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NATIONAL BUREAU OF STANDARDS-1963-A

Final Report

ONR Contract N00014-77-C-0656

Start: 1977/July/01   End: 1985/June/30

Precision Atomic Beam Spectroscopy using Stabilized Lasers

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The goal of our work has been to investigate a few well-chosen effects in laser spectroscopy under "clean" experimental conditions which facilitate a sharp and meaningful contact with theory.

The initially-defined task was to study large pulse-area effects in single upward transitions from metastable atoms in a fast, monovelocity Ne* beam. It proved possible as well to investigate multiple-pulse transitions on a cw basis. Ramsey fringe resonance signatures were clearly observed and for the first time in the optical domain, using three pulse excitation. 1546,1638 Basically the first two zones of light provide initially a coherence and secondly an atomic population in the excited state. The counter-running fields in the second zone and third zones convert excited state population into a coherence again and finally into a nonlinear (with intensity) change in the excited and ground state populations. In view of the time gap T in the preparation phase, followed by the same time interval during the readout phase, one could anticipate and did observe narrow "Ramsey" fringes which vary as $\cos(\delta\Omega\, T)$ in the middle of the single zone excitation linewidth function ("Rabi pedestal"). The neon beam employed was rather fast ($v/c \cong .001$) and, being produced by charge transfer had an exceptionally narrow velocity distribution, $\delta v/v \cong 10^{-4}$. These characterisics permitted unambiguous measurements of the fringe shapes and facilitated useful contact with theory. 1974

A second extremely successful experiment was the combination of laser excitation of two-photon Doppler-free transitions in the $5S \to nS$ series in Rubidium with precise <<Lambdameter>> interferometer techniques to accurately measure the transition wavelength. (Refs.

1470,1632: Patent 1) Theoretical quantum defect models for high n Rydberg states (n>10) lead on to expect a beautifully simple scaling of the transition energy with quantum number, vis.,
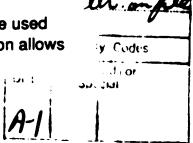
$$E = E_\infty - R_m / (n + \epsilon)^2 \quad ,$$

where E_∞ is the ionization energy of the initial 5S state, R_m is the Rydberg constant for the isotope mass species M, n is the principal quantum number, and the quantum defect ϵ is taken to be of the form

$$\epsilon = \epsilon_0 + (\epsilon_1 + \epsilon_2 / n^2) / n^2 \cdot$$

In practice for one electron atoms such as Rb this series converges extremely rapidly so that ϵ_2 was only marginally significant, even though our data was eight-digit quality. The elegant result of this work is that transition wavelengths could be calculated at 8-digit accuracy for any n (between 10 and 100) by a handheld calculator, using its stored values for the four parameters (E_∞, $R_{m,\epsilon}$ ϵ_0, ϵ_1). This is a profound example of "information condensation" which follows from the beautiful simplicity of 1-electron Rydberg atom physics. (Ref 1788) The wavelength aspect of this concept has been extended by others to other spectral domains as we had suggested and continues to be a useful capability in dye laser labs around the world. Eventually it will be interesting to make a new determination of the wavelengths at even higher accuracy using the new vacuum Lambdameter. The Lambdameter was also used to confirm the absolute wavelength scale of a Fourier transform spectrum of Uranium, intended to be a line reference atlas. (Ref. 2268)

An important theme in our work for many years has been the evolution of techniques to enhance the sensitivity and accuracy in laser spectroscopy. For example serious early work concerned the design of frequency-stable dye laser spectrometers. (Refs 1493, 2392) Probably the most significant advance was the re-invention with R. W. P. Drever of the powerful method of "sideband" or "heterodyne" spectroscopy. Only after this technique was well developed in the optical domain did it become clear that it was equivalent to an rf klystron-locking scheme used originally by R. V. Pound. In both frequency domains the modulation allows

one to process signal information at a suitable rf frequency so as to avoid the region of excess noise at low frequencies usually found in all real laser and data processing systems. A signal/noise improvement of 80dB was measured for our dye laser using this approach. This in turn made available spectacular advances in dye laser stabilization, to below 100 Hz linewidth. (Refs. 2626, 2771, 2383, 2146) Clearly these same ideas have significance also for laser spectroscopy more generally, and we have studied several aspects of such applications (Refs. 2288, 2347, 2469, 2707; Patent 2)

One development recently has been a systematic attack on the problems that can accompany the use of the powerful methods of FM spectroscopy. The most immediate problem here concerns the elimination by servo techniques of parasitic AM modulation which is usually produced by known FM modulator techniques. Our system is an elegant closed-loop automatic servo technique capable of driving the parasitic signal to zero to within the shotnoise measurement limit. It works by applying, in addition to the usual rf field incident on our travelling-wave electrooptic modulator, a small dc bias field to introduce a controllable phase delay between the two orthogonally-polarized optical fields. In this way we can produce a small AM deliberately to cancell the one produced by piezoelcetric stress-induced birefringence, depolarized light scattering from micro-inclusions in the modulator crystal, etc.

A suitable second-order servo design with a few kiloHertz bandwidth was able to suppress baseline defects very well indeed: in the published paper we displayed an absorption spectrum of water vapor taken in the visible at atmospheric pressure. The line selected is a very weak overtone vibrational line near 590 nm which gave an absorption of about 50 ppm in our 30 cm cell. We confirmed that the demonstrated part-per-million absorption sensitivity was quantitatively at the limit fixed by shotnoise of the detection process. (Refs 3077, 3155)

Two systems for guiding the dye laser (or other tunable laser, e.g. color center or laser diode) have been demonstrated during this funding period. The first and more precise makes use for the laser locking of a frequency-offset sideband produced by modulation. The frequency synthesizer source is computer controlled so that scanning, jumping over "empty" parts of a spectrum etc are easily implemented in software. This capability in turn makes possible some extremely powerful drift-cancelling algorithms based on repetitively rescanning the central

region of a strong resonance. Essentially one measures and stores the frequency offset between the atomic absorber's line center and that of the high finesse Fabry-Perot cavity used for the locking. A measured vector, whose changes represent frequency drift of the reference cavity, is stored and used in a background task to update the offset supplied to the frequency synthesizer driver routine. We find that problems of the reference cavity reliability are almost suppressed. Measurements of the isotope and hyperfine structure of the mercury 546.1 nm line were completed at the 30 kHz level by M.D.Rayman in his PhD thesis work on this project. Considering that these power broadened lines were about 30 MHz wide, covered a spectral interval of more than 30 GHz, and had intensity ratios of almost 100:1 among the measured lines, it is clear that we are discussing an extremely powerful technique. It makes available a level of precision of scanning a single tuneable laser which previously could only be attained by heterodyne methods using two (expensive) tunable lasers. A paper describing the system hardware and software concepts is being readied for publication in JOSA B.

An exciting alternative system to accomplish these laser scanning tasks has just recently become operational as well. The standard method of laser tuning involves locking the laser to a cavity whose resonance frequency can be tuned, for example with an internal Brewster plate to change the optical path. This system does work in a general kind of way, but is completely useless for fine scans such as those needed to measure the details of subDoppler features. The problem is that the global scan is obtained as the addition of a large number of fine increments. Thus terrible nonlinearity (>5%) is to be expected as the same galvanometer movement must deliver both small and global ranges of motion. What our new laser scan system does is to use the spectral periodicity of a fixed interferometer to obtain a large scan as the sum of a possibly-large number of free spectral intervals of the reference. The fine scan is obtained by interpolation through a single phase circle, corresponding to a single order of the interferometer. This fine scan process may indeed have some nonlinearity or other errors, but when one repeats the phase condition the pattern repeats. Thus one can distinguish periodic vs accumulating errors.

One interesting interpolation scheme was suggested a number of years ago by Juncar, Pinard, and Jacquinot. This "Sigmameter" idea makes use of the map between optical frequency changes and the change in phase

of an interference pattern. They introduced a nice way to control the phase, but their system has not been widely applied because the information about the interference phase (and hence about the optical frequency) is contaminated by dc problems such as fringe visibility, stray light, and dc drift. Our new system may be called the "rf Sigmameter" to respect its philosophical origin, but the ability to use modern rf methods such as phase-locked loops for the data processing brings a quantum leap in the capability of the new system.

To implement this system, essentially we take the input laser beam, divide it into two parts and frequency shift them by two different rf frequencies with a convenient difference, say 100 kHz. The present system uses two acoustoptic modulators, driven at 80.0 and 80.1 MHz. The interferometer contains several beam splitters to divide and combine these two input beams. It combines the two beams once to form after photodetection an rf reference phase. The beams are recombined a second time after a differential delay of l, say l=24 cm. Simple analysis shows that an optical frequency shift of the input laser by $c/2l=625$ MHz will cause a relative phase shift between the two 100 kHz detected outputs of 2 pi. With rf phaselock loop technology we divide each circle of 2 pi phase into a large convenient number of steps, 256 in the present generation. Thus each step represents 625 MHz/256 = 2.44 MHz. The basic optical interpolation ploblem has now been mapped into the rf domain where it may be efficiently and permanently solved with a few IC chips. For still higher resolution we are dividing each step into 10 substeps by matching the phase-detector analog voltage against a digitally-derived staircase. The errors of the substeps, like the errors of the steps themselves, are non-accumulating. It is hard to overstress the significance of this fact relative to long-range, accurate laser scanning. A patent application is being prepared.

The first measurements with this system have been planned to show the scanning capability and relative freedom from drift. We have been able to scan through some sharp hyperfine components in the I_2 spectrum near 612 nm, then scan away a few GHz, then return to rescan the original lines. The retrace quality is excellent- say 1/10 substep or better- and the drift was less than 1/3 substep in about 10 minutes. This value would correspond to a temperature change of the air in the interferometer by only a few milliKelvin, so we look for a significant improvement when the the new evacuated interferometer system is ready. We regard this device as being potentially of great significance in tunable laser spectroscopy in

view of the following desireable properties:

    1.   The linearity errors of the scan are described by a repeating (small) error pattern which does not accumulate. A basic linearity of 1/10,000 of this period - or better - is obtained in early measurements. For our 625 MHz interferometer period this corresponds to substantially less than 100 kHz rms error.

    2.   The frequency scan produced by the system is rigorously linear over large frequency intervals -say across the visible spectrum.. With thoughtful choice of reflector surface coatings (e.g. Al) to reduce wavelength-dependent reflection phase shift, the rf Sigmameter will enable one to tune a significant fraction of the optical frequency and still have knowledge of the change in frequency units. Further, it should be possible to determine the absolute length and hence order number for the interferometer. It would then be possible to determine the absolute frequency of any optical laser input beam to within a few MHz with a bootstrap scheme using a Lambdameter to give the interferometer's order number and the rf Sigmameter's output phase to subdivide the equivalent interferometric free spectral range.

    3.   With reflective design for the catseye retroreflectors one can design the system to reproduce the input laser spatial distribution on the beam combiner even though the two beams travel different pathlengths in the interferometer. This feature will allow vastly improved orthogonality/isolation between *alignment* of the input optical beam and the indicated optical frequency. In turn one may be able to eliminate the present use of fiber optic incoupling to obtain drastically wider spectral coverage. Apart from possible detector changes the same optical system could be used at least from 10.6 um to the usual uv limit near 200 nm.

    4.   The signal processing electronics employ straight-forward digital phase-locking techniques operating at conservative counting speeds (25MHz in the present version). While some care and attention must be invested in layout of the printed circuit boards to achieve low cross-talk, this is a one-time investment. The optical part of the system makes use of "catseye" retroreflectors, so that the required mechanical adjustments of the interferometer are minimal. Thus we project a non-critical and readily duplicatable system. Future growth to achieve still higher resolution could be based on implementing the phase-lock circuits with ECL rather than TTL logic chips.

One attractive area of application of these laser techniques concerns fundamental physical questions, tests of principles such as special relativity, isotropy of space, accuracy of QED, etc. Several delicious measurements of this type were partially funded under this ONR program. For example a highly successful collaboration with colleagues at the National Bureau of Standards led to measurement of the wavelength and frequency of the same methane-stabilized laser, and resulted in an improved value for the speed of light. Confirming and refining work in other laboratories, coupled with a serious attention to improved accuracy of the visible frequency measurements (Ref 2547) led in 1984 to a redefinition of the International Metre in terms of the speed of light: "The Metre is the length of the path (in vacuum) travelled by light in 1/299,792,458 of a second." . Another important measurement was the thesis work of L. Hollberg who was able to use precise laser frequency control techniques to show that, however attractive it is to discuss isolated atoms, they are in reality coupled to the enviornment in measureable ways. In this particular experiment it was shown that Rydberg atoms of Rubidium have their energy levels shifted by about 1 kHz due to their interaction with the room temperature thermal bath, a fractional shift $\approx 10^{-12}$. (Refs. 2729, 2875) This effect on Cesium frequency standards is near 10^{-14} , not far below the level of interest. A collaboration with S. Chu and A. Mills at Bell Labs produced a measurement of the $1\,^3S_1$ -- $2\,^3S_1$ frequency splitting in positronium, based on Doppler-free spectroscopy of a dozen or so thermal positronium atoms. (Ref. 2891) Being a purely leptonic atomic system, the QED calculations can be made with improved accuracy. Current experiments by Chu are on muonium for which the basic Coulomb /Dirac atom problem is more amenable to solution. Other measurements attempted included one on the relativistic time dilation using a fast atom beam. (Ref. 2354) Several papers addressed the role of precision laser-based measurements in testing fundamental physical theories (Refs. 2194, 2432), the progress in and applications of laser frequency standards (Refs 1802, 2383, 3322), and more recently the possibility of building an interferometric gravitational wave antenna in space. (Refs 2670, 3012)

The extreme demands for laser stability in this space laser application have motivated a continuing and extremely successful effort to try to

understand and approach the fundamental limits fixed by quantum mechanics or other inescapable boundaries. Experiments with Zeeman He-Ne lasers led, on the other hand to useful laser stabilization techniques
(Ref 2103; Patent 3) for the 10-9 accuracy domain of general practical interest, for example in geophysical measurements of local "g" as a way to get a handle on pre-earthquake crustal vertical motion. Another interesting application in this accuracy domain is to calibrate equipment intended to resolve vertical motions of the sun's photosphere by measuring the small resultant Doppler shifts of the luminous matter. (Ref 2213)

However our main thrust has been toward the high accuracy end, where sub-Hz accuracy locking to a reference cavity was achieved. Of couse the enviornmental effects on such a reference are severe at our sub 10-14 level. Temperature stability in the nanoKelvin range is needed eventually, for the duration of the measurement of interest. During this period the "quiet house" has been brought into effective operation to improve our laser stability experiments. (Ref. 3343) This 5-sided acoustically-isolating box - can be lifted overhead on a dual leadscrew arrangement to allow access to the lasers, modulators, isolators,etc. Then when all the adjustments are satisfactory, we can lower the "house" to seal against the floor and thus shut out the room noise. Approximately 36 dB reduction is obtained at 1 kHz, and 18 dB even at 30 Hz.

These JILA experiments attempt to separate the laser locking physical problems by asking two questions: How well can we lock to the reference cavity?, and How stable is the reference cavity itself?. We find that we can lock to the cavity with about 2 Hz accuracy and with a stability near or below 100 milliHertz! The cavity drift rate still appears to be temperature driven so that we are removing the first-order thermal ramp after closing the box by use of large area "coldness radiators" inside the box. These Al plates are cooled by water-cooled Peltier units so that a thermal servo can be easily implemented in the future. The minimum heat input is 4 watts each in two HeNe plasma tubes and 0.6 watts in each of 4 acousto-optic modulators: all non-essential heat-producers have now been located outside the "house".

At these unprecedented stability levels of 2×10^{-16} even gravity forces become urgently important. For example, tilting the cavity support system by 1 milliradian as the isolation table's air legs move within their deadband gives many kiloHertz shifts due to deformation of the massive interferometer spacer (a Zerodur rod 15 cm dia. by 30 cm length) under

differentials of its own weight. A powerful tilt stabilization concept has been demonstrated using as sensor a pendulum-supported cube-corner retroreflector illuminated offcenter by a LED collimated light source. Motion of the pendulum relative to the table top is detected with a quadrant photodiode. A convenient transducer to apply force to the table top without transmitting vibrations also can be obtained inexpensively as a "long-throw woofer" from the local Radio Shack. Noise levels apparently in the microradian range were obtained in exploratory experiments. We are optimistic that many of the manifestly-inadequate aspects of the laser stability measurements will be finessed or cured in the next funding interval.

The expected output of this work is, on the one side laser stabilization techniques and "know-how" that should be useful for a variety of applications in science and applied technology. Of possibly less direct interest to the agency's immediate goals, but still of significant cultural and scientific interest will be refined tests of our "cherished physical principles" in the domain of relativity theory. We expect to be able to perform a Kennedy-Thorndike type of experiment to compare the frequency of a length-stabilized laser with that of a laser stabilized on Iodine. This type of experiment checks the equivalence of the transformation of length and time as the earth's surface velocity relative to a potential preferred frame (represented by the cosmic blackbody background) is sidereally modulated by the rotation. This experiment will complement the earlier JILA experiment which showed the isotropy of space at a 4000-fold improved sensitivity. (Refs. 1853, 1976)

At a somewhat less fundamental but nonetheless interesting level, these techniques earlier had made it possible to resolve the minute frequency splitting associated with the recoil effect, even with infrared photons. These high resolution techniques were also applied to the study of hyperfine structure in a $^{13}CH_4$ line at 3.39 μm (Ref 1918). Working with these stabilization techniques and a color center laser led to the discovery of a large unexpected change (17%) in hyperfine coupling constants when an HF molecule was vibrationally excited. (Ref. 2711) A theory paper is almost ready for publication. Various interesting spectroscopic measurements of hyperfine structure of optically-excited states in Bi were performed also with a frequency-controlled dye laser. (Ref. 1753) Discussions about precision measurements in Hydrogen with T. W. Hansch during a brief sabattical at Stanford led to the active development of an external frequency stabilizer which can be used to control the intensity and

frequency of any cw laser beam - after it has been produced by the laser! (Ref 2986; Patent 4) Colleagues in the laser industry are interested in producing this instrument commercially.

One of the key problems in high resolution spectroscopy concerns the motion of the atoms. If we associate them into an aggregate of some kind, their random velocity is greatly reduced and we can hope for an interaction time long enough for our measurements to avoid broadening due to the Uncertainty Principle. Of course in exchange we have interatomic interactions, and it seems unlikely that a simple enough enviornment can be produced such that all atoms experience the same frequency shift. So we prefer free atoms, at low enough pressure to be collision-free on the time scale of our interest. Now their thermal velocity gives Doppler broadening, which we avoid by various nonlinear spectroscopies. But the real problems are still there: the relativistic Doppler shift amounts to a hundreds up to 10^4 laser linewidths for the present laser systems. Basically, the only serious choice is to slow atoms down to near zero velocity. Among several known methods of maintaining the resonance condition as the atoms lose velocity, we believe the most attractive is to "chirp" the laser frequency to keep up with the changing Doppler shift. Experiments were performed at JILA using our efficient broadband modulator (referred to above) to produce the swept-frequency sideband. An atomic beam of Sodium was slowed, brought to rest, even reverse accelerated back toward the atomic beam oven! (Ref 2971) A serious search was made to identify other atoms suitable for this kind of research (Ref 2675), and the design of an optimally-versatile apparatus was considered. (Ref 2674) Later a detailed theoretical model was offered which includes Monte Carlo simulation as well as numerical integration of the equations of motion. (Ref 3348)

We have had some very good runs of the atom-cooling experiment recently. As the velocity widths become strongly reduced the relative frequency noise of the two dye lasers becomes important. We have eliminated this source of ambiguity by using a single laser to provide both the swept cooling output at high intensity and the swept interrogation scan at low intensity. The physical question addressed was the prediction by the theory of Stenholm and colleagues, confirmed by simulations, that even an unswept laser can produce velocity-narrowing. We swept the cooling sideband frequency by 900 MHz, and then stopped the scan, staying "parked"

at this frequency for various post-cooling times from microseconds to tens of milliseconds. Then the intensity was reduced a factor 500, the frequency set to a new value for the velocity distribution measurement. After 20 us settling time the resonance fluoresence photopulses were counted for 50 us. Then the cooling cycle was reintitiated. A cycling rate of 200 Hz was used. After 10 cycles a slightly different interrogation frequency was presented to scan over the velocity distribution produced by the cooling sweep. Then the macro cycle was repeated to build up the signal to noise ratio.

Representative data obtained with essentially zero post-sweep "cooling" showed that the peak of the velocity distribution "rides the surf-front" about 14 MHz ahead of the swept laser frequency, using a cooling power of 13 mW. The measured linewidth for this distribution was 12.1 MHz. Considering that the natural linewidth of Na is 10MHz, there is obviously little space left for laser noise or velocity distribution width. We estimate the Gaussian width to be 5 MHz FWHM, corresponding to 3 m/s FWHM. This is an important result because it shows the error of the simple idea that the final linewidth in velocity space is a direct image of the natural linewidth, which would be 6 m/s in our case.

Presumably the true linewidth is substantially less than we derived from our data also, since the measurements were made with the "two-mode" method of operating the dye laser. This laser technique gives real problems to the existing stabilizer system, so the laser frequency noise could easily have been a MHz or so during these experiments. A new rf multiplexer will allow both sweeping and repumping frequencies to be applied to a single travelling-wave modulator.

The next round of experiments are being prepared to use two-stage cooling. The first laser will slow the atoms down to a few m/s as described above. Then we will apply a beam at 285 nm produced by frequency-doubing a second dye laser. This beam will drive the 3S -- 5P transition in Na, which is 20-fold weaker than the resonance line. This 20-fold linewidth reduction will then end us up at a velocity width in the neighborhood of 10 cm/s! A new interaction region is just ready for the first tests of the "atom bounce-trap" principle. Simulation suggests that rather impressive storage times can be obtained by a repeated cycle of cooling, interrogation, and recooling. Ramsey fringe techniques will be used to distinguish between newly arrived slow atoms and those with a coherent mixture of ground state hyperfine levels prepared by previous interactions. It should be possible to make contact with the theory of infinite order

pulse echoes studied recently by Hashi at Kyoto, and other workers.

In summary, in joint funding over an 8 year interval by the Office of Naval Research, the University of Colorado, the National Science Foundation, the National Bureau of Standards, and very recently the Air Force Academy, the result has been an extremely productive and cost effective research investment. The work has led to 3 PhD thesis students and 13 postdocs being trained, three patents, and about 40+ papers. Counting JILA Visiting Scientists, other professional-level visitors, and postdoctoral participants, about 25 people have been involved in the work, typically for a one or two year interval. A publication list and a personnel list are attached.

Hall*labs Personnel >July 77

PhD Students

Jim C. Bergquist	National Bureau of Standards	PhD 1978
Leo Hollberg	Bell Labs	PhD 1984
Marc D. Rayman	Jet Propulsion Labs	PhD 1985
Miao Zhu	current	>Jun 82
Mike Winters	current	>Jun 84

PostDoctoral Associates

Christian J. Borde	Univ. Paris North, Villetaneuse	<1975, summer 85
Alain Brillet	CNRS, Orsay, France	Oct 77 - Oct 78
Ove Poulsen	Univ. Aarhus, Denmark	Jan 77 - May 78
Siu-Au Lee	Colorado State Univ., Fort Collins	Nov 76 - Nov 78
Frank Kowalski	Colorado School of Mines	Aug 78 - Aug 80
Tom Baer	Spectra Physics, Mountain View, CA	Mar 79 - Aug 81
Paul Nachman	TRW, Los Angeles, CA	Oct 82 - Sept 83
Martin Hohenstatt	Univ. Heidelberg, W. Germany	Aug 80 - Feb 82
David Nesbitt	Univ. California, Berkeley	Aug 81 - Jan 82
Rainer Blatt	Univ. Hamburg, W. Germany	Oct 82 - Oct 83
Wolfgang Ertmer	Univ. Bonn, W. Germany	Dec 82 - Dec 83
Christian Breant	CNRS, Saclay, France	Dec 82 - Sep 83
Christophe Salomon	Ecole Normal Superieure, Paris	Sep 84 - Oct 85
N. C. Wong	MIT, Cambridge, MA	Jan 84 - Aug 86

JILA Visiting Fellows

Kiyoji Uehara	Keio Univ., Tokyo	Sep 74 - Sep 75
Hugh G. Robinson	Duke Univ., Durham, NC	Aug 80 - May 81
Jim Hough	Univ Glasgow, Scotland	Feb 83 - Jul 83
Peter Zoller	Univ. Innsbruch	Sep 82 - Aug 83
Peter Toschek	Univ. Hamburg, W. Germany	86 - 87
Larry Davis	Univ. Idaho, Moscow, ID	Aug 81 - Sep 82

Other Professionals

Jurgen Helmcke	P.T.B., Braunschweig, W. Germany	78-79
Dieter Hils	current	>Nov 81
Ron W. P. Drever	Cal Tech, Pasadena	Sep 79
Ma Long-sheng	East China Normal Univ., Shanghai	Jun 82 - Sep 83
Wang Yiqui	Peking Univ., Beijing	Dec 83 - Sep 85
Tatehisa Ohta	Doshisha Univ., Kyoto	Sep 82 - Aug 83
Jean-Marie Chartier	BIPM, Sevres, France	Sep 81 - Mar 86
H. Jeff Kimble	Univ. Texas, Austin	Jun 85 - Jan 86

Technical Support

Deborah Bass	student, electronics	
Terry Brown	electronics	>Jun 84

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