Office of Naval Research

Final Report

for

Contract N00014-89-J-1227

Title of Contract: **Precision Atomic Beam Laser Spectroscopy**

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Final Report ONR Contract N00014-89-J-1227 HallLabs at JILA

Program Objective: The ONR contract has provided partial support for a vigorous program of optics and physics research involving approximately 12 researchers at all levels of training from beginning students, through thesis-level, postdoctorals, and visiting faculty researchers. The organizing principles of our work are to enhance the coherence and general utility of laser sources by appropriate servo control techniques and to apply these sources to scientific problems of outstanding physical interest.

Research Description. This ONR funding provided essential and flexible partial support for a vigorous ongoing research effort involving at any moment typically 10 people, including 2-3 postdoctoral researchers, 3-4 graduate students, and two visiting faculty members. During the 3 years of this funding, 4 students have earned their PhD's and left our group: Dr Mark Eickhoff joined a local laser-related firm (95), Dr. Chris Oates won an NRC Postodoctoral position in NIST-B (95), Dr Steve Swartz went into private industry in Boston (96), Dr Jun Ye accepted the Millikan Prize Fellowship at CalTech (97), and Dr Kurt Vogel won a NRC Post-doctoral position in NIST-B (98). The focus of the work is the development of precision laser techniques and their application to physical problems of outstanding scientific interest, including laser frequency stabilization at/below the Hertz level, cold atomic "fountains", optical frequency standards, ultra-resolution spectroscopy, measurement of optical frequencies, and advanced tests of physical principles. The main successes during this grant were to complete our frequency measurements of the stabilized Nd laser, to accurately measure the natural lifteime of Sodium, to exploit our new and precise spectroscopic technique based on intracavity molecular dispersion in overtone bands, to demonstrate a new Optical "Frequency-Comb" Generator, to get a new sealed atom cell/trap for Sr atoms on line, demonstrate "second-stage" cooling and trapping with it, and to bring the stable diode lasers together with these ultra-slow atoms. With these enabling results, the best is just ahead: Perhaps it will always be so.

Scientific Problem - the Guiding Dream : Future Scientific Opportunities enabled by this completed Research

Using the developing tools of ultrastable lasers, optical frequency measurement and microKelvin atomic trap/fountain technologies we are exploring the prospects for advanced physical measurements. We believe it will soon be possible to build an optical frequency standard of unprecedented performance. We expect an optical Ramsey resonance lineshape of about 10 Hertz width at a center frequency of about 10^{15} Hertz, and the large signal to shotnoise ratio characteristic of utilizing some million atoms, namely ~1000:1. The optimum servo control of the laser using this signal could evidently produce a laser linewidth in the domain of a dozen milli-Hertz! What is particularly attractive about this system is the expectation of extremely high accuracy as well, because of the absence of incalculable velocity-dependent shifts, combined with the absence of collisional effects. Thus the inaccuracy of such an optical standard must surely be in the sub-Hertz domain. Magneto-Optic trapping techniques in a sealed cell, coupled with our advances in stabilizing diode lasers can lead to more simple and portable realizations of these techniques in the future.

A large number of interesting scientific problems will be accessible with such sources. We foresee atom interferometers with frequency readout of infinitesimal Sagnac-induced or gravitational-gradient-induced phase-shifts, atomic velocity measurements at the level of a few microns/sec which lead in turn to a drastically improved limit for the charge neutrality of atoms and, potentially, a useful measurement of the gravitational response of individual atoms. The wave-mechanical nature of the atoms themselves also gives rise to interesting and potentially useful quantum interference effects. A test of T symmetry via setting a better limit on an atomic electric dipole moment may be feasible in the future. Measurement of the frequency of this atomic fountain reference against the microwave frequency standard opens the door to exciting further tests of our fundamental physical postulates, such as the invariance of atomic frequency ratios in time or against changes of gravitational potentials and/or fields.

An exciting new possibility under active consideration is the measurement of the 4-vertex QED process which could be called "light by light scattering," but which will be measurable as a birefringence of the vacuum, induced by a string of 2 SSC magnets (6 Tesla $\rightarrow \Delta n/n = 2 \times 10^{-22}$). A collaboration with other academic and FermiLabs people has been initiated, and 2 magnets are already installed at FNAL.

Occasionally an opportunity presents itself to simplify laser technology or provide better performance for the same investment: several items in our line of "better, simpler, cheaper" advances have attracted cooperation with US laser industry and a number of such JILA-developed products are being sold.

Achievements in the Laboratory

ULTRA-SENSITIVE SPECTROSCOPY

Noise-Immune, Cavity-Enhanced Optical Heterodyne Molecular Spectroscopy: We have achieved a detection sensitivity of 5×10^{-13} for absorption, which is by two orders better than the best results achieved to date by cavity ring-down or any other laser/intracavity absorption spectroscopy methods. Using C_2HD for stabilization of a 1.064 μm laser, we have already achieved a stability of 1×10^{-13} at 1 s and better than 5×10^{-15} after 1000 s. This method can be called Noise-Immune, Cavity-Enhanced Optical Heterodyne Molecular Spectroscopy, ie NICE OHMS, and is the object of intense interest by spectroscopic research groups worldwide. In this connection we have had specific visits on this topic from colleagues at NISTB, MIT, the University of Innsbruch, the European Laboratory for NonLinear

Spectroscopy in Florence, the NRLM inTsukuba, Colorado State University, Montana State University, Air Force Philips Lab, and the FermiLabs.

A: PRECISION MEASUREMENTS, LASER STABILIZATION ...

Frequency-stabilization of Nd:YAG laser using I_2 resonances: Two independent lasers systems have been stabilized to the 532 nm Iodine resonances using our (patented) "modulation transfer" spectroscopic technique[1]. Very strong resonances of nearly ideal symmetry are obtained. The Allan variance of the beat between two dissimilar systems represents a stability unprecedented for any visible laser: σ_y ~60 Hz (1×10^{-13}) at 0.1 sec , 30 Hz at 1 s, improving below 4×10^{-15} for T> 800 sec. The reproducibility at present is ~300 Hz, about 1×10^{-3} units of the operating linewidth. These results with the doubled-Nd 532 nm green are some 200-fold better than those obtained with the 633 nm Iodine-stabilized HeNe laser, and this is after 24 years development work on the 633 nm system in countless national standards labs!

Frequency measurement of 532 nm using 780 nm Rb line and HeNe I_2 laser at 633 nm as references: Evidently, good high-sensitivity techniques allow use of reduced power which also helps reduce the expected shifts for the Rb. These changes made it possible to demonstrate ~2 kHz reproducibility on the Rb D_2 line, comparing an rf sideband spectrometer with one based on FM "dither" and third-harmonic locking. Considering that the natural linewidth is 6 MHz, we are *accurately* splitting these tricky lines to 1 :3000. We project a "final" measurement of the Nd frequency can be performed with << 10 kHz uncertainty relative to the Rb 778 nm two-photon reference.

We measured the 1.015 Thz frequency difference between the Rb two photon reference line at 778 nm, and the Rb D_2 reference line at 780 nm. This was done with Schottky-diode technology, with integral harmonic generation from a 90 GHz Gunn oscillator source. This high frequency is probably the highest that will be measureable this way, because the attainable S/N was only 15 dB in a 30 KHz bandwidth: for the laser sources employed, this was very near the phase-lock limit. The observed laser frequency reproducibility was ± 3 KHz, while the stability of 3.5×10^{-12} at 1 s improved to $<2 \times 10^{-13}$ after 2500 s.
Work done by Jun Ye, Steve Swartz, Pierre Dubé, and S. Waltman.

We are developing the new technique of Optical Comb Generation for this kind of work in the future. A low loss phase moulator crystal, driven at 10.6 GHz, is located within a high finesse optical cavity. A modulation index of >1 radian has been observed, along with a reasonable finesse. Calculations (and experiment!) indicate that useful sidebands beyond 1.5 THz should be available. This work is

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[1] L. S. Ma, L. Hollberg, J. H. Shirley, and J. L. Hall, "Modulation transfer for stabilizing lasers," US patent #4,590,597, issued May 20, 1986

far from being mature, but we have already obtained ~100-fold higher optical efficiency with a new coupled-cavity scheme.

We have locked a MISER Nd:YAG laser to a finesse 50,000 cavity with a noise density below 22 milliHz/sqrt(Hz), corresponding to a potential Lorentzian linewidth around 1.5 milliHertz! [Assuming no other noise was present in the cavity, which is surely not the case. But this shows the locking quality.] It was necessary to broaden the servo bandwidth in order to obtain this high a gain,which was accomplished using an external AOM frequency shifter, in addition to the MISER's own PZT.

We have gotten excellent resonances at 1.064 μm with HCCD using the NICE-OHMS spectroscopic system of FM spectroscopy of molecules within a high-finesse optical cavity. In this system, the ~10 mTorr gas sample gives a length-integrated absorption of ~0.25 ppm, while the saturated absorption feature is about 8% of this absorption. With our NICE-OHMS method, we achieve a S/N of about 9,000:1 and so an integrated absorption ~5 $\times 10^{-13}$ is observable in 1 s averaging. We have used these narrow resonances for frequency stabilization of course, obtaining 2 $\times 10^{-13}$ at 1 s and <5 $\times 10^{-14}$ at ~800 s . This is the best reported stability for any visible source, and can surely be improved with higher cavity finesse and better gas purity. Then we must apply the method to Iodine, which has absorption about 500,000 -fold stronger!

LASER SPECTROSCOPY

As part of the optical frequency measurement, we determined the electric quadrupole and hyperfine coupling parameters for the ^{87}Rb 5 $P_{3/2}$ state with a ~10-fold accuracy increase.

New form of lineshape distortion with FM spectroscopy of Rb atoms using a frequency-stabilized Ti:Sapphire laser: The lineshape effect is easily observable for a range of modulation frequencies from 1-10 units of the linewidth, and is manifest as a phase-shift of the received rf modulation on the probe beam with increasing probe-beam intensity. The phase-shift arises when the atomic dipole vector begins to see the phase modulation of the carrier as important relative to the natural relaxation rate. Theoretical calulations based in the carrier-frequency rotating frame led to a clear understanding of the intensity-dependent phase as a phase lag of the dipole response to the carrier's phase perturbation associated with the modulation process. These effects of non-equilibrium response are very general and should be present in all spectroscopic methods with time-modulated fields.

4. Improved Iodine-stabilized Nd:YAG laser: We have analyzed, articulated and made convincing demonstration of the advantages of the Iodine-stabilized Nd:YAG laser as a practical working standard, with frequency stability and reproducibility at least 50-fold superior to that of the ubiquitous Iodine-stabilized HeNe laser at

633 nm. All frequency intervals within the ~50 GHz accessible region have now been measured at the <1 kHz level. At the September 1997 meeting in Sèvres of the Comité Consultatif pour la Définition du Métre, the scientific/metrological case for inclusion of the new 532 nm standard within the manifold of internationally-sanctioned references (the so-called "Mise en Practique") was made by personal presentations, augmenting detailed information in documents and reprint s which were earlier submitted to the BIPM. It is worth noting that JILA's historical contributions to this international wavelength reference process have been viewed as so significant that JILA is the only laboratory that that is a CCDM member on the basis of its contributions, rather than its administrative position as a national lab.

B: TRAPPING & COOLING

Lifetime and hfs of Sodium studied in MOT: Chris Oates has defended his PhD thesis, the first part of which presents the uv line position measurements in Na 5P that improved the hfs parameters by 40-fold. The second part of thesis is the first precision lifetime measurement of any atomic system using *frequency-domain* techniques, and by far the most extensive study of what the *real* single atom resonance lineshape is. Measurement of the limiting linewidth at low intensity gave directly the frequency equivalent of the atomic lifetime, with an accuracy which is about ~0.2%. It is interesting that another precision experiment (this one in Kaiserslautern using fast beams) was also done to address the persistent 1% discrepancy between theory and the best previous experiment, both thought to be only <0.25% uncertain. Both new experiments agree with the theory.

Trapped Strontium: In collaboration with the group of A. C. Gallagher, we have a Magneto-Optic trap operating well with Sr vapor, using Wieman's sealed cell approach. To obtain adequate vapor pressure we have heated the entire cell, using the alumina ceramic-sapphire vacuum sealing technology developed at JILA by Gallagher's group. Strontium is a most interesting atom for trapping studies for at least three reasons. Regarding collisions, the absence of any structure in the ground level leads to a realistic prospect for detailed understanding of the long-range interactions between extremely cold atoms. For study of the MOT process, there are some amusing decay pathways from the excited 5P $^1P_1$ state into singlet and triplet D, perhaps also directly into ^3P as well. Repumping experiments show great promise to increase the density further, using 717 nm to empty 4d $^1D_2$ and 679 nm for the $^3P_0$ - 6 $^3S_1$ repumping transition. We studyied the dependencies of the large density increase observed when both repumping beams are present. For optical frequency standards work, we have prepared a frequency-stable diode laser to probe the intercombination line at 689 nm. Trapping on this transition should be possible for atoms with velocities below a few cm/s. We may locate this red trap about 1 cm above the blue trap to catch the atoms at their apogee.

NONLINEAR OPTICS & preparation for QUANTUM OPTICS

Frequency-summing into the UV: We have built a reliable apparatus using the nonlinear crystals $LiNbO_3$ and $LiIO_3$, respectively, to double 1.06 μm, and to add the resulting green and IR frequencies, obtaining at present 1/4 mWatt of the 355 nm output. This will be heterodyned with the doubled output of a diode laser at 710 nm, which can be locked to various Bromine lines in this region. This may be the critical step in a table-top optical frequency synthesizer.

Stable operation of Type I OPO in $KNbO_3$: We have operated a type I OPO in $KNbO_3$ under extremely tight servo control of the cavity length relative to the pump wavelength, using a frequency-offset-locking scheme. This should make it possible to be quantitative about OPO performance in this very fragile but potentially useful system. The application will be to test the quantum noise-reduction scheme discussed relative to a Mach-Zehnder interferometer fed with correlated light beams. Burnett & Holland showed that input Foch states can lead to a $\Delta\Phi\ \Delta n$ uncertainty principle of the form $\Delta\Phi * n = 1$.

3) Efficient doubling and Optical Parametric Oscillator based on KTP and $KNbO_3$. This efficient doubling research began at JILA, but this demonstration was carried out at Cal Tech, beginning as part of our collaborative project, but finally pursued to a very successful conclusion by Eugene Polzik, Jeff Ou, and Jeff Kimble, using some JILA-made electronics. For new quantum optics experiments at JILA we are exploring the use of type II-matching in KTP to form an OPO pumped by a 514 nm Argon laser. We have seen parametric fluorescence but no parametric oscillation has been obtained so far in KTP. However KTP and both $KNbO_3$ and $LiNbO_3$ work well with 532 nm pump.

ELECTRO-OPTICS TECHNOLOGY

Optical Frequency Comb Generator with Selective Output Coupler: We have excellent results using a strongly-driven electro-optic modulator situated within a low-loss and resonant cavity. World-wide interest in these devices is exploding for their use as an "optical comb generator" in optical frequency synthesis schemes. We have better parameters than have been so far reported, although a just-published paper by my former Postdoc, Franco Wong, has challenged this assertion in one detail. A novel frequency-selective cavity mirror allows effective in-coupling of the monochromatic light to be modulated, and out-coupling of the selected frequency-shifted "comb" component. So far we observed useful sidebands shifted by > 1.5 THz. The frequency of a delicious line in a simple Neon discharge was measured relative to our HeNe/Iodine 633 nm standard using the comb generator.

Practical Stabilized Laser for Interferometry: We are working toward a low-cost and attractive prospect for a practical stabilized laser for lithography and many other practical applications. Our system is an external-cavity 633 nm laser diode working with the Ne* atomic $1S_5$-$2P_8$ transition which, remarkably, is only 468 GHz from the usual red HeNe standard. (We have already measured beats above 620 GHz.) We have now stabilized this diode laser to a cavity to ~10 kHz, the measurement level set by the HeNe reference used in the first experiment. A solid etalon, thermally-controlled to ~0.3 mK will offer sub-MHz stability for the stabilized diode frequency.

Stabilized 612 nm HeNe system, locked to an external cavity containing an Iodine cell: This portable apparatus is expected to provide frequency stability and reproducibility in the <100 Hz level in the size of an airlines-carry-on package. It is a joint project with the BIPM in Sévres, France. This project is temporarily on hold pending completion of the absolute frequency measurements in the green.

Technique and apparatus for accurately measuring the fractional fringe order of Fabry-Perot ring fringes: Our scientific application will be the precise measurement of Fabry-Perot rings to obtain accurate laser wavelengths when tuned to some interesting atomic transition. An important engineering application of this interference-phase measuring capability is the readout of atmospheric refractivity for industrial interferometric length/position control applications. Our software gives 2×10^{-4} rms orders *accuracy* in fringe fitting of synthetic data constructed with 5% rms random noise. Experimental confirmation has been shown to 1×10^{-3}, limited by small systematic deviations of the actual fringe lineshapes relative to the expected Airy fringes. An extended comparison of three approaches to real-time determination of atmospheric refractivity has been carried out, with agreement at the 10^{-7} level, with some systematic deviations which may point to humidity retention in/on one of the coatings. This work formed part of the basis for the thesis of M. L. Eickhoff and a major paper was published in Applied Optics. The refractometer system patent was filed by NIST on July 1, 1991 and issued June 8, 1993 as US Patent # 5,218,426. NIST is now seeking licensees for application of the refractometer, for example as an adjunct measurement tool for on-line use in semiconductor wafer fabrication and other manufacturing facilities where high accuracy distance measurements are made by interferometry in the ambient air.

Project to measure the Magnetically-induced QED Birefringence of the Vacuum: Relative to the exciting possibility of measuring the birefringence induced by QED in a strong magnetic field, our consortium of CU, CSU and FermiLabs researchers has submitted a proposal to NSF for infrastructure development, namely the development of an interferometer able to accurately measure birefringence in the 10^{-22} range. Unfortunately, in the first round it was not funded. An experiment proposal to FermiLabs also was not directly acted on. However, Director Peoples of FermiLabs has expressed a great interest in having the experiment done there, and two SSC magnets to produce the QED-induced birefringence measurements were moved from Texas to FNAL and have been installed in a new building constructed for this experiment.

Cavity-stabilized laser: Locking Improvements.

Experiments by Jun Ye and Professor Ma have led to an unprecedented sensitivity level for cavity locking with low intensity red laser light: we find it is possible to measure the cavity mirrors' birefringence at the ~10 mHz level, where 1/2 wave shift would be equivalent to 541 MHz. This sensitivity is ~5 $\times 10^{-17}$. The main limitation was inadequate isolation. If we use instead a few mW level of green laser light, one finds some expected but unwelcome photorefractivity effects at the ~1 $\times 10^{-17}$ level which will require study before reaching the desired sensitivity level in the sub 10^{-22} domain.

Cancellation of phase noise in an optical fiber to milliHertz level:

In the course of comparing the stabilized output of the Nd:YAG laser with our precise reference cavities –which are located two rooms away in our "Quiet House" – we discovered that 25 m of ordinary sheathed mono-mode polarization-maintaining fiber can introduce a tremendous amount of noise onto an otherwise phase-stable light beam: more than 1 kHz of spectral broadening was written onto the light by phase-noise variations of the fiber's transmission phase. The perturbations include acoustic noise, micro-bending induced by vibration, and micro-thermal variations. With a frequency-offset coding at the remote end on a weak returned beam, by heterodyne at the source end we obtain two units of the fiber's insertion phase. This is used with a phase-locked VCO and digital divide-by-two to form a servo system using an additional AOM, accurately "pre-cancelling" the phase noise before the beam enters the fiber. In this way it was possible to reduce the fiber's output bandwidth from *kilo*Hz to the sub-*milli*Hertz level. Patent disclosures have been submitted to both CU and NIST on this work.

Improved phase stabilization of low-cost laser diodes using external resonators and fast electrical feedback.

A nice method for measuring the diode's current/frequency transfer function was developed, and is being written up for publication in RSI. Optimal phase equalizers were designed to allow substantial increase of the servo bandwidth to ~10 MHz, which allowed capture of ~99.8 % of the emitted power in the phase-locked spectral delta-function. This work was done in collaboration with a former JILA student, Kurt Gibble, during his postdoc time at Stanford, and with Robert Wynands, a student in the Max Planck group of Professor T. W. Hänsch in Munich.

ELECTRONICS

Low Noise Diode Laser Current Source:

A next-generation current controller for laser diodes has been developed with 3-fold lower noise than our previous best, the circuit I developed while at CalTech. The most important additional change is the automatic crossover to a light-controlled regime when the AR-coated diode is used in an external resonator. Otherwise the diode laser power goes from μW to beyond burnout for an infinitesmal change of drive current or feedback return loss. This system operates near the shotnoise limit, almost ten-thousand-fold below the expensive commercial system I worked with at the Max Planck.

Absolute Temperature measurement via Johnson Noise:

In a collaboration with Ivan Getting of CIRES I have shown that it will be possible to measure absolute temperature up to ~2000 K by direct measurement of the Nyquist resistor noise, at < ±1K accuracy. This is interesting in studying earth minerals at high temperature and pressure, as the calibrated thermocouple is pressure-deformed ~30% and surely has lost its precision NIST calibration in the meantime. The passive resistance of our compressed resistor can be directly measured, whatever the change of its value, while its thermally generated noise serves as our temperature readout via a dual-channel correlation technique. This thermal-calibration-free approach to temperature measurement is made possible by advances in low-noise analog amplifiers, band-limiting filters, and precision wideband multipliers. Proof of electrical performance at << 1 K level was shown by measuring relative to a calibrated thermocouple.

Results of Special Significance

Analysis of the sensitivity limits in intracavity spectroscopy leads to the conclusion that high finesse is desireable. However laser frequency noise is then efficiently converted into amplitude noise and the useful sensitivity is in fact drastically compromised. We have invented an "ideal" detection scheme in which the full sensitivity of optical heterodyne detection is preserved with ZERO sensitivity to small laser/cavity frequency noises. The new method is called Noise-Immune, Cavity-Enhanced, Optical-Heterodyne Molecular Spectroscopy, conveniently shortened to "NICE OHMS." With it we have demonstrated an absorption sensitivity of 5×10^{-13} integrated absorption, for 1 s averaging time, a value 2 orders better than reported using other sensitive methods such as Cavity Ring-down and IntraCavity Absorption. This technique will have important applications in spectroscopy, laser stabilization, and trace component measurement.

Publications:

a). Papers published in Refereed Journals:

1. "Absolute frequency measurement of molecular transitions near 532 nm," IEEE Transactions on Measurement and Instrumentation **44**, 151-4 (1995), P Jungner, S. Swartz, M. Eickhoff, J. Ye, J. L. Hall, and S. Waltman.

2. "Developing an Optical frequency standard at 532 nm," IEEE Transactions on Measurement and Instrumentation **44**, 155-8 (1995), M. L. Eickhoff and J. L. Hall.

3. "Delivering the same frequency in two places: Accurate cancellation of phase noise introduced by optical fiber or other time-varying path," Optics Letters **19**, 1777 (1994), L. S. Ma, P Jungner, J. Ye and J. L. Hall.

4. "Phase-shifts and Intensity Dependence in Frequency Modulation Spectroscopy," J. Opt. Soc. Am. **B11**, 721-730 (1994), H.-R. Xia, J. I. Cirac, S. Swartz, B. Kohler, D. S. Elliott, J. L. Hall, and P. Zoller.

5. "High Precision Linewidth Measurement of Laser-Cooled Atoms: Resolution of the Na 3p $^2P_{3/2}$ Lifetime Discrepancy," Phys. Rev. Lett. **76**, 2866 (1996), C. W. Oates, K. R. Vogel, and J. L. Hall.

6. "Sub-Doppler optical frequency reference at 1.064 μm by means of ultra-sensitive cavity-enhanced frequency modulation spectroscopy of a C_2HD overtone transition," Opt. Lett. **21**, 1000 (1996), J. Ye, L.-S. Ma, and J. L. Hall.

7. "Hyperfine Structure and absolute frequency of the ^{87}Rb 5 $^2P_{3/2}$ state," Opt. Lett. **21**, 1280 (1996), J. Ye, S. Swartz, P. Jungner, and J. L. Hall.

8. "Thermally-induced self-locking by overtone absorption from acetylene gas in an external optical cavity," J. Opt. Soc. Am. B, **13**, 2041-2054 (1996), P. Dube, L.-S. Ma, J. Ye, and J. L. Hall.

9. "Free-induction decay in molecular iodine measured with an extended-cavity diode laser," Opt. Lett. **22**, 184-186 (1997), P. Dubé, M. D. Levenson, and J. L. Hall.

10. "Real-time precision refractometry: new approaches," Appl. Opt. **36**, 1223-1234 (1997), M. L. Eickhoff and J. L. Hall.

11. "Ultra-stable optical frequency reference at 1.064 micrometers using a C_2HD molecular overtone transition," IEEE Trans. on Instrumentation and Measurement **46**, 178 (1997), J. Ye, L.-S. Ma, and J. L. Hall.

14. "Highly-selective terahertz optical frequency comb generator," Opt. Lett. **22**, 301-3 (1997) J. Ye, L. -S. Ma, J. L. Hall, and T. Day.

b. Articles published in books:

1. "Stability and absolute frequency of molecular iodine transitions near 532 nm," in *Laser Frequency Stabilization and Noise Reduction*, SPIE Proc. Vol. 2378,(San Jose, 1995), pp. 22-34, J. L. Hall, P. Jungner, M. Eichkoff, S. Swartz and J. Ye.

2."Accurate cancellation (to milliHertz levels) of optical phase noise due to vibration or insertion phase in fiber transmitted light," in Laser Frequency Stabilization and Noise Reduction, SPIE Proc. Vol. 2378, (San Jose, 1995), pp. 165-175, L.-S. Ma, P. Jungner and J. Ye, and J. L. Hall.

3. "A new modulation method for sensitive nonlinear spectroscopy - application to molecular overtones as visible frequency references," in *Laser Spectroscopy XII* International Conference (M. Inguscio, M. Allegrini and A. Sasso, Eds., World Scientific, Singapore, 1996), pp. 199-203, J. L. Hall, L. -S. Ma, J. Ye, and P. Dube.

4. "Frequency Stabilization of Tunable Lasers," in *Experimental Methods in the Physical Sciences*, vol 29C, Atomic Molecular and Optical Physics: Electromagnetic Radiation, ed. by F. B. Dunning and R. G. Hulet (Academic Press, San Diego, 1997) pp.103-136, Miao Zhu and J. L. Hall.

5. "Precise Wavelength Measurement of Tunable Lasers," in *Experimental Methods in the Physical Sciences*, vol 29C, Atomic Molecular and Optical Physics: Electromagnetic Radiation, ed. by F. B. Dunning and R. G. Hulet (Academic Press, San Diego, 1997) pp.311-342, J. L. Hall and Miao Zhu

6. "Optical Frequency Standards –some improvements, some measurements, and some dreams," by John L. Hall, Jun Ye, Long-Sheng Ma, Steve Swartz, Peter Jungner, and Steve Waltman, in *Frequency Standards and Metrology*, ed. by J. C. Bergquist, (World Scientific, Singapore, 1996) pp. 267-276.

7. "Ultrasensitive high resolution laser spectroscopy and its application to optical frequency standards," Proc.28th Annual Precise Time and Time Interval, 1996 (USNO,Washington, 1997) pp.289-303.

8. "Sr Detection in a vapor cell MOT," in *Methods for UltraSensitive Detection*, ed. by B. L. Fearey, SPIE v3270, in press 1998, K. Vogel, T. Dinneen, A. Olivas, A. C. Gallagher, and J. L. Hall.

9. "Cavity-enhanced Frequency Modulation Spectroscopy: Advancing Optical Detection Sensitivity and Laser Frequency Stabilization," in *Methods for UltraSensitive Detection*, ed. by B. L. Fearey, SPIE v3270, in press 1998, Jun Ye, Long-Sheng Ma, and J. L. Hall.

c. Work Sponsored by ONR, but published after contract ended:

1. "Ultrasensitive detections in atomic and molecular physics -- demonstration in molecular overtone spectroscopy," J. Opt. Soc. Am. B**15**, 6-15 (1998), Jun Ye , L.-S. Ma, and J. L. Hall.

2. "Influence of decorrelation on Heisenberg-limited interferometry with quantum-correlated photons," Phys. Rev. A, **57**, 4004-4013 (1998), Taesoo Kim, Olivier Pfister, Murray J. Holland, Jaewoo Noh, and J. L. Hall.

3. "Ultrasensitive Detections of Weak Resonances - Application to Optical Frequency Standards," in *Proc 13^{-th} International Conference on Laser Spectroscopy,*

Hangzhou, 2-7 June 1997, ed. by Yu-Zhu Wang (World Scientific, Singapore, 1998) Jun Ye, L.-S. Ma, and J. L. Hall.

4. "Optical Frequency Standards: Progress and Applications," in *Proc 13-th International Conference on Laser Spectroscopy*, Hangzhou, 2-7 June 1997, ed. by Yu-Zhu Wang (World Scientific, Singapore, 1998) J. L. Hall, Jun Ye, L.-S. Ma, K. Vogel, and T. Dinneen.

5. "Methods for "Using FM Methods with Molecules in a high-finesse Cavity: a demonstrated path to <10-12 absorption sensitivity," in *Cavity Ring Down Spectroscopy—A New Technique for Trace Absorption Measurements.*, ed. by K. Busch and M Busch (American Chemical Society, Washington DC, in press 1998), John L. Hall, Jun Ye and Long-Sheng Ma.

Results presented in Conference Proceedings

1. C. W. Oates, K. R. Vogel and J. L. Hall, "Improved frequency-domain lifetime measurement of the Na 3p level in a magneto-optic trap," Conference on Quantum Electronics and Laser Science, QELS '95, Baltimore MD, May 21-26, 1995, Digest pp. 145-6. Invited presentation.

2. Long-Sheng Ma, Pierre Dubé, Peter Jungner, Jun Ye, and John L. Hall, "Saturation spectroscopy of molecular overtones for laser frequency standards in the visible and near-visible domain," Conference on Quantum Electronics and Laser Science, QELS '95, Baltimore MD, May 21-26, 1995, Digest page 18.

Total Number of FTE Graduate Students and PostDocs Supported: 8 (partial)

Graduate Students partially supported under this contract: 5

Mark Eickhoff ->	Ophir Research, Denver
Steven Swartz ->	Science Research Laboratory, Sommerville MA
Christopher Oates ->	NIST, Boulder
Jun Ye ->	CalTech, Pasadena CA
Kurt Vogel ->	NIST, Boulder

Postdoctorals partially Supported under this contract: 3

Jaewoo Noh	University of Rochester -> Univ Inchon, Korea
Dr. Pierre Dubé	University of Toronto -> Triumf, Vancouver BC
Dr. Olivier Pfister	University of Paris XIII -> Duke Univ, Durham NC

(Note: No scientifically-qualified minority students could be identified for support during this period. However I did serve as faculty and thesis co-advisor for a gifted female student, Elizabeth Downly, who elected to finish her PhD in Zurich.)

<u>Other full-time staff</u>:

Prof. Ma Long-Sheng	East China Normal University, Shanghai

<u>1-year visitors:</u>

Dr. Marc D. Levenson	Levenson Associates, Saratoga CA
Prof. Tae Soo Kim	Seoul National University, Seoul Korea
Prof. Ennio Arimondo	University of Pisa, Pisa Italy Nov 94-Oct 95