American Physical Society, 1987-1988.

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, 1984-1990.

S. R. Leone, Member, NRC Committee, Army Research Office Review Board,

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Physics Division (525)

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 for the International Conference "A Decade of Ultraviolet Astronomy with the IUE Satellite," to be held in Greenbelt, Maryland, April 12-15, 1988.

J. L. Linsky, Member, International Ultraviolet Explorer (IUE) Proposal Review Panel.

J. L. Linsky, Member, Infrared Astronomy Satellite (IRAS) Proposal Review Committee.

J. L. Linsky, Member, Science Advisory Council, Mount Wilson Institute.

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

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Physics Division (525)

Workshop on Cool Stars, Stellar Systems, and the Sun, Boulder, Colorado, July 7-10, 1987.

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.

J. L. Linsky, Member, External Committee to Evaluate the Astronomy Program at the University of Maryland.

D. J. Nesbitt, Member, Organizing Subcommittee for IQEC '88, "Fundamental Laser Spectroscopy and Physics."

D. W. Norcross, Member, Panel on Theoretical Atomic and Molecular Sciences of the Committee on Atomic and Molecular Sciences of the National Research Council.

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.

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.

A. C. Gallagher

Dr. Gallagher is consulting with the Lamp Division and Corporate Research Division of General Electric Corporation.

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:

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 and with Spectra Technology on laser chemical physics.

CONSULTING

Quantum Physics Division (525)

J. L. Linsky

Dr. Linsky consults with NASA concerning (1) future programs in the area of ultraviolet X-ray 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	NASA	Detailed translocation analysis of regional LAGEOS crustal movement data.
P. L. Bender	NASA	Integrated water vapor calibrator measurements.
P. L. Bender & J. E. Faller	NASA	Laser gravitational wave observations in space.
G. H. Dunn	DOE	Determine atomic, molecular, and nuclear data pertinent to the magnetic fusion energy program.
J. E. Faller	AFGL	Absolute gravity studies.
J. E. Faller	DMA-N	Absolute "G" co-op program.
J. E. Faller	MERADCOM	Fabrication of two gravity gradiometers for subsequent field testing and evaluation.
J. E. Faller	NASA	Examination and evaluation of the laser lunar ranging multi-lens telescope.
J. E. Faller	NGS	Routine maintenance of the absolute instrument during fiscal year 1987.
J. E. Faller, P. L. Bender, & R. T. Stebbins	NSF	Development of very low frequency isolation systems for ground-based gravitational-wave interferometers.
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 glow discharges used to produce hydrogenated amorphous silicon films.
K. B. Gebbie & J. Toomre	NASA	X-ray bright points on the quiet Sun and rapid UV brightening in active regions.

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.
J. L. Hall	ONR	Precision atomic beam spectroscopy using stabilized lasers.
D. G. Hummer	NASA	High resolution spectrograph observing program.
D. G. Hummer	NASA	Astrophysical theory program.
D. G. Hummer	NSF	Theory and observation of expanding atmospheres of early type stars.
S. R. Leone	AF	Diode laser probing excited iodine atoms.
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	AFOSR	Laser measurements of state-resolved Ga and atom scattering.
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	Interdisciplinary scientist on the Advanced X-ray Astrophysical Facility (AXAF).
J. L. Linsky	NASA	Hubble Space Telescope Imaging Spectrograph
J. L. Linsky	NASA	An Einstein survey of the soft X-ray

		background and young stars in the Orion Nebula.
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).
J. L. Linsky	NASA	A test of the Golub et al scaling laws.
J. L. Linsky	NASA	HEAO-2 Data Analysis Proposals.
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. J. Nesbitt	SLOAN	SLOAN Research Fellowship.
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.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

P. L. Bender

October 13-17, 1986 - Washington, D.C.
Attended a meeting of the NASA Crustal Dynamics Working Group;
Attended a meeting of NASA Lunar Laser Ranging Working Group;
Consulted with Dr. G. Newton at NASA Headquarters concerning optical imaging interferometry in space.
Sponsor: NASA Goddard.

November 7-12, 1986 - Cambridge, Massachusetts.
Presented an invited talk at the Workshop on Gravitational Wave Physics and Astronomy;
Consulted with Dr. R. Reasenberg and others.
Sponsor: Massachusetts Institute of Technology.

December 9-11, 1986 - San Francisco, California.
Attended the Fall Meeting of the American Geophysical Union.
Sponsor: NASA Goddard.

February 7 - March 7, 1987 - Canberra, Australia.
Participated in the meeting of the NASA Operational Lunar Laser Ranging Management Operations Working Group and the NASA Operational Readiness Review.
Sponsor: NASA Goddard.

March 22-31, 1987 - Pasadena, California.
Attended meetings of the NASA Crustal Dynamics Working Group, the NASA Management/Operations Working Group on Lunar Laser Ranging, and related groups at the Jet Propulsion Laboratory;
Consulted with Professor R. Drever and others at Cal Tech and with Dr. J. Williams at JPL;
Attended meeting of NASA Technical Working Group on Imaging Interferometry in Space at the Jet Propulsion Laboratory.
Sponsors: NASA-Goddard.

May 17-22, 1987 - Baltimore, Maryland.
Attended the meeting of the American Geophysical Union.
Sponsor: NASA Goddard.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

Bender (cont.)

August 17-21, 1987 - Vancouver, B.C., Canada.
Attended 19th General Assembly of the International Union of Geodesy and Geophysics.
Sponsor: NASA Goddard.

G. H. Dunn

November 9-12, 1986 - Denton, Texas.
Attended the Ninth Conference on the Application of Accelerators in Research and Industry at North Texas State University and gave an invited talk.
Sponsor: Department of Energy.

November 28- December 17, 1986 - Bombay, Ahmedabad, New Delhi, and Varanasi, India.
Visited Dr. Mathur and others at the Tata Institute of Fundamental Research for Nuclear Science and Mathematics (Bombay);
Visited with Dr. V. B. Sheorey, Dr. D. P. Dewangen and others at the Physical Research Laboratory (Ahmedabad);
Visited the National Physical Laboratory (New Delhi);
Attended the VI Indian National Workshop on Atomic and Molecular Physics and presented an invited paper (Varanasi).
Sponsor: National Science Foundation.

January 11-13, 1987 - Argonne, Illinois.
Attended a Workshop on "Opportunities For Atomic Physics Using Slow, Highly-Charged Ions," at the Argonne National Laboratory.
Sponsor: Argonne National Laboratory.

J. E. Faller

October 16-17, 1986 - Washington, D. C.
Attended Management Operation Working Group Meeting on Laser Ranging at Goddard Space Flight Center.
Sponsor: Defense Mapping Agency Hydrographic/Topographic Center.

Faller (cont.)

February 6-14, 1987 - Canberra, Australia.
The Lageos and Lunar Laser Ranging Facility as part of the Laser Ranging Management Operations Working Group (MOWG) has not been performing up to expectations for 2 years. Accordingly, NASA asked Dr. Faller, as a member of the MOWG, to help salvage it and make the large U.S. government investment cost-effective.
Sponsor: NASA Goddard.

March 24-26, 1987 - Los Angeles, California.
Attended Lunar Laser Ranging Management-Operations Working Group Meeting.
Sponsor: AF Geophysics Laboratory.

May 18-21, 1987 - Baltimore, Maryland.
Attended meeting of the American Geophysical Union where Dr. Faller's absolute gravimeter was on display.
Sponsor: Defense Mapping Agency, Hydrographic/Topographic Center.

A. C. Gallagher

January 24-28, 1987 - Palo Alto, California.
Attended the 1987 Amorphous Silicon Subcontractors' Review Meeting and presented an invited talk.
Sponsor: Solar Energy Research Institute.

March 17-19, 1987 - New York, New York.
Attended meeting of American Physical Society.
Sponsor: Solar Energy Research Institute.

April 26-May 1, 1987 - Baltimore, Maryland.
Attended the Conference on Lasers and Electro-Optics, and XV International Conference on Quantum Electronics;
Gave a talk at the IQEC Meeting.
Sponsor: Solar Energy Research Institute.

May 17-22, 1987 - Cambridge, Massachusetts.
Attended the American Physical Society meeting and contributed 3 posters.
Attended the DOE Chemical Science-Fundamental Interaction Branch Contractors Conference and gave an invited talk.
Sponsor: Solar Energy Research Institute.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

J. L. Hall

November 9-17, 1986 - Boston, Massachusetts.
Participated in the NSF panel concerned with Gravity Wave Research in the U.S.;
Attended a Dean's Committee Meeting for faculty recruiting at Harvard University.
Sponsors: National Science Foundation and Harvard University.

December 9-11, 1986 - Ottawa, Canada.
Interacted with colleagues at the National Research Council concerning stable lasers, laser techniques, and realization of the meter; presented an invited colloquium.
Sponsor: National Research Council.

January 21-23, 1987 - Tucson, Arizona.
Presented an invited lecture, "Phase-Stable Lasers - Progress and Applications," and interacted with colleagues in the Optical Sciences Center, University of Arizona, regarding scientific problems of mutual interest.
Sponsor: University of Arizona.

May 4-25, 1987 - Sydney, Surfers Paradise, Brisbane, Canberra, and Melbourne, Australia.
Visited university and government research labs (Sydney, Surfers Paradise, Brisbane, Canberra, and Melbourne);
Presented the Frew Lecture at the National Meeting of the Australian Academy Science and Institute of Physics (Canberra).
Sponsor: Australian Academy of Science.

D. G. Hummer

September 20 - October 20, 1986 - London, England and Munich, West Germany.
Worked with M. J. Seaton and P. J. Storey on opacity project and recombination calculation and attended meeting and Steering committee meeting of Collaborative Computational Project on Stellar Atmospheres (London);
Worked with R. P. Kudritzki and J. Puls on radiation-driven stellar winds (Munich).
Sponsor: NATO Grants.

Hummer (cont.)

November 9-15, 1986 - Boston, Massachusetts.
Ongoing collaboration with Professor G. B. Rybicki of Harvard-Smithsonian Center for Astrophysics on transfer of radiation high-speed gaseous flows.
Sponsor: Smithsonian Institution.

December 8-18, 1986 - London, England.
Attended meeting of Opacity Project and worked with P. J. Storey on collisional-radiative recombination.
Sponsor: NATO Grants.

January 23-25, 1987 - Austin, Texas.
Attended a workshop on accretion disks and gave an invited paper on our calculation of line profiles formed in accretion disks.
Sponsor: University of Texas.

April 26-29, 1987 - Washington, D. C.
Met with S. Heap (NASA) and R. Kudritzki to plan High Resolution Spectrograph program for hot stars.
Sponsor: NASA Goddard.

June 18 - August 21, 1987 - London, England; Munich, West Germany; Paris, France.
Worked with Dr. Peter Storey, University College London, on ongoing collaboration on collision-radiative recombination calculations (London);
Worked with Professor R. Kudritzki, Institute for Astronomy and Astrophysics, Munich, on new method of distance determination to hot stars (Munich);
Attended Opacity Project Meeting at Paris Observatory and presented two papers (Paris);
Worked with Dr. Peter Storey (London).
Sponsors: NATO Grants.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

S. R. Leone

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; Okazaki, Tokyo, Japan.

Six-week Fellowship from the Japanese Society for the Promotion of Science (JSPS) during which time Dr. Leone visited various universities & 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.

(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.

Delivered lectures and collaborated on experiments. (Tokyo, Sendai, and other nearby cities);
Attended the Chemical Reaction Dynamics Symposium and gave an invited talk (Nagoya);
Visited the Institute for Molecular (IMS) Science and visited labs, gave invited talks, and collaborated on IR diode laser studies of excimer laser photochemistry with Professor Hirota (Okazaki);
Gave talks at labs and universities (Kyoto, Nara);
Visited Professor T. Ogawa (Kyushu University) and other laboratories and universities in various cities (Kyushu District);
Visited the IMS (Okazaki);
Sponsor: Japanese Society for the Promotion of Science.

Leone (cont.)

December 8-9, 1986 - St. Louis, Missouri.
Visited Washington University and presented a seminar.
Sponsor: Washington University.

March 15-19, 1987 - New York, New York.
Chairman at a meeting of the Division of Chemical Physics of the American Physical Society;
Participated in meeting of the American Physical Society for which Dr. Leone had organized a major symposium on "Innovative Chemical Processes on Semiconductors and Surfaces."
Sponsor: The American Physical Society.

April 23-25, 1987 - Santa Barbara, California.
Presented a seminar and gave a talk at the University of California.
Sponsor: University of California, Santa Barbara.

May 22-29, 1987 - Mt. Fuji, Japan.
Presented an invited talk at the 13th International Hot Atom Symposium and interacted with colleagues.
Sponsor: International Hot Atom Symposium.

July 12-17, 1987 - Oglebay Park, West Virginia.
Attended the 1987 Conference on the Dynamics of Molecular Collisions and presented an invited "overview" talk on experimental reaction dynamics.
Sponsors: The Conference.

September 6-17, 1987 - Bowness-on-Windemere, Birmingham, United Kingdom.
Attended NATO Advanced Research Workshop and presented an invited talk (Bowness-on-Windemere)
Attended Faraday Discussion #84 and presented an invited paper (Birmingham).
Sponsors: NATO Advanced Research Workshop and Faraday Discussion.

J. L. Linsky

October 6-7, 1986 - Tucson, Arizona.
Attended a meeting of the National Optical Astronomy Observatory Visiting Committee.
Sponsor: National Optical Astronomy Observatories, Association of Universities for Research In Astronomy, Inc. (AURA).

Linsky (cont.)

October 9-10, 1986 - Greenbelt, Maryland.
Attended a meeting of the Astrophysics Management Operations Working Group at Goddard Space Flight Center.
Sponsor: Battelle.

October 27-29, 1986 - Cambridge, Massachusetts.
Attended a meeting of the AURA Committee on Future Directions for the National Optical Astronomy Observations at the Center for Astrophysics.
Sponsor: National Optical Astronomy Observatories (AURA).

November 3-5, 1986 - Greenbelt, Maryland; Huntsville, Alabama.
Attended a meeting of the IUE Long Range Planning Committee (Greenbelt, Maryland);
Attended a meeting of the AXAF Science Working Group (Huntsville).
Sponsors: Creative Management Corporation and NASA George C. Marshall Space Flight Center.

November 9-10, 1986 - Greenbelt, Maryland.
Attended a meeting of the AXAF Science Working Group.
Sponsor: NASA George C. Marshall Space Flight Center.

November 30 - December 2, 1986 - Washington, D. C.
Attended a meeting of the Committee on Space Astronomy and Astrophysics of the National Academy of Sciences.
Sponsor: National Academy of Sciences.

December 9-12, 1986 - Baltimore, Maryland.
Attended a meeting of the Astrophysics Management Operations Working Group.
Sponsor: Battelle.

December 18, 1986 - Pasadena, California.
Attended a meeting of the Mount Wilson Institute.
Sponsor: National Optical Astronomy Observatories (AURA).

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

Linsky (cont.)

January 14-16, 1987 - Tucson, Arizona.
Attended a meeting of the National Optical Astronomy Observatory's Committee on Future Directions for NOAO.
Sponsor: National Optical Astronomy Observatories (AURA).

January 27-30, 1987 - Tucson, Arizona; Washington, D. C.
Attended a meeting of the SYNOP Spectrograph Committee (Tucson);
Presented an invited Colloquium at the Naval Research Laboratory (Washington, D.C.).
Sponsors: Naval Research Lab and NASA George C. Marshall Space Flight Center.

February 8-10, 1987 - Washington, D. C.
Attended a meeting of the NASA Astronomy Relativity Management Operations Working Group (ARMOWG).
Sponsor: NASA Goddard.

February 17-18, 1987 - Albuquerque, New Mexico.
Gave an invited colloquium at New Mexico Tech and discussed collaborative observing programs with Dr. David Gibson and astronomers at the NRAO Very Large Array.
Sponsor: New Mexico Institute for Mining and Technology.

February 23-24, 1987 - Baltimore, Maryland.
Attended a meeting of the Astrophysics Management Operations Working Group.
Sponsor: Battelle.

March 10-12, 1987 - Greenbelt, Maryland.
Participated in the International Ultraviolet Explorer (IUE) Proposal Review.
Sponsor: Creative Management Corporation.

March 19-21, 1987 - Phoenix, Arizona.
Gave an invited Physics Department Colloquium.
Sponsor: Arizona State University.

TRIPS SPONSORED BY OTHERS

Quantum Physics Division (525)

Linsky (cont.)

March 29-31, 1987 - Pasadena, California.
Participated in the IRAS Proposal Review at the California Institute of Technology.
Sponsor: California Institute of Technology.

April 7-10, 1987 - Greenbelt, Maryland.
Attended a meeting of the Space Telescope Imaging Spectrograph Team.
Sponsor: NASA Goddard.

May 17-19, 1987 - Tucson, Arizona.
Chairman of the SYNOP Meeting which met at the NOAO.
Sponsor: National Optical Astronomy Observatories, (AURA).

May 21-22, 1987 - Washington, D.C.
Attended a meeting of the NASA Supernova Science Working Group at the Goddard Space Flight Center.
Sponsor: NASA.

May 31 - June 5, 1987 - Madrid, Spain.
Attended a meeting of the IUE Long Range Planning Committee and the NASA-ESA-SERC Three Agency IUE Coordinating Committee.
Sponsor: Creative Management Association.

June 9-11, 1987 - College Park, Maryland.
Attended a meeting of the AXAF (Advanced X-ray Astronomical Facility) Science Working Group.
Sponsor: NASA George C. Marshall Space Flight Center.

June 15-20, 1987 - Vancouver, British Columbia, Canada and Victoria, British Columbia, Canada.
Attended a meeting of the American Astronomical Society (Vancouver);
Attended a meeting of the Space Telescope High Resolution Spectrograph Team (Victoria).
Sponsor: NASA Goddard.

David J. Nesbitt

October 14-17, 1986 - Boston, Massachusetts.
Attended an AFOSR Meeting.
Sponsor: AFOSR.

Nesbitt (cont.)

January 12-17, 1987 - Los Angeles, California.
Attended SPIE Conference and presented a talk;
Presented talk at University of California at Irvine;
Presented talk at University of Southern California.
Sponsors: SPIE, University of Southern California, and University of California at Irvine.

February 2-4, 1987 - Salt Lake City, Utah.
Presented a talk at the University of Utah;
Presented a talk at Utah State University.
Sponsors: University of Utah and Utah State University.

July 12-17, 1987 - Oglebay Park, West Virginia.
Attended 1987 Conference on Dynamics of Molecular Collisions and presented a talk.
Sponsors: The Conference.

D. W. Norcross

May 21-22, 1987 - Cambridge, Massachusetts.
Attended DOE Atomic Physics Workshop.
Sponsor: Department of Energy.

July 1-4, 1987 - Washington, D. C.
Met with Physics Division, National Science Foundation.
Sponsor: Department of Energy.

July 16 - August 3, 1987 - England.
Attended ICPEAC Conference and Satellite meetings in Daresbury, Egham, and Oxford.
Sponsor: Department of Energy.

A. V. Phelps

July 6-10, 1987 - Zagreb, Belgrade, Yugoslavia.
Visited the Institute of Physics of the University Zagreb (Zagreb);
Visited the Institute of Physics, Belgrade, (Belgrade).
Sponsors: U.S. - Yugoslavia Joint Board.

Phelps (cont.)

September 28 - October 1, 1987 - Monterey,

	California. Attended 1987 SDIO/DARPA Services Annual Propagation Review. Sponsor: AFWAL, Wright-Patterson AFB.
D. M. Sonnenfroh	July 12-17, 1987 - Oglebay Park, West Virginia. Attended the 1987 Conference on the Dynamics of Molecular Collisions. Sponsor: Air Force Weapons Lab, Kirtland.

UNIVERSITY AND DEPARTMENT COMMITTEE MEMBERSHIPS

Quantum Physics Division (525)

P. L. Bender

Thesis Committees for:

D. N. de Vries
Physics Department, University of Colorado

T. M. Niebauer
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

Chairman of JILA

Graduate Committee, Department of Physics

JILA Shops Committee

Member, several Ph.D. examinations committees

Thesis Committees for:

M. Alexander
Chemistry Department, University of Colorado

S. Jefferts
Physics Department, University of Colorado

M. Schauer
Physics Department, University of Colorado

C. Timmer
Physics Department, University of Colorado

J. Van Doren
Chemistry Department, University of Colorado

E. Wahlin
Physics Department, University of Colorado

UNIVERSITY AND DEPARTMENT COMMITTEE MEMBERSHIPS

Quantum Physics Division (525)

J. E. Faller — Geophysics Committee, Department of Physics

Graduate Advisor for:

H. Godwin
Physics Department, University of Colorado

M. McHugh
Physics Department, University of Colorado

T. Niebauer
Physics Department, University of Colorado

A. C. Gallagher — JILA Space Committee

Chairman, Thesis Committees for:

J. Doyle
Physics Department, University of Colorado

K. Gibble
Physics Department, University of Colorado

X. Han
Physics Department, University of Colorado

M. O'Callaghan
Physics Department, University of Colorado

G. Schinn
Physics Department, University of Colorado

M. Troyer
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

UNIVERSITY AND DEPARTMENT COMMITTEE MEMBERSHIPS

Quantum Physics Division (525)

J. L. Hall — Chairman, Thesis Committees for:

Z. Miao
Physics Department, University of Colorado

M. Winters
Physics Department, University of Colorado

D. G. Hummer — Thesis Committees for:

P. Becker
Astrophysical, Planetary, and Atmospheric Sciences Department, University of Colorado

J. Doggett
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 — Final Ph.D. Defense Committee for:

M. Alexander
Chemistry Department, University of Colorado

K. Carleton
Chemistry Department, University of Colorado

K. Lykke
Chemistry Department, University of Colorado

J. Smedley
Chemistry Department, University of Colorado

JILA Visiting Scientists Office.

UNIVERSITY AND DEPARTMENT COMMITTEE MEMBERSHIPS

Quantum Physics Division (525)

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

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

Chairman, Chemical Physics After Dark Seminar Series

D. W. Norcross

JILA Executive Committee, January 1985 - December 1986.

Chair, JILA Computing Committee

Chair, JILA Building Committee

Comprehensive Exam Committee, Department of Physics

JILA Data Center Advisory Committee.

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. Doyle
Physics Department, University of Colorado

M. O'Callaghan
Physics Department, University of Colorado

G. Schinn
Physics Department, University of Colorado

GRADUATE STUDENTS AND POSTDOCTORAL RESEARCH ASSOCIATES SUPERVISED

Quantum Physics Division (525)

	Graduate Students	Postdoctoral Research Associates
P. L. Bender	S. D. Swartz S. J. Walter X. -P. Wu	M. A. Vincent
G. H. Dunn	A. Cachelin S. Jefferts M. Schauer K. Timmer E. Wahlin	J. L. Forand K. Rinn D. Swenson
J. E. Faller	H. Godwin M. McHugh T. Niebauer	
A. C. Gallagher	J. Doyle K. Gibble X. Han M. O'Callaghan G. Schinn M. Troyer	P. Arcuni M. Harris G. Lin
J. L. Hall	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 Y. Yan
S. R. Leone	K. Carleton (NSF) L. Cousins W. Hess K. Knutsen G. H. Lin J. Smedley R. Smilgys C. Taatjes E. Woodbridge	H. Beijers V. Bierbaum (25%) W. Bussert D. J. Donaldson (NSERC) R. Dressler R. Fletcher H. Meyer R. Robinson D. Sonnenfroh (NRC) K. Yamasaki

GRADUATE STUDENTS AND POSTDOCTORAL RESEARCH ASSOCIATES SUPERVISED

Quantum Physics Division (525)

	Graduate Students	Postdoctoral Research Associates
J. L. Linsky	J. Neff S. Saar	C. Ambruster J. Bookbinder A. Brown J. P. Caillault P. Judge K. Schrijver
D. J. Nesbitt	W. Hovingh C. Lovejoy A. McIlroy A. Schiffman M. Schuder	D. Nelson (NRC)
D. W. Norcross	T. Gorczyca H.-L. Zhou	S. Alston J. Mitroy A. Pradhan G. Snitchler
A. V. Phelps		V. T. Gylys A. B. Wedding

COURSES TAUGHT AT UNIVERSITY OF COLORADO

Quantum Physics Division (525)

J. L. Hall	Laser Stabilization - Physics 696
S. R. Leone	Physical Chemistry Laboratory Course - Development and Construction of New Experiments
J. L. Linsky	Special Topics in APAS: Stellar Atmospheres - APAS 650 (Fall 1987)
D. J. Nesbitt	Chemistry 558 - Quantum Chemistry (Fall 1986)
	Chemistry 452 - Quantum Chemistry (Fall 1987)
D. W. Norcross	Recitation - Physics 112 (Spring 1987)
A. V. Phelps	Physics III - Recitation (Fall 1986)

BACKGROUND ON JILA

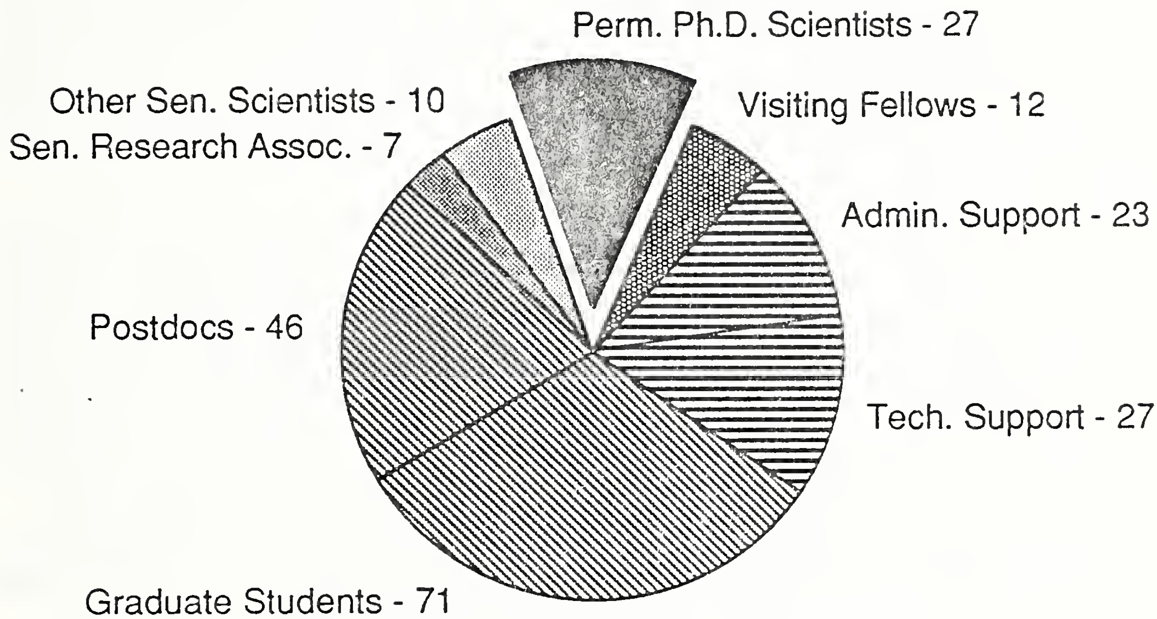
Quantum Physics is the division through which NBS participates in the Joint Institute for Laboratory Astrophysics, a cooperative enterprise between NBS and the University of Colorado (CU). In collaboration with University faculty and visiting scientists, the Division conducts the kind of long-term, high-risk 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 postulates of physics such 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 1960s 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 1987-1988

Total - 223



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.

QUANTUM METROLOGY DIVISION
SUMMARY OF ACTIVITIES
FISCAL YEAR 1987

BACKGROUND & OVERVIEW

This relatively small group evolved from earlier organizational forms and is associated with efforts whose emphasis and scope have changed notably over the past decade. A persistent core has been, however, a conscious attempt to focus on those areas of fundamental physics where progress is conditioned on advancement of measurement technology. Of the several directions in which such a program might take form, ours has emphasized unification of the electromagnetic (frequency/wavelength) scale. Although some of our earlier work included establishing linkages between the radio-frequency domain and the visible region, by far the dominant part has concerned extension of this congruent scale through the x-ray region and into the γ-ray region, thus far reaching approximately 4 MeV. To accomplish this work, parts of which remain in progress, it was necessary to make significant progress in the measurement of small distances and small angles. Dividends from these efforts have included determination of elementary particle masses, tests of QED in few-electron and muonic atoms, determination of fundamental constants and atomic energy levels. A synoptic view of the present state of this work will be given below.

A second theme having long persistence has focussed on clarifying the mechanisms responsible for the finer details of inner-shell spectra from atoms, molecules and simple solids. The particular conundrum formulated by one of us (RDD) thirty years ago concerns the aliasing effect of multi-vacancy processes on phenomenological spectra. Far from being small and readily recognizable, these effects are easily shown to be large and so entangled with the presumably better understood single-vacancy spectra as to make progress very slow - slow to the point that the field was effectively abandoned. Since even single-vacancy processes are difficult to treat satisfactorily from the theoretical side, good calculations of the normal complement of multi-vacancy contaminants remain prohibitively laborious. One needs instead an experimental approach capable of separating this complex phenomenology into its components and effectively stripping away the multiple-vacancy contributions. This much was already understood in principle and been given some limited demonstration over twenty years ago, but systematic applications had to await not only the coming of age of dedicated synchrotron radiation facilities but also the development of high efficiency beamline optics and their dedication to systematic investigations in this area. All of this is now realized (as will be shown below) in the Division's Beamline X24-A at the National Synchrotron Light Source (NSLS) in Brookhaven. Not only has this ansatz borne out these expectations but the facility has opened already several new domains, perhaps even more tantalizing than the original conundrum.

Beyond the core programs, others have come and gone over the past decade sometimes reflecting individual interests, sometimes special opportunities, and sometimes new directions for possible programmatic growth. Examples include: a laser chemistry program which evolved from a need (still present) for producing kilogram quantities of ^{28}Si which became a pioneering effort in laser catalysis and isotope enrichment. This, in turn, dissolved in the face of overwhelming external competition but yielded several excellent smaller programs which remain productive elsewhere in NBS. An opportunity to collaborate with Jesse Beams in his later years became a serious long-term, though ultimately sub-critical, effort on the Newtonian gravitational constant, G, its spatial derivative and the associated assertions of the equivalence principle; this work is terminated but might re-awaken, its principal protagonist (Luther) is at Los Alamos. A market for semi-good laser wavelength measurements led to several inventions in this area by J.J. Snyder, one of which (the Fizeau wavemeter) is reasonably well commercialized by now. Snyder is at Lockheed Research Laboratories (Palo Alto).

We are presently embarked on yet another excursion with G. Greene as the main driving force. This aims at developing a fundamental physics beamline at the new NBS Cold Neutron Guide Hall and at several specific neutron physics experiments to be carried out initially at the High Flux Reactor of the Institut Laue-Langevin (ILL) in Grenoble. Significant external support has emerged (from DOE) for the initial phase of this work while additional resources are being made available through the Guide Hall project itself. The present situation is reviewed below while it remains to be seen if the potentially large growth in this area can be accommodated within this small group.

At the risk of some distortion, the Division's work has been amalgamated into three categories, namely: precision spectroscopy of x-rays and γ-rays (including x-ray interferometry and lattice intercomparisons); inner-shell physics (including both synchrotron radiation work and that done here with conventional sources as well as surface studies and dynamical diffraction); and, neutron physics. Not included in this year's report are reports on our efforts on x-ray spectroscopy from earth-orbiting platforms and the Z-systematics of x-ray spectra.

TECHNICAL ACTIVITIES

<u>Precision X-Ray Spectroscopy</u>:

Extension of optically based electromagnetic wavelength measurements from the visible through x-ray and into the γ-ray region was, in its modern form, initiated in the Division. The key concept is elementary and easily stated while full realization of its potential remains a formidable exercise. One begins by appreciating the extraordinary uniformity of synthetic semiconductor crystals (especially Si) with which we have been gifted by the industrial community. One notes, as well, that laser interferometry is easily refined to sub-atomic dimensions. Evidently given any procedure for registering the passage of lattice planes on a carriage whose progress is otherwise noted by optical means secures a lattice parameter measurement in terms of a visible wavelength. Nowadays one might think of noting the passage of lattice planes by tunneling microscopy (as occupied some of our pre-1964 thoughts); as it turned out the realization of crystal Moire interferometry by Bonse and Hart furnished a more readily accessible lattice passage decoder which has been used in all work to date.

Given a calibrated crystal from the above XROI (x-ray/optical interferometry) exercise, determination of reference wavelengths is a straightforward application of the Bragg-Laue condition ($\lambda=2d\sin\Theta$) provided absolute angle-measurement of the requisite refinement is at hand. There were (and are) two rather different domains: At longer wavelengths, $\lambda\approx d$, relatively large angles are involved (30°-60°) for which a variety of encoding and circle-reading schemes offer sub-ppm capability when carefully operated and calibrated from first principles, i.e., circle closure. At shorter wavelengths, $\lambda \ll d$, small diffraction angles are involved (typically $\lambda/d\approx 10^{-2}$) where a particularly refined form of angle interferometry ($\delta\theta \ll 10^{-3}$ arcsec) was needed and new forms of first-principles calibration had to be developed. Nowadays we are approaching 0.01 ppm in this type of work. A step of considerable practical importance was omitted from the discussion so far to emphasize its conceptual simplicity. Specifically, crystals emerging from the XROI exercise are not well suited to other purposes, e.g., γ-ray diffraction or soft x-ray diffraction. This problem has been addressed by development of several schemes for comparing slightly unequal crystal repeat distances. The most recently realized and most refined of these techniques appears capable of robust operation at the 0.01 ppm level but is presently limited to somewhat worse errors by sample perfection and specimen preparation problems.

Until about ten years ago one might have imagined that our work would terminate with production of well-documented secondary standards in the x-ray and γ-ray region. That is to say we considered that other groups would then apply these to the wavelength calibration of spectra appropriate for QED tests (muonic and electronic atoms) and for the determination of elementary particle masses (especially pions and kaons as well as $\Sigma^{(-)}$ and the neutron). Actually, much of the early effort went in this direction, but we began to realize the utility of being more directly involved in the final experiments. Direct involvement provides unique opportunities, for example, the possibility of directly measuring the n-p capture γ using our primary instrumentation, i.e., avoiding additional error contribution due to use of transfer standard and a (much lower resolution) bent-crystal instrument. We also became active in accelerator-based experiments by introducing a family of high-resolution focussing instruments with position sensitive proportional counters as detectors. This process has led to several experimental activities both in the U.S. and in Europe at heavy-ion accelerators as well as further work (described below) at the Grenoble high-flux reactor.

In spite of all these positive developments, this entire area of work spent several of the past years under a serious cloud. The circumstances leading to this long and difficult period was that subsequent to the initial NBS XROI experiment, work at the PTB in Braunschweig gave a discordant value for the crystal repeat distance in a similar specimen (albeit one having different ancestry). The discrepancy emerged around 1980 and its resolution resisted analysis for several years. A major decision around 1983 was to re-establish the NBS experiment with important improvements especially as regards control of systematic sources of error. In January 1986 a rather subtle but quite serious error in the early NBS work became clear from the new experiment. Its elimination cleared up most of the discrepancy, but left our need for a definitive new result unsatisfied. (This is a hard experiment to bring into anything resembling statistical control and has grown harder with the addition of on-line diagnostics which are themselves subject to drift and error). As described below these problems have yielded (grudgingly) to persistent effort including a very recent "breakthrough" that has tripled the useful XROI scan range. Interferometric measurements appear now (August 1987) to be yielding data at the level of 0.01 ppm (statistical uncertainty) per overnight run.

<u>Gaithersburg activities</u>:

As mentioned above, 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 four years, we established two major efforts to deal with this important question. Firstly, the entire x-ray/optical interferometer (XROI) experiment was reconstructed with major improvements. These include (1) use of a frequency-agile, offset-locked slave laser to drive the system through each x-ray interference profile studied; (2) provisions of a unique and sensitive 4-beam path curvature interferometer for on-line trajectory characterization; full computer-controlled automation; and, (3) 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.

At the last panel meeting it was possible to report that the origin of the NBS-PTB discrepancy had been identified and that the delta-d machine had achieved initial operation with a promising outlook. 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 in the winter of 1986 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 gave numerical values which substantially remove the NBS-PTB discrepancy. Small differences actually remained but these were well within the range of generally expected sample-to-sample variability.

The year since was devoted to progressively more successful efforts to achieve a result having defensible accuracy consonant with the evident potential in this experiment. This has required still more intense attention to path interferometry and, ultimately to the correction of the path itself. As operated last year, loss of fringe contrast limited the XROI scan range to ≈ 72 optical orders while requiring appreciable corrections for "pitch" and "yaw" errors in the trajectory. It was very recently (June 1987) possible to eliminate most of the "yaw" error mechanically while introducing an electrically driven pitch corrector which substantially eliminates pitch error. The last mentioned step allows a much greater scan range which is ultimately limited by drifts which accumulate with the time required to cover the scanned range. At present, a viable compromise seems to be a scan of 198 optical fringes with a resulting statistical error for each round trip (3 hours) of about 0.02 ppm.

It is presently proving difficult to analyze the data thus obtained in a way that fully exploits its potential accuracy but progress appears at hand with a now hoped for estimate of accuracy to be below 0.03 ppm. (All work on this project is carried out by RDD with occasional but vital assistance from AH.)

Meanwhile progress on the Δd machine and its operation has continued (through the efforts of EGK with sample preparation by AH). Several serious technical problems were encountered and overcome, however, the main challenge and difficulty remains associated with production of sufficiently uniform specimens having adequately controlled thickness values. The Δd diffractometer is equipped with a sub-millisec angle interferometer having a range of ±15°. It is mounted on a massive vibration isolated surface plate in the basement. The instrument is surrounded by a curtain-type enclosure and the crystals are thermally shielded. Two x-ray tubes are used to permit simultaneous recording of "left" and "right" (non-dispersive) curves. Operation of both tubes is with a single x-ray power supply and two constant potential units. Computer software automatically controls the spectrometer and permits round-the-clock comparisons of four crystal samples.

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 ($\delta t<10\ \mu$) thickness showed the expected 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 precise. Although great care was exercised during the crystal preparation to insure that crystal thicknesses were within the required tolerances, we are still apparently limited by this step. First profiles were recorded in the spring of 1986 and, after some modifications to improve both performance and convenience, profiles containing symmetric distinct fine structure were obtained. As of September 1986 the instrument's potentialities had been well demonstrated. With the then evident clear delineation of expected hyperfine detail one easily saw lattice constant differences (Δd's) near 0.05 ppm with the expectation of accuracies at or below 0.01 ppm after more careful analysis.

The intervening months have seen development of progressively more refined temperature measurement and control as required for realization of potential accuracy indicated above. They have also seen the "discovery" that the generation of crystals we have in hand appear to have non-flat atomic planes. These are apparently spherical with curvature centers on the growth axis and radii > 10 km. While we are aware of new efforts (for example at Wacker Electrochemie) to remedy this difficulty, it represents a distinct practical limit to what can be done with specimens currently available.

X-Ray Spectroscopy - Brookhaven:

The Division has been involved for several years in the NBS/NRL Participating Research Team (PRT) at the National Synchrotron Light Source (NSLS). The PRT supports five beamlines using radiation from a single bending magnet on the x-ray ring. Following the long-standing interest in x-ray and inner-shell physics noted above, we built and now operate beamline X24-A which is equipped with a double-crystal monochromator designed to deliver x-rays in the 1-5 keV photon-energy range; this complements other PRT beamlines that deliver lower (10-2000 eV) and higher (3-12 keV) photon energies, respectively. In its operable energy range, X24-A provides the most intense and narrowest-band-width synchrotron-radiation beam presently available in the world by virtue of several novel design features. These features include horizontal collection of a full 8 mrad of radiation from the NSLS bending magnet, novel mirror coatings, and pre-monochromator collimation and post-monochromator focussing optics to improve resolving power. The available energy range of X24-A includes inner-shell thresholds for all but the lightest elements, making it useful for several forms of x-ray spectroscopy, including high-energy-resolution x-ray fluorescence and x-ray photoemission, as well as for studies of surface diffraction and interference effects in crystals.

The beamline has performed well since becoming operational in late FY85. However, its productivity is naturally linked directly to the schedule and performance of the NSLS facility. Fortunately, for the first five months of FY87, the x-ray ring at NSLS performed exceptionally well, setting new records in maximum beam current (>200 mA) and lifetime (>24 h) during this period. Unfortunately, at the beginning of March, 1987, the x-ray ring was turned off for the NSLS Phase II shutdown to install several insertion devices, to improve beam injection capabilities, and to make many other changes. We expect this shutdown to last well into FY88.

During the available beam time in FY87, four of the five months were concentrated on x-ray spectroscopy of atoms, molecules, and simple solids. With the x-ray ring, the beamline, and a high-energy-resolution secondary fluorescence spectrometer all in good working order during this period, several new avenues of research in inner-shell physics were opened. Molecular studies, in particular, experienced a renaissance; advances in several aspects of molecular x-ray spectroscopy occurred almost simultaneously. One especially exciting development has been the observation of strongly polarized x-ray fluorescence following core-electron excitation to unoccupied valence molecular orbitals. Initial studies of this "new" phenomenon in the Cl K-edge regions of CH_3Cl and the freons have illustrated its possible utility as a structural tool that is both atom-specific and highly sensitive. Its sensitivity is enhanced by the rapid decay times involved in x-ray fluorescence which effectively preclude vibrational or rotational disorientation, producing a "snapshot" of the molecular excited state. The polarized-fluorescence results also suggest many other experiments, including further spectroscopy in the gas phase and orientational studies of solids and adsorbates.

Other phenomena also have been observed at sub-threshold resonances in molecules. With resonant excitation, we have observed for the first time (in the freons and CH_3Cl) that the $K\beta$ fluorescence (electrons in valence molecular orbitals filling the Cl 1s vacancy) shifts to lower energy by a few electron volts in comparison to high-photon-energy excitation (i.e., well above the Cl 1s threshold). These energy shifts reflect screening of the valence electrons by the "spectator" electron which is put into an excited-state valence orbital by the resonant sub-threshold excitation. Changes in fluorescence photon energy with incident photon energy also can be induced by the resonance Raman effect, a phenomenon which has been observed in all the systems studied and from which the "state specific" chemical shift is clearly distinguished.

Using above-threshold incident energies, the previously mentioned fluorescence-polarization phenomena have been shown to be sensitive to the molecular symmetry of continuum resonances such as shape resonances. Small, but significant degrees of polarization at these continuum features have aided in their spectral assignment. Further above threshold, multi-vacancy, or satellite, transitions become energetically accessible. It is now possible, with beamline X24-A and its accompanying secondary spectrometer, to carefully study the threshold behavior of these satellite transitions by observing their fluorescence decay as a function of incident photon energy. Extensive studies along these lines have been made for the molecule CH_3Cl, as well as for the solid KCl.

While the Cl-containing molecules studied at X24-A have illustrated several interesting and newly observed phenomena that are generally explainable within our present understanding, work on the molecule SF_6 appears to show qualitatively different effects which do not conform to conventional wisdom. For example, in measurements of S $K\alpha$ fluorescence, which results from an inner-shell S 2p electron filling the S 1s vacancy in SF_6, the spin-orbit doublet of the $K\alpha$ radiation normally has a 2:1 intensity ratio. However, in a range of incident energies below the S 1s threshold, this intensity ratio becomes approximately 1:1, and even 1:2 at certain energies. Also in this sub-threshold energy range, two very broad symmetric and unstructured peaks are observed in the $K\alpha$ fluorescence spectrum which change in energy with the incident photon energy. These two observations in SF_6 are unprecedented in molecular x-ray spectroscopy, and indicate the likely presence of new inner-shell phenomena not hitherto expected.

Along with the molecular x-ray spectroscopy studies, work continued on atoms and solids, too. Additional results, taken with high fluorescence energy resolution, have been obtained for sub-threshold excitation in atomic Ar. These new results for Ar $K\alpha$ radiation clarify the importance of resonant-Raman effects, especially when the incident photon energy is de-tuned from the sub-threshold excitation energy. More studies of multi-vacancy states in Ar above the K-shell threshold have been completed, also with higher resolution and improved statistics. For solids, we have studied the $K\alpha$ and $K\beta$ radiation near the K edges of both potassium and chlorine in KCl. The primary goal of this work has been to elucidate the multi-vacancy components of the rather complicated absorption spectra at these two edges; this work has enjoyed good success but produced few unanticipated results.

The remaining usable beam time at X24-A, approximately one month, was devoted to two collaborative efforts. The first, in association with J. Rowe and F. Sette of AT&T Bell Laboratories, studied the adsorbed species S, Cl, Se, and Te on a Cu(100) single crystal. The conventional technique of surface extended x-ray absorption fine structure (SEXAFS) was used to determine the geometric site of each adsorbate on the Cu crystal. In conjunction with SEXAFS a new technique, back-reflection x-ray standing-wave analysis, was applied to the same systems, both to compare the two techniques and to obtain complementary information to the SEXAFS results. The new technique shows great potential, especially coupled to the high energy resolution of the X24-A beamline. The results also demonstrate the power of x-ray standing-wave analysis to determine short-range order even at elevated temperatures. This capability is unique to this approach, and may become thereby the most useful characteristic of all types of x-ray standing-wave techniques.

The second collaborative effort was with J. Kortright, P. Plag, and R.C.C. Perera of the Center for X-Ray Optics at the Lawrence Berkeley Laboratory (LBL). The LBL workers developed a plane multilayer-coated mirror that was installed in beamline X24-A in place of the usual first mirror. The multilayer, which consisted of 16 layer-pairs of SiC and V (≈147 Å thickness for each layer-pair) on a SiC substrate, represented the first such device designed specifically for use as an optical element in a synchrotron-radiation beamline. In this first attempt, we were able to confirm three basic requirements for multilayer-based optics. First, the multilayer survived the in situ heat load of a 100 mA, 2.5 GeV beam from the NSLS x-ray ring with no apparent damage. Second, the reflectivity properties of the multilayer as a function of mirror tilt and photon energy were generally reasonable, in some cases approaching theoretical values. Finally, the heat load on the first crystal of the X24-A double-crystal monochromator was reduced significantly, lowering its normal operating temperature (uncooled, except radiatively) from 90°C to 60°C.

At the beginning of March, 1987, the x-ray ring was shut down for an extended time and is presently scheduled for recommissioning to begin in January 1988. During the shutdown period over the latter part of FY87, work is proceeding in two directions. First, one member of the X24-A team, P.L. Cowan, has been working at HASYLAB in Hamburg, West Germany since April. There, he is continuing the study of x-ray standing-wave effects, just getting under way at X24-A before the shutdown, in collaboration with G. Materlik's group at DESY. Studies of the effects of non-dipole transitions in x-ray standing-wave measurements, application of x-ray standing-wave analysis (both conventional and in back reflection) to studies of electrochemical deposition on metals, and studies of the Diffraction of Evanescent X-rays during Total External Reflection (DEXTER) are underway. The DEXTER studies may include further work on the production of narrow x-ray beams and the potential to exploit x-ray standing-wave effects produced in this geometry for structural studies of both epitaxial overlayers and monolayer adsorbates on surfaces.

Second, a major upgrade of beamline X24-A is proceeding during this shutdown. Many improvements in the operation and performance are expected, some of the most important of which are listed below. Several new beam-position and beam-intensity monitors will be installed in the beamline. Particularly important will be the installation of a beam-position monitor close to the electron-beam source that will be sensitive to beam motions of 50 microns or less. The present system of orbital-position monitoring in the x-ray ring has been insufficient to monitor and control the beam to the tolerances required by X24-A. This new position monitor constitutes a first step in solving this very serious problem.

The collimating and focussing mirrors in the beamline also will receive needed attention. The support structures providing angular and linear motion for both mirrors will be reworked to improve sensitivity and stability. In addition, the second mirror, which focusses the monochromatic synchrotron radiation onto the sample, will be repolished. It was found recently to have a gross surface roughness of approximately 75-100Å rms, 10 times worse than the best available. Repolishing should improve both its reflectivity and its focussing properties.

The double-crystal monochromator also will be enhanced, primarily by increasing the number and types of available crystals, and by water-cooling the first crystal, the one which "sees" intense white radiation reflected from the first mirror. New crystals to be developed and tested include quartz and beryl, both of which will allow us to utilize the beamline at lower energies (down to and below 1 KeV) than presently available with Si(111) crystals. Water-cooling of the first crystal will promote stability of the monochromator, possibly enhancing resolution, and will permit use of low-melting-point crystals.

At the experiment end of the beamline, more improvements are planned. Additional vacuum components will be installed to permit gas-phase photoemission experiments. These experiments will augment and complement the present x-ray spectroscopy measurements. Also to be included in the upgrade is a larger and faster computer system for data collection, transfer, and analysis, making X24-A a more effective user-oriented facility.

During FY87, the Quantum Metrology Group (QMG) supported two full-time staff (P.L. Cowan and D.W. Lindle) and one full-time NSLS technician (B. Karlin) at BNL. Additional collaborative support has come from R.E. LaVilla, R.D Deslattes, J. Cooper, and A. Henins of the QMG, and from T. Jach of the Center for Radiation Research.

Fruitful collaboration with scientists from other institutions has continued in FY87. Already mentioned were joint projects with scientists from AT&T Bell Laboratories, and from Lawrence Berkeley Laboratory. The molecular x-ray fluorescence studies have benefitted from the help of R.C.C. Perera (LBL) in the work on the freons. We have also received theoretical support from P.W. Langhoff and his group at Indiana University for the work on fluorescence polarization. A joint article on our findings and their calculations for CH_3Cl is in preparation. Further experimental work on x-ray diffraction effects was done on the NBS Materials Science Beamline by P.L. Cowan in collaboration with members of the Institute for Materials Science. Preliminary results of this work indicated the possibility of producing extremely narrow x-ray beams, with potential application to x-ray microscopy and lithography. Finally, discussions have begun with A.C. Parr (Center for Radiation Research) and J.L. Dehmer (Argonne National Laboratory) on the feasibility of bringing their high-resolution photoelectron spectrometer to X24-A to initiate gas-phase photoemission in this energy range. To date, only two such studies in the 2-5 keV photon-energy range have been published.

X-Ray Spectroscopy - Gaithersburg:

Both independently and in support of X24-A work our longstanding efforts in x-ray physics continue "in-house." The $K\alpha_{1,2}$ emission profile from a number of 3d metals have been reported in the past with highly divergent results. Some investigators found fine structure on the profiles and others with comparable resolution reported a smooth profile. In view of the future use of a few of these emission lines for calibration markers of the highly ionized one-electron spectra, we recorded the $K\alpha_{1,2}$ profile of Fe, Co, and Cu with high dispersion, high statistical quality and the absence of any mechanical motion. The source, analyzing crystal and position sensitive detector were oriented on a large granite surface plate. No fine structure was observed with spectra that had one million counts in the peak channel.

A current high quality theoretical calculation of the wavelength for the 2s→1s and 3s→1s transitions of high-Z elements has stimulated the remeasurement of L spectral lines of some selected elements including the measurement of the xenon L spectrum.

Theoretical studies have shown that the 5s hole level of the actinide metals and compounds should be very much influenced by $5s^{-1} \rightarrow\leftarrow 5p^{-1}5d^{-1}5f(\epsilon f)$ super-Coster-Krönig (sCK) fluctuation or configuration interaction. The Th M x-ray spectrum was obtained by direct excitation from ThO_2. The measured Th M_3O_1 emission profile provides the first experimental evidence of the splitting with an unusual width of the 5s hole level of thorium.

Theoretical work in support of the X24-A experiments has been initiated by J. Cooper, who recently joined the Division. The overall goal of this theoretical support effort is to provide a more detailed understanding of near-threshold inner-shell processes than is currently available. In the present context this involves activity in the following areas:

A. Identification of effects that are well understood and are likely to be important in the reduction of existing data,

B. Theoretical calculations of energy levels and of absorption cross sections and fluorescence intensities to compare with existing data, and

C. Suggestions for new experiments.

None of the above activities are carried out in a vacuum; (A) and (C) involve active collaboration with other members of the QMG, and (B) involves collaboration with other theorists both at NBS and elsewhere.

A survey of the literature of existing work on the resonant Raman effect has revealed that the major effort both experimentally and theoretically has been directed towards the study of structure in emission spectra due to two-electron processes, but that relatively little has been done on spectra taken with excitation energies close to threshold where two-electron excitation is forbidden by energy considerations. The classic work in this area is the work done at SSRL by the Divison, which demonstrated the "turning off" of K-β satellites in argon when the incident photon energy was lowered to below the double-excitation threshold. The same work also revealed multiple emission structures at incident energies near or below the threshold for single-vacancy production which were interpreted as being due to resonant Raman, Rayleigh, and Compton scattering.

The more recent data taken at the NSLS seems to indicate that the resonant Raman effect; i.e., the shifting of the main emission line to lower energies when the incident energy is tuned below the single-vacancy ionization threshold accompanied by one or more additional peaks due to discrete single-electron excitation, is extremely important and has been observed in most of the spectra obtained. Recent theoretical work has shown that it should be possible to "sort out" the resonant Raman effects via a deconvolution of the observed absorption spectrum followed by an integration to obtain a predicted emission spectrum. The predicted spectrum can then be compared with the observed one to assess the importance of other effects.

K-shell photoionization has until recently been regarded as a well-understood process. Simple screened hydrogenic calculations typically yield cross sections which agree with experiment to within 10-20% and better agreement is obtained using central-potential models. Such calculations have now been performed for all elements of the periodic table and are an important part of the NBS data base of x-ray attenuation coefficients; they are also used to provide estimates of cross sections where experimental evidence is not available. Recently there have been attempts to improve the theoretical calculations via more sophisticated models, particularly in the near-threshold region where discrepencies with experiment are largest. Argon has been a "test case" in most of these calculations because the cross section is well known and one does not have to worry about solid-state effects. The most sophisticated of these calculations (Dirac-Fock approximation including all effects of core relaxation) yields results near threshold which are still 8% lower than experimental values. Earlier attempts to improve the cross sections led to discrepencies.

In order to examine in more detail the various effects which should be considered in the absorption calculations near threshold, as well as to provide more detailed understanding of the doubly excited resonances in argon which have been observed both in the NSLS experiments and in earlier work at SSRL, a series of detailed calculations have been undertaken. Fortunately, the "apparatus" needed for these calculations, a set of computer programs written by R. Cowan of Los Alamos, was available and had been installed on the NBS computer system by members of the atomic-spectroscopy group. Thus the usual start-up time of large scale-computations was avoided. Results (to date) of these calculations are as follows:

1. The results of previous calculations have been confirmed. As in previous work, the effects of core relaxation have been found to be extremely important and the calculations provide a detailed

analysis of these effects.

2. Although the programs used are not fully relativistic, the major relativistic effects on the wave functions can be included. Relativistic effects on the cross sections are below the 1% level as expected.

3. The calculations have led to a new interpretation of the structure observed in the region 15-50 eV above threshold. The first two features which have been tentatively assigned as $1s\ 3p^5 4s^2$ and $1s3p^5 4p^2$ now appear to be due to $1s3p^5 d^2$. While the analysis is not complete, the strengths, energy positions, and asymmetries of these resonances obtained from the calculations are consistent with the observed spectra.

Grenoble Activities:

Crystals whose lattice spacing have been accurately measured are used to make wavelength measurements for x- and gamma-rays. Since the wavelengths are determined through the Bragg-Laue relation $\lambda=2d\sin\theta$ and the crystal lattice spacing d is known, the wavelength measurements are diffraction angle measurements. Our goal is to make 0.1 ppm wavelength measurements of 5 MeV ($\lambda=2\times10^{-13}$m) gamma-rays and along the way determine the combination of fundamental constants $N_A h/c$, to make a better determination of the neutron mass from a measurement of the deuteron binding energy, and to make precise measurements of gamma-ray widths (nuclear lifetimes) and wavelengths (i.e., binding energies) which are of interest to the nuclear physics community.

These γ-ray measurements are taking place at the high-flux reactor operated by the Institut Laue-Langevin in Grenoble, France. This is the only reactor in the world which has a horizontal beam tube for viewing samples held near the core and facilities to change samples during reactor operation. The spectrometer (GAMS-4) is a double flat crystal spectrometer equipped with polarization sensitive Michelson interferometers for diffraction angle measurements. The interferometers are calibrated by measuring the external angles of an optical polygon and constraining the sum of the angles to equal 2π.

During the past year the question of the proper choice of crystals for the diffraction of 5 MeV radiation was carefully considered from both the theoretical and experimental side. Since the efficiency of the GAMS-4 spectrometer is very low ($\approx5\times10^{-12}$ at 5 MeV) and the diffraction angles are very small ($\approx$0.1 deg. for Si [440] at 5 MeV), the crystals must be chosen to optimize the count rate and resolution. In the dynamical theory of diffraction from perfect crystals, there is a phenomenon called thickness pendellösung intensity oscillations. By careful selection of the crystal thickness for a given energy and diffraction order, the available integrated intensity can be increased by a factor of $\approx$3.5. This permits an increase in the order of diffraction which results in larger diffraction angles and higher resolution.

In November, 1986, Si and Ge crystals tuned for the 1.381 MeV line from the reaction $^{48}Ti\ (n,\gamma)^{49}Ti$ were tested. The Ge crystals (1.83 and 2.92 mm thick mixed orders) were designed for the [220] and [440] reflections, while the Si crystals (1.62 mm thick) were designed for the [440] reflection. Profiles were recorded for the above mentioned energy and orders as well as for other orders and energies. The agreement of the theoretically predicted and the experimentally measured profiles and relative intensities for Si was excellent, but the Ge crystals showed excess broadening and reduced intensity which appears to be related to crystal imperfection. The data recorded during this run clearly demonstrated the ability to maximize count rate and resolution by careful choice of crystal thickness. Theory predicts rocking curve widths of 0.014 arcsec (resolving power, $S=6.9\times10^4$) for the Si [440] reflection at 1.381 MeV. The measured widths were ≈ 0.016 arcsec ($S=6.0\times10^4$).

Two new sets of Si crystals were manufactured to take full advantage of the thickness pendellösung intensity oscillation phenomenon. One set with a thickness of 2.72 mm was chosen for the Si [660] reflection of the above mentioned 1.381 MeV line Ti (predicted width = 0.006 arcsec, $R = 2.6\times10^5$) while the other set (mixed orders) with thicknesses of 4.41 and 6.95 mm was chosen for the Si [220] and Si [440] reflections of the 5 MeV gamma-rays from the reaction $^{14}N(n,\gamma)^{15}N$. In May 1987, the 2.72 mm Si crystals were tested. The measured width of the Si [660] reflection at 1.381 meV was 0.014 arcsec, more than double the predicted width. Acoustical and floor vibration noise broaden the profile about 0.006 arcsec but probably cannot account for the entire excess width. Further data analysis and measurements, one hopes, will provide an explanation. Efforts to further reduce environmental noise are proceeding.

Also in May and June 1987, precision measurements of the 1381 keV line and several angle calibrations were made in order that this intense line could serve as a local standard and the frequency of angle calibrations could be reduced. The angle calibrations were stable at the 2×10^{-7} level and the wavelength measurements had an uncertainty of 5×10^{-7}. In the course of temperature and pressure stabilization of the spectrometer, another instability may have been introduced. Also, as the resolution has increased, the contribution of mechanical and acoustical vibrations to profile widths has become larger. In order to robustly achieve an accuracy of 1×10^{-7}, a factor of 5 improvement is needed. Vibration isolation, pressure and temperature stability, interferometer stability, and electronics stability are all being carefully investigated as contributors to measurement instability.

In addition to the high-energy, high-accuracy measurements, the GAMS-4 facility has been used extensively for excited-state nuclear lifetime measurements during the past year. When a nucleus at rest emits a gamma-ray, it recoils. If this same nucleus emits a second gamma-ray while it is recoiling, the second gamma-ray will be Doppler broadened.

Knowledge of the velocity distribution of the recoiling nucleus and a measurement of the Doppler broadening of the line profile of the second gamma-ray permits an estimation of the lifetime of the excited nuclear state. The high resolution of the GAMS-4 spectrometer permits the direct determination of Doppler broadening of the gamma-ray profiles. Non-wavelength dispersive parallel scans are compared to wavelength dispersive anti-parallel scans to obtain estimates of the Doppler broadening.

This technique has been applied to the 1381, 1498, 1585, and 1761 lines from the reaction $^{48}Ti(n,\gamma)\ ^{49}Ti$ and appears to be valid for lifetimes in the 10^{-12} to 10^{-16} sec range. The broadening is not a small part of the measured widths as the following results show: 1498 keV - FWHM = 518 eV, instrumental width = 202 eV; 1585 keV - FWHM = 290 eV, instrumental width = 214 eV; 1761 keV - FWHM = 386 eV, instrumental width = 237 eV. Lifetime measurements have also been recorded for excited states of ^{54}Ci and ^{57}Fe. Many of the transitions of interest are quite weak so that recording times of 5 to 10 hours per profile are needed to obtain adequate statistics.

The careful choice of crystals for diffraction has opened up another area of opportunity for the GAMS-4 facility. The same fine structure oscillations used on the Δd machine to compare lattice spacing have been seen on the GAMS-4 spectrometer with gamma-rays. By comparing the measured oscillating profiles with the theoretical prediction, electronic structure factors can be derived. Electronic structures have been accurately determined in this manner using x-rays. The GAMS-4 facility makes it possible to extend these measurements into the gamma-ray region where questions of crystal thickness and absorption are less critical. Scientists whose main interest is solid state physics are interested in collaborating with us on these measurements and a joint proposal for beam time is being submitted.

Reactor beam time is awarded through peer-reviewed proposals. Since the reactor port is shared by GAMS-4 and two curved crystal spectrometers (GAMS-1, R=5.8 m; GAMS-2-3, R=24 m) competition is keen for reactor time. In addition, the demonstration that nuclear lifetimes in the 10^{-12} to 10^{-16} sec range and electronic structure factors can be measured with the high resolution GAMS-4 spectrometer has created significant demand by nuclear and solid-state physicists for the use of GAMS-4. In the long run, intense scientific interest in the NBS GAMS-4 facility is a very positive factor, but for the short run we face rather intense competition for beam time for the high accuracy, high energy fundamental constants measurements which are our primary interest.

Neutron Physics:

As part of a major new initiative aimed primarily toward neutron scattering, the NBS has initiated construction of a National Cold Neutron Facility adjacent to the existing NBS research reactor. This facility, employing cold neutrons from a new in-pile cyrogenic source will include a large experimental hall and numerous experimental stations. Two of these stations are to be used for the study of basic neutron physics and their operation will be the responsibility of the Division.

An initial scientific program is now underway and planning for a longer range program is in progress. The initial effort is aimed at the determination of the neutron lifetime and investigating new methods for high accuracy neutron dosimetry. The longer range projects include a ultra low vibration, inertial platform for neutron interferometry and the establishment of a high-flux polarized neutron facility for weak interaction physics including tests of parity and time-reversal invariance.

The neutron lifetime is a fundamental physical constant which is of considerable importance in several areas of nuclear, particle, and astrophysics. It is a primary input for calculations concerning the details of the Big Bang, the nature of supernova core collapse, and the rate of production of neutrinos in the sun. It is also a necessary parameter for tests of the standard model of weak interactions as well as for calculations giving limits on the number of neutrino species. Two experiments involving Division participation are in progress. The first a collaboration between NBS and the University of Sussex (U.K.) which is supported primarily by grants from the Department of Energy (to NBS) and the Science and Engineering Research Council, U.K. (to Sussex). This work is provisionally scheduled for a preliminary run at ILL in the summer of 1988. The apparatus will then return to the U.S. for final data collection on the (then completed) Cold Neutron Facility. The second experiment is a collaboration between Los Alamos, NBS, Drexel, and Harvard and will have it's initial runs at the NBS reactor.

As an outgrowth of both of these lifetime efforts, a variety of new techniques for absolute neutron flux determination are under development. In collaboration with personnel from the NBS neutron dosimetry group, and the European Center for Nuclear Measurements (Geel, Belgium); these new techniques will be intercompared and tested with existing standards. If successful, these new methods could provide new primary neutron dosimetry standards as well as leading to improved neutron cross-section determinations for important nuclear materials.

In addition to this work, one of us (GLG) has continued active participation in various planning groups for future neutron facilities. These include the National Steering Committee for the Advanced Neutron Source and the National Academy of Sciences Panel on University Research Reactors.

INVITED TALKS

Quantum Metrology Division (526)

Paul L. Cowan, "Novel Crystal Geometries for X-Ray Monochromators," at the Stanford Synchrotron Radiation Laboratory Workshop on High-Power X-Ray Crystal Monochromators, Palo Alto, CA, October 22, 1986.

Paul L. Cowan, "Research Activities at NSLS Beamline X-24A," at the National Synchrotron Light Source Lunchtime Seminar at Brookhaven National Laboratory, Upton, NY, January 29, 1987.

Paul L. Cowan, "X-Ray Fluorescence Spectroscopic Studies of Atoms and Molecules," at the Division of Applied Physics Seminar - Brookhaven National Laboratory, Upton, NY, February 17, 1987.

Paul L. Cowan, "Polarization Effects in X-Ray Fluorescence," at the Workshop on New Directions in Soft X-Ray Near-Threshold Phenomena, Asilomar Conference Center, Pacific Grove, CA, March 3, 1987,

Paul L. Cowan "Research Results from A High Energy Resolution Synchrotron Radiation Beamline," At the Stanford Synchrotron Radiation Laboratory, Palo Alto, CA, March 5, 1987.

Paul L. Cowan, "Research Results from a High-Energy-Resolution X-Ray Beamline," at the Hamburger Synchrotron Strahlungslabor, HASYLAB at DESY, Hamburg, W. Germany, May 15, 1987.

Paul L. Cowan, "Predictions and Observations of the Diffraction of Evanescent X-Rays," at the Institut fur Grenzflachenforschung und Vakuumphysik KFA Julich, Julich, West Germany, May 21, 1987.

Paul L. Cowan, "Predictions and Observations of the Diffraction of Evanescent X-Rays," at the Physics Department of the University of Munich, Munich, West Germany, June 2, 1987.

Paul L. Cowan, "New Directions in X-Ray Emission Spectroscopy," at the BESSY synchrotron radiation facility, Berlin, West Germany, June 11, 1987.

Paul L. Cowan, "Research Results from a High-Energy-Resolution X-Ray Beamline," PTB, Berlin, W. Germany, June 12, 1987.

John W. Cooper, "Resonant Raman Revisited," Chemistry Department, Indiana University, May 22, 1987.

Maynard S. Dewey, "High Accuracy, Absolute Wavelength Determination of Capture Gamma Ray Energies for E ≤ 5 MeV and the Direct Determination of Binding Energies in Light Nuclei," International Symposium on Capture Gamma-Ray Spectroscopy," at Leuven University, Brussels, Belgium, August 31, 1987.

Richard D. Deslattes, "Why Precision Spectroscopy Needs Naked Ions," at the University of Virginia, Charlottesville, VA, October 3, 1987.

Richard D. Deslattes, "High Resolution X-Ray Experiments," at the Ninth Conference on the Application of Accelerators in Research and Industry, North Texas State University, Denton, Texas, November 10, 1986.

Richard D. Deslattes, "The Unification of the Electromagnetic Scale," at the School of Physics, Georgia Tech., Atlanta, Georgia, January 7, 1987.

Richard D. Deslattes, "A New Approach to Sub-Picosecond Nuclear Lifetimes," at the Nuclear Physics Seminar, Michigan State University, Lansing, MI, February 17, 1987.

Richard D. Deslattes, "Atomic Spectroscopy with Nuclear Machines," at the Physics Colloquium, Michigan State University, Lansing, MI, February 17, 1987.

Richard D. Deslattes, "X-Ray Fluorescence Near Threshold," at the Workshop on New Directions in Soft X-Ray Near-Threshold Phenomena, Pacific Grove, CA, March 1, 1987.

Richard D. Deslattes, "Accurate Spectroscopy in the X-Ray Region," at the Symposium on Atomic Spectroscopy and Highly-Ionized Atoms," Lisle, Illinois, August 17, 1987.

Richard D. Deslattes, "Fluorescent and Scattered Spectra: Near-Threshold Excitation of Atoms, Molecules and Solids," at the 14th International Conference on X-Ray and Inner-Shell Processes (X-87), Paris, France, September 14, 1987.

Geoffrey L. Greene, "Fundamental Neutron Physics," at a Colloquium, University of Missouri, Columbia, Missouri, January, 20, 1987.

Geoffrey L. Greene, "Controls and Safeguards for University Research Reactors," at the National Academy of Sciences Workshop on University Research Reactors, Berkeley, CA, February 2, 1987.

Geoffrey L. Greene, "The Investigation of Fundamental Interactions with Cold Neutrons," at the University of Virginia, Charlottesville, VA, April 13, 1987.

Geoffrey L. Greene, "Cold Neutrons and Hot Physics," at NBS, University of Colorado, Boulder, Colorado, May 14, 1987.

Geoffrey L. Greene, "Requirements for Fundamental Neutron Physics at the Advanced Neutron Source," at the National Steering Committee Meeting for the Advanced Steady State Neutron Source, Crystal City, Virginia, June 19, 1987.

Geoffrey L. Greene, "Fundamental Neutron Metrology," for the Colloquium at the Commission of European Communities, Central Bureau for Nuclear Measurements, Geel, Belgium, August 13, 1987.

Geoffrey L. Greene, "Determination of the Neutron Mass and the Implications for Fundamental Constants," at the International Conference on Neutron Physics, Kiev, USSR, September 22, 1987.

Robert E. LaVilla, "X-Ray Spectra of Molecules," at a Chemistry Department Seminar, Indiana University, Bloomington, Indiana, November 20, 1987.

Dennis W. Lindle, "Atomic Physics with an Intense Synchrotron-Radiation Source: Experimental Aspects of the Emerging Possibilities," at the Workshop on New Directions in Soft X-Ray Near-Threshold Phenomena, Pacific Grove, CA, March 3, 1987.

PUBLICATIONS - 1987

Quantum Metrology Division (526)

1. In Print

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*C.E. Brion, D.W. Lindle, P.A. Heimann, T.A. Ferrett, M.N. Piancastelli, and D.A. Shirley, "Photoelectron Branching Ratios and Partial Photoionization Cross Sections for Production of the $(2a_1)^{-1}$ State of H_2O up to 200 eV," Chem. Phys. Lett. 128, 118 (1986).

P.L. Cowan, S. Brennan, T. Jach, M.J. Bedzyk, and G. Materlik, "Observations of the Diffraction of Evanescent X-Rays at a Crystal Surface," Phys. Rev. Lett. 57, 2399 (1986).

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*P.A. Heimann, U. Becker, H.G. Kerkhoff, B. Langer, D. Szostak, R. Wehlitz, D.W. Lindle, T.A. Ferrett, and D.A. Shirley, "Helium and Neon Photoelectron Satellites at Threshold," Phys. Rev. A 34, 3782 (1986).

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*D.W. Lindle, T.A. Ferrett, P.A. Heimann, and D.A. Shirley, "Increasing Quantum Yield of Sodium Salicylate Above 80 eV Photon Energy: Implications for Photoemission Cross Sections," Phys. Rev. A 34, 1131 (1986).

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*J.W. Cooper, C.W. Clark, C.L. Cromer, T.B. Lucatorto, B.F. Sonntag, and F.S. Tomkins, "Resonant Structure in 3p Subshell Absorption of Excited and Ionized Manganese," Phys. Rev. A 3970 (May, 1987).

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2. In Press, In Review, or Nearing Completion

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F. Hoyler, H. Börner, S. Robinson, G.L. Greene, and E.G. Kessler, Jr., "Recent Developments at the ILL (n,γ) Facilities," Proceedings of the 6th International Symposium on Capture Gamma-Ray Spectroscopy (submitted) (1987).

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3. Patents

G.L. Greene, Non-Contacting, Electro-Pneumatic Servo for Vibration Isolation. (U.S., E.E.C., and Japanese Patents Pending)

*Based on work performed prior to joining QMG.

TECHNICAL AND PROFESSIONAL COMMITTEE PARTICIPATION AND LEADERSHIP

Quantum Metrology Division (526)

John W. Cooper - Board of Editors, Atomic and Nuclear Data

John W. Cooper - Physics Editor, NBS Journal of Research

John W. Cooper - Member, NBS Washington Editorial Review Board

John W. Cooper - CBS Representative, NBS Computer Users Committee

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

Richard D. Deslattes - American Physical Society, Division of Electron and Atomic Physics, Chairperson, 1986-1987

Richard D. Deslattes - Member, Panel on Scientific Opportunities for the Use of Cooled Heavy Ion Storage Rings.

Richard D. Deslattes - Member, Organizing Committee of the 14th International Conference on X-Ray and Inner-Shell Processes (X-87)

Geoffrey L. Greene - Member, Ad Hoc National Steering Committee for the Advanced Neutron Source (1986 -)

Geoffrey L. Greene - Member, National Academy of Sciences/National Research Council Committee on University Research Reactors (1986-)

Dennis W. Lindle - Co-Chairman, Organizing Committee for "Workshop on New Directions in Soft X-Ray Near-Threshold Phenomena," Asilomar, CA, March 1987

Dennis W. Lindle - SSRL User's Organization Executive Committee, 1984-86

COLLABORATIONS, CONSULTING, MISCELLANEOUS ACTIVITIES

P.L. Cowan is collaborating with Michael Seuls of AT&T Bell Laboratories on developing total reflection standing waves for studies of organizing monolayers.

P.L. Cowan is collaborating with Ken Liang of EXXON Research Labs involving glancing incidence x-ray diffraction studies of surface and interface structure.

P.L. Cowan and D. W. Lindle are collaborating with Jack Rowe and Francesco Sette of AT&T Bell Laboratories on structure studies of adsorbates on crystal surfaces, development of a new experimental technique (normal incidence x-ray standing wave analysis), and studies of post-collisional interactions of Auger electrons.

P.L. Cowan and D.W. Lindle are collaborating with J. Kortright, P. Plag, and R.C.C. Perera of the Center for X-Ray Optics, Lawrence Berkeley Laboratory on multi-layer mirrors as power filters in synchrotron-radiation beamlines.

P.L. Cowan, R.E. LaVilla, and D.W. Lindle are collaborating with R.C.C. Perera of Lawrence Berkeley Laboratory on x-ray fluorescence of freons.

R.D. Deslattes is collaborating with Robert Dunford, Argonne National Laboratory

R.D. Deslattes is collaborating with the University College, London on the high resolution Bragg crystal spectrometer for the HESPP Mission. (also with the Rutherford Appleton Laboratory).

R.D Deslattes is collaborating with H. Beyer, Gesellschaft für Schwerionenforschung (GSI) Darmstadt, FRG on spectra of heavy ions.

G.L. Greene is collaborating with J. Byrne and P. Dawber at Sussex University on the measurement of the neutron half life.

G.L. Greene is collaborating with Los Alamos, Drexel University and Harvard University on the measurement of the neutron half life.

G.L. Greene is collaborating with D. Gilliam (Center for Radiation Research, NBS) and J. Pauwels (European Center for Nuclear Measurements, Geel, Belgium) on absolute neutron dosimetry.

D.W. Lindle is collaborating with P.W. Langhoff (Indiana University) on polarization of molecular x-ray fluorescence.

NBS-114A (REV. 2-8C)

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5. AUTHOR(S)

Peter L.M. Heydemann

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. 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 1987. These activities include work in the areas of electricity, temperature and pressure, mass and length, time and frequency, quantum metrology, and quantum physics.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

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

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