progress is still rapid and more techniques are becoming conveniently available for use on problems of physical, chemical, or even biological interest.

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Stabilized Lasers and Precision Measurements

J. L. Hall

With the pervasive spread of lasers in scientific research, industry, and education, it may be interesting to consider a laser field that has been active since the very beginning of the laser era but that is just now coming toward fruition. This research area is concerned with precision measurements made with the use of stable laser techniques. Indeed, the laser pioneers Charles Townes, Ali Javan, Art Schawlow, and Bill Bennett were well aware of the possibilities of making precision measurements with their lasers. I can remember the audience excitement at the 1962 American Physical Society meeting when Javan played a tape recording of the actual audio beat frequency between two of those early optical masers (*1*). The spectral width of those masers was below 100 hertz, and their optical frequency was about 3×10^{14} Hz. It was clear to everyone that it would be possible to do experiments of unprecedented resolution with these new sources. Indeed, after more than 15 years of work by a large number of dedicated people, this situation is now approaching reality.

In this article I trace the concepts that have led to the present circumstance where in perhaps six laboratories in the world a useful resolving power of about 10^{-11} is possible and in perhaps another dozen laboratories it is possible to make measurements of time-averaged quantities in this domain and below. Although this capability now is mainly confined to national measurement laboratories, the development and availability of commercial equipment based on some of these concepts is bringing a new interest and capability into the hands of the larger scientific community. Thus we may look forward in the next few years to an explosive growth in the application of laser frequency control techniques to precision measurements.

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Introduction of Frequency Metrology into the Optical Domain

In view of the demonstration by Javan and his colleagues (*1*) of a laser fractional spectral width of about 10^{-13} and an earlier experiment by Cedarholm and Townes (*2*) which showed that the frequency of an ammonia maser was independent of the direction of motion of the ammonia molecules to a precision of better than 10^{-12}, it seems quite natural that these researchers at the Massachusetts Institute of Technology (MIT) would turn to a laser version (*3*) of the Michelson-Morley experiment.

In the 1887 "ether drift" experiment of Michelson and Morley (*4*), a path length of 36 feet (11 meters) was multiply folded onto a 5-foot sandstone optical table floating in mercury. The earth's orbital velocity gives a value for $(v/c)^2$ of $\simeq 10^{-8}$ (where v is the earth's orbital velocity and c is the speed of light), and so an expected path length change for the "ether shift" of about 0.4 fringe for Michelson's apparatus. His readings did not exceed 0.02 fringe. In spite of the consequences of this null result (the invention of the special theory of relativity by Einstein, Lorentz, and others) and the significance of potential improvements in this experiment, no major advances were made for 77 years. Basically the experiment was limited by the techniques of length measurement: one cannot subdivide interferometric fringes forever with the use of ordinary techniques. The MIT group took advantage of the optical heterodyne process—made prac-

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tical by the coherence of the laser source—to produce extremely high sensitivity in the readout of very small length changes. For example, the 30-Hz frequency variation of Javan's lasers corresponds to about one part in 10^{13} of the optical frequency or wavelength and so to a change of 2×10^{-7} fringe out of the 2×10^{6} fringes within the 1-m cavity length of the MIT lasers. This remarkable enhancement in sensitivity by the use of frequency metrology rather than wavelength metrology characterizes most modern experiments. Indeed, with contemporary stabilized lasers, fringe changes of still smaller fractions can be measured. For example, the limiting sensitivity in Michelson's experiment was about 5×10^{-10}, corresponding in the laser optical heterodyne method to a beat frequency of about 150 kilohertz: this is to be compared with a noise level of something like 100 Hz. Thus, an advance in measurement sensitivity of a factor of 1000 was potentially available with the use of frequency rather than length metrology.

Unfortunately, the length etalon that was measured in the MIT experiments was the laser resonator itself, including the necessary plasma column inside which provides the gain to overcome mirror losses. When a pair of these lasers, oriented at 90°, was placed on a rotating table, beat frequency excursions of about 275 kHz were observed, associated entirely with laboratory-fixed environmental factors, presumably the geomagnetic field. (It was suggested that the magnetic field affected the laser frequency through magnetostrictive length changes of the Invar rods which separated the mirrors. Perhaps there was also a small influence on the electron density of the plasma with orientation of the earth's magnetic field.) In any event, by making observations in both morning and evening, the experimenters were able to establish that any genuine cosmic effect was perhaps 100 times smaller than the spurious effects that they observed (*3*). This result provides an important object lesson for those interested in precision measurements. Although sensitivity of measurement is necessary, it is not sufficient: one must also be sure that the measurement is free of spurious other effects. (I discuss below a current version of the Michelson-Morley experiment.)

Summary. This article traces the development of stabilized lasers from the Massachusetts Institute of Technology passive-stabilization experiments of the early 1960's up through the current epoch of highly stabilized helium-neon and carbon dioxide and continuous wave dye lasers. The utility, present performance, and limitations of stabilized lasers as standards of length or frequency for precision measurements are discussed. Examples considered of laser applications to physical measurements of outstanding scientific interest include determination of the speed of light, redefinition of the meter, resolution of the photon recoil-induced spectral doubling, use of optical "Ramsey" interference fringes from ultrahigh-resolution spectroscopy, and two improved tests of special relativity.

The MIT stable laser experiments in the mid-1960's had a profound effect on our way of thinking about precision measurements. They introduced the use of optical heterodyne spectroscopy to achieve the enormous resolution and sensitivity that go implicitly with frequency measurement. Although digital instruments are commonplace today and we are accustomed to many instruments which transduce physical variables to frequency (because of its measurement convenience), it is the accuracy and precision capability of frequency measurements that are of primary interest in connection with this article. Basically the time interval of frequency measurement can be extended, perhaps by a factor of decades, to increase the total number of integral cycles counted so that the imprecision in the measurement of the remaining phase will be a correspondingly smaller fractional quantity. With specialized instrumentation it is now feasible to measure frequency differences below 1×10^{-17} for a 1-day measurement.

Development of Stabilized Lasers

Laser stabilization was a very interesting subject in the mid-1960's (and still is), and a number of ingenious techniques had been developed. Unfortunately, none of them seemed to provide the long-term stability that would be needed for precision physical experiments such as a differential interferometric measurement of the speed of light (*5*). A conceptual roadblock was overcome in 1967 by Lee and Skolnick with their introduction of a pure Ne, low-pressure absorption cell within the resonator of a He-Ne laser (*6*). Their use of two gas cells allows separate optimization of the conditions necessary for the gain and wavelength-reference functions. A saturation feature or inverse Lamb dip was observed at the center of the Ne absorption profile. Of course, this separation of the oscillator and reference atomic absorber functions was well known in the microwave domain. Even so, that paper had a major impact on the development of the field of stabilized lasers, and in short order discussions were going on in many laboratories throughout the world about lasers stabilized to molecular absorption cells.

Molecules are attractive for the wavelength reference, since they have many lines beginning on thermally populated levels. One can thus hope to find an accidental spectral overlap of the laser with a totally quiescent absorber. Also, one can hope to find an exceptionally narrow reference line. The stabilization of the He-Ne laser at 3.39 micrometers to the saturation feature in low-pressure methane (CH_4) gas was described in 1968 (*7*). It was quickly followed by the stabilization of the usual red He-Ne laser line to a transition in molecular iodine (I_2) (*8*). Both of these lasers have extremely good performance and make possible meaningful measurements in the domain well below 10^{-11}. The CH_4 peak is more narrow and so potentially of higher precision but is troubled by internal structure to be discussed below. The I_2 peak stabilizes a visible laser for which optical devices and mirror coatings of excellent quality are available. International intercomparison (*9*) of the I_2-stabilized lasers have shown the reproducibility to be better than 10^{-10}. The CH_4-stabilized lasers show an independent reproducibility of about 10^{-11}; in some high-resolution experiments (*10*) to be described later an absolute accuracy capability of approximately 10^{-13} was obtained (*11*).

Another technique introduced at this time was frequency offset locking (*7*). This technique enabled one to treat such a stabilized reference laser as a source of stability to be transferred with r-f servo techniques to other lasers of interest. Our modern phase-lock techniques can keep the phase of the controlled optical frequency within a few tens of milliradians of the programmed value. There is thus a programmable frequency offset introduced by the servo but no degradation of the stability. Or we can use the wavelength and its standing wave pattern in an interferometer to stabilize that interferometer with a suitable modulation-based servo system. We can also use these r-f/optical locking techniques to

read the length of the interferometer in a Vernier and extremely sensitive manner. This technique of frequency offset locking, combined with the many types of stable lasers, promises to open the door to many kinds of precision measurements throughout the spectrum. I present a few examples below.

A Definitive Laser Speed-of-Light Measurement

The first laser measurement of c (*12*) made good use of these servo-locking techniques. Microwave modulation is used to produce optically resolvable side bands on the laser frequency. Servo techniques maintained the standing wave condition in an interferometer for the carrier and its side bands simultaneously, thus establishing the optical frequency as a (large) multiple of the microwave frequency. Measurement of the laser wavelength then led to the value c = (299,792,462 ± 18) meters per second.

Although the differential interferometry experience at the Joint Institute for Laboratory Astrophysics (JILA) of the National Bureau of Standards (NBS) (*5*) was useful in stimulating the development of several frequency control techniques, it was made obsolete as a measurement of c by the rapid development of direct laser frequency measurement. This work on optical frequency synthesis was begun by Javan and his associates at MIT, using special point-contact diodes to directly measure the frequency of the HCN laser at a wavelength of 337 μm. That frequency of 897 gigahertz was measured as a harmonic of a 70-gigahertz klystron. Later measurements extended to the D_2O vapor laser at 84 μm and pulsed measurements to still shorter wavelengths (5 μm). This work (*13*) attracted the attention of scientists involved in precision measurements everywhere, especially at the NBS in Boulder, Colorado, and at the National Physical Laboratory (NPL) in England. Evenson and his colleagues at Boulder extended the continuous wave measurement technique to the 28-μm H_2O vapor laser, soon reached the carbon dioxide (CO_2) laser at 9.3 μm, and later reached the He-Ne laser at 3.39 μm (88 terahertz) (*14*). The mixing element used in these frequency-mixing experiments was a tungsten whisker pressed upon a nickel post diode. It functions both as a harmonic generator and as a mixing element to produce an intermediate frequency from two optical frequencies and a microwave input frequency which was generally required to give a beat frequency in the convenient r-f range. Although the physics of operation of these diodes is still being studied, they have been refined to allow measurements of frequencies higher than 88 THz (3.39 μm), notably 3.5 μm, 2.0 μm (*15*), and, most recently, 1.5 μm (*16, 17*).

This direct frequency measurement capability enables one to calculate c from the fundamental equation $c = \lambda \nu$ (where λ is the wavelength and ν is the frequency), and readily made obsolete the earlier differential experiment. The 1972 frequency measurement (*18*) of the 3.39-μm CH_4-stabilized laser gave $\nu(CH_4)$ = 88,376,181,627 ± 50 kHz, with the ± 6×10^{-10} limitation due mainly to inadequate laser stabilization. An analogous totally independent measurement at NPL (*19*) gave $\nu(CH_4)$ = 88,376,181,610 ± 70 kHz. The excellent agreement is satisfying, especially since the NPL group used different CO_2 transitions and a different mixing technique in the first step (Josephson junction). To obtain c, one also needs to know the wavelength of the radiation and I now turn to a brief discussion of that determination.

The NBS (Boulder) measurements (*20*) were made by Barger and Hall, who used an interferometer whose length was controlled by the wavelength of a 3.39-μm frequency-offset laser, in turn controlled in frequency relative to the CH_4 saturation peak. The idea behind the wavelength measurement scheme was that for short times the interferometer was stabilized by reference to the CH_4 laser so as to provide a precise measurement of the transmission fringe of either the CH_4-stabilized laser or of the radiation of the krypton standard lamp, which defines the international meter. The fringe of either the laser or the standard lamp was then used to stabilize the frequency of the laser with a slow attack time (approximately seconds). Thus one had the optimum combination of short-term stability from the laser source and the long-term line center information from the fringes of interest.

With the resulting high sensitivity ($\lesssim 10^{-9}$), the accuracy of this measurement was dominated by problems inherent in the krypton-based definition of the meter. We observed a modest radial dependence of the wavelength across the bore of the capillary and confirmed the existence of a small profile asymmetry (*21*). As these problems were unknown when the krypton meter definition was adopted in 1960, there was no convention on how the defined wavelength (6.057 802 106 $\times 10^{-7}$ m) was to be applied to the observed profiles. On the occasion of the 1973 meeting of the Comité Consultatif pour la Définition du Mètre (CCDM), the assembled experts from all the national standards laboratories generally agreed that the "as maintained" definition of the meter corresponds to applying the defined wavelength to the point midway between the peak of intensity and the center of gravity. It was satisfying that on this basis the laser wavelengths reported in meters by all of the participating laboratories were in mutual agreement to within ± 4×10^{-9}. At this level the laser irreproducibility contributes nearly nothing, and one thus has shown that the international meter as used has an uncertainty of about four parts in 10^9.

Since that time several other precision wavelength determinations have been made. In one two-step experiment by Deslattes and his colleagues at the NBS in Gaithersburg, Maryland, the comparison between the krypton and I_2-stabilized visible laser was made with conventional interferometry (*22*) and then frequency-controlled interferometry was used to make the comparison between I_2 and CH_4 (0.633-μm and 3.39-μm wavelengths) (*23*). The achieved accuracy of the second stage was improved by about an order of magnitude over measurements relative to krypton. Another clever idea, introduced by Baird *et al.* (*24*) at the National Research Council of Canada (NRC), was to heterodyne the unknown infrared radiation into the visible by way of sum- or difference-frequency generation in a suitably oriented nonlinear crystal (proustite). In this way, one is comparing wavelengths of a similar magnitude and there is a tendency for some of the systematic errors to cancel. However, high resolution is necessary for the same reason. In one of the most recent experiments of this type, Rowley and his associates (*25*) at NPL used a frequency-controlled Fabry-Perot interferometer to measure the sum and difference frequencies of CO_2 and visible He-Ne lasers. An accuracy of ± 1.4×10^{-9} was obtained for the wavelength ratio. A review of the various frequency-mixing techniques is presented in (*26*).

At the 1973 meeting the CCDM recommended wavelengths for these two lasers: λ_{CH_4} = 3,392,231.40 $\times 10^{-12}$ m and $\lambda_{^{127}I_2,\ \text{peak i}}$ = 632,991.399 $\times 10^{-12}$ m. Both recommended wavelengths have an uncertainty of ± 4×10^{-9} associated with the practical realization of the krypton meter definition. On the basis of frequency measurements of the CO_2 and CH_4 lasers by NBS and NPL researchers, the CCDM was also able to recommend

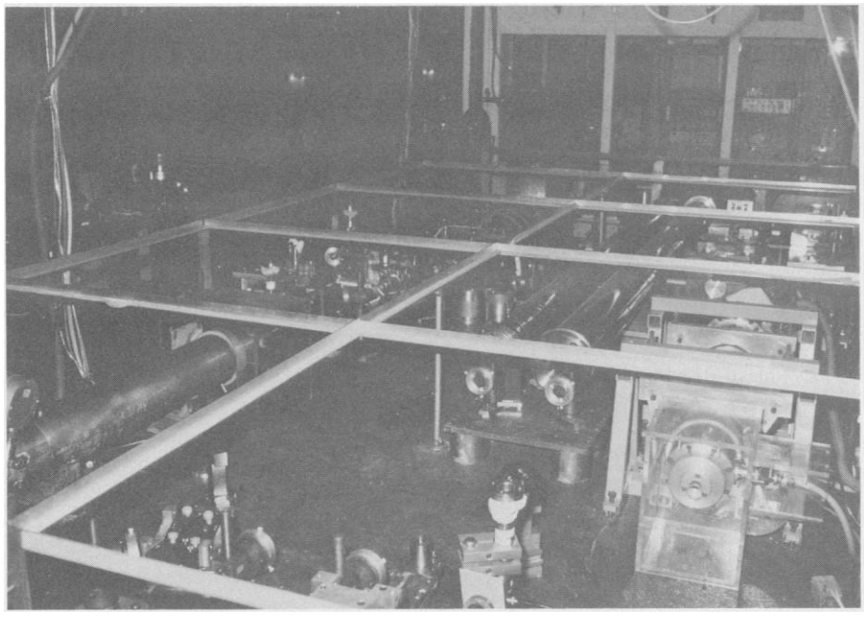

Fig. 1. Frequency-controlled laser spectrometer, Laboratoire de Physique des Lasers, Université de Paris-Nord, Villetaneuse, France. Several highly stable CO_2 lasers of conventional and wave guide design are mounted on a massive vibration-isolated table. The large vacuum chamber (70 cm by 20 m) at the far left contains two independent optical systems of 30-cm aperture for saturated absorption studies. The separate electronics control room (right rear) helps to minimize acoustic and thermal disturbances.

a corresponding value for c (*27*), 299,792,458 m sec^{-1}, again with a $\pm$ 4 $\times$ 10^{-9} fractional uncertainty. This value was in agreement with earlier determinations and had an uncertainty 100 times less. Considering the fundamental role of c in physics and astronomy, spokesmen for the CCDM further expressed the hope that future fine adjustments would be taken in the meter so as to leave c at the recommended value. Certainly there is hope that an appropriate redefinition of the meter may be undertaken soon, but in the meantime precision measurements containing the dimension of length may be preserved with nearly no loss of accuracy if they are referred to the wavelength of a laser stabilized with either CH_4 or I_2. If still higher precision is warranted, the frequency of the laser may be measured relative to the primary cesium frequency standard and the dimensions converted to those of length on the basis of the CCDM-recommended value of c.

At this juncture a philosophical issue arises which is being actively discussed today by the members of the CCDM. The question is whether it is more useful to make a new meter definition based on the (assumed) constant value for c or one based on the wavelength of a particular stabilized laser.

Some people think it is too early to redefine the meter. Improved stabilized lasers are almost sure to be found, and one of overwhelming superiority would be a strong candidate for a meter definition of the same type as has been used before. However, another school of thought prefers a definition based on c, as it enables one to realize the meter with greater or lesser accuracy as the case may require. Several suggestions have been made, and the subject is still under active discussion. For example, one recommendation by the Committee Consultative for the Units (CCU) proposes a definition based on the adopted frequency ($\sim$ 9 GHz) of the standard cesium hyperfine transition and the recommended value for c, 299,792,458 m sec^{-1}. For some people this is not a comfortable definition because precision length metrology implied in a meter definition would be clumsy indeed with a radiation whose wavelength is 3 centimeters (due to diffraction). For astronomers, the travel time of light is a natural distance unit and so a definition that gives the meter as the distance that light travels in some fraction of a second might be attractive. However, in a laboratory scale of distance this proposal suggests a time domain measurement capability that we do not now have. A third alternative for basing the meter on c would be that the wavelength of a coherent optical radiation would be given in meters by the formula $\lambda = c/\nu$, where c has the conventional value (299,792,458 m sec^{-1}) and the frequency of the laser source may be determined with a precision appropriate for the purpose. With this type of definition one could use newly duplicated stabilized lasers as practical standards of length, whereas for the ultimate realization of the meter a laboratory frequency intercomparison against cesium would be indicated. Although at present this intercomparison is an involved procedure, the rapid technical development in this field (*28*) coupled with new proposals (*29*) to further simplify the technique, make it seem reasonable that a definition along these lines would not create major inconveniences. Another point to be considered is that the optical domain may well provide frequency standards of improved performance relative to cesium and so the frequency multiplication problem may be appreciably reduced. At present, it seems that the pressure for improved frequency standards is occurring about equally in the microwave domain (for the global positioning system) and in the optical domain for various fundamental precision measurements, some of which will be described below. Thus, until a new simplified frequency multiplication or division scheme connecting optical and microwave domains is invented, one or the other community will not be totally satisfied.

Stabilized Lasers and Their Application to Spectroscopy

At present, we have three types of stabilized lasers. In the first, an accidental overlap between a laser transition and an absorber line is utilized. The second type has many laser lines overlapping absorber lines since the same molecule is used for both functions. The third type is continuously tunable. The system of this first "accidental overlap" type with the best demonstrated performance is the He-Ne laser at 3.39 μm which saturates The $F_2(2)$ Coriolis component of the $P(7)$ line in the ν_3 band of CH_4 (*7*). The small intrinsic offset between line centers ($\sim$ 100 MHz) may be compensated for by a He-Ne pressure shift or the use of ^{22}Ne in the laser amplifier. As the CH_4 natural line width is $\sim$ 10 Hz, all systems used up to now have been instrumentally limited in their resolution. The principal limit is simply the transit time limitation imposed by the finite laser beam diameter. At JILA, a reasonably serious effort has been made to understand and reduce this limitation (*30*). Our reference He-Ne/CH_4 laser has an internal telescope to magnify the laser mode in the CH_4 absorber, thus producing a strong but narrow ($\sim$ 60 kHz) saturation peak. For an averaging time of 0.1 second, this laser

has a stability of 100 Hz. For shorter times we use a robustly constructed local oscillator laser which has a spectral width of ~ 20 Hz and a drift rate of ~ 100 Hz in 0.1 second. The phase-lock loop transfers this short-term stability (and a modulation wave form) to the telescope laser. Its long-term stability suppresses the drift of the local oscillator laser. The result is that another more powerful laser may be phase-locked relative to the local oscillator laser with an absolute frequency stability and line width of less than 100 Hz.

The experiment of interest performed with this source was the measurement of the recoil spectral doubling in saturation spectroscopy (*10*). The expected kinematic shift $\Delta\nu/\nu = \pm h\nu/2Mc^2$ (1.081 kHz) (where h is Planck's constant and M is the absorber's mass) is a simple consequence of momentum and energy conservation between the radiation field and the free-flying molecule and was first studied by Kol'chenko *et al.* (*31*). To obtain a resolution of this magnitude ($\Delta\nu/\nu \sim 10^{-11}$), it was necessary to use very large, flat wave fronts in the absorption cell. A cascade of three reflective telescopes and spatial filters produced a collimated beam of 24-cm mode diameter, flat to $\lambda/5$ at 3.39 μm. (The confocal parameter is about 25 kilometers.) Low pressure (~ 30 microtorr), necessary to reduce collision-broadening, encouraged the use of a long absorption cell, 13 m in our case. Figure 1 shows a photograph of a similar setup of this type in the Laboratoire de Physique des Lasers in Villetaneuse, north of Paris. (It is more fully described in the section on CO_2 lasers.) Another such external cell system that uses CO_2 lasers is in the Laboratory for Spectroscopy near Moscow (the group of V. S. Letokhov and O. Kompanetz).

The transit time broadening in our cell is calculated to be 670 Hz: lines as narrow as 970 Hz (half width at half maximum) were observed. The x's in the lower curve in Fig. 2 show the derivative spectrum obtained, which has been integrated to provide the top (nonderivative) absorption signal. The basic triplet structure arises from the well-understood hyperfine structure of CH_4 (*32*). The resolution of each hyperfine structure component into a doublet is caused by the recoil effect and shows the direct evidence of quantized momentum exchange between the radiation field and the free-flying molecules. Observation of a doublet structure is rather specific to saturation spectroscopy; three-level saturation reasonances are only shifted, and Doppler-free, two-photon absorption peaks are not affected by recoil. The lower solid line in Fig. 2 is a least-squares fit to the data (x's) and produces a recoil splitting in agreement with the expected 2.163 kHz. Hyperfine constants derived from these optical spectra are in agreement with microwave molecular beam results at the 200-Hz level (*32*). An earlier version of this frequency-controlled laser spectrometer was used to study the hyperfine spectra of a few methyl halide transitions (*33*).

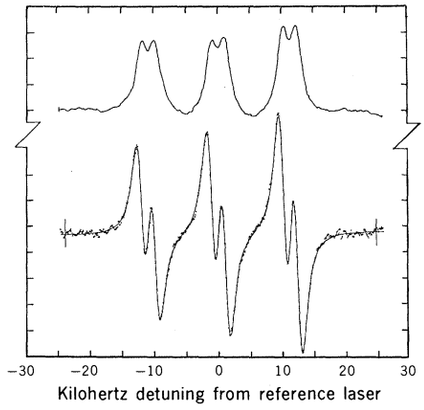

Fig. 2. Ultrahigh resolution spectrum of CH_4. The lower trace (derivative data) shows the three main peaks produced by CH_4 hyperfine interactions, nearly resolved into doublets by the recoil effect. A least-squares fit (bottom solid line) gives a width of 1.27 kHz (half width at half maximum) and a recoil doublet splitting of 2.150 kHz. Methane pressure, 70 μtorr, room temperature, 36-hour signal accumulation. The upper curve, integrated from a sample of such data, shows that each hyperfine component is spectrally doubled by the recoil effect.

Bagayev *et al.* (*34*) have refined the design and operating characteristics of the CH_4-stabilized laser in several important ways. Using two long devices (5 m) of massive construction, they have obtained impressive frequency stability results. Two independently stabilized lasers had a beat frequency phase so slowly varying that it could be plotted with a chart recorder. A laser spectral width of 7 Hz was reported. Long-term stability of 10^{-14} and better can be obtained. Unfortunately, analysis and experiment reveal problems in the connection between the center of the observable laser peak and the idealized Bohr frequency of an isolated molecule (*11*). The dominant offset of $\sim 2 \times 10^{-12}$ is caused by the second-order Doppler shift associated with molecular thermal motion. Saturation spectroscopy is a nonlinear process and results in an enhanced contribution by the slower molecules. Even with a detailed theory (*35*), it seems difficult to reach an accuracy capability below $\sim 2 \times 10^{-13}$ with known techniques.

In addition to the I_2-stabilized laser wavelength measurements against krypton described above, there was an interesting comparison of this laser wavelength and the crystal repeat distance of a special silicon crystal (*36*). Suitable cutting of the single crystal prepared three raised zones to be used as x-ray interferometer mirrors and beam combiners while allowing the microtranslation needed to scan the x-ray fringes. A miniature optical interferometer was translated by the same motion to establish the displacement in laser wavelength units (meters). Finally, these reference crystal lattice measurements were transferred to other crystals and then to the wavelength and energy of the ^{198}Au γ-ray reference line at 411 kiloelectron volts (*37*). An overall accuracy of 0.4 part per million was obtained.

In addition to the well-known He-Ne laser line at 3.39 μm which saturates CH_4 and the He-Ne line at 0.633 μm which saturates I_2, several other systems are known. Work has recently been reported (*38*) on a new overlap in the He-Ne/I_2 system where a prism is used in the laser resonator to force oscillation on the relatively weak 0.61-μm He-Ne line. This orange radiation may be of great future interest since even early experiments gave peaks of high contrast. The overlap of the 0.514-μm Ar^+ laser with the $^{127}I_2$ (43 ← 0) $P(13)$ line is another particularly favorable case and is being actively studied. For example, Ezekial and his colleagues (*39*) have accurately measured line positions by sequentially locking a stabilized Ar^+ laser to the several I_2 hyperfine components in a molecular beam. An equivalent system was used as the frequency reference for the optical heterodyne measurements. Inclusion of nuclear magnetic octopole and scalar spin-spin interactions was necessary to secure agreement approximating the experimental uncertainty of 5 kHz root mean square. More recently, Bordé *et al.* (*40*) have used frequency-controlled saturation spectroscopy to measure the relative positions of these lines with a precision of better than 1 kHz. By also measuring $\Delta F = 0$ transitions sharing a common upper or lower level, Bordé obtained good evidence for the 5.9-kHz recoil shift. The wavelength of such I_2-stabilized Ar^+ lasers has been measured by Spieweck (*41*).

Another visible laser of potentially excellent quality is the optically pumped Hg laser at 564 nanometers. In work at Stanford University, an overlap of the ^{202}Hg laser with a strong $^{127}I_2$ line was identified (*42*). This system may be of particular significance for the highest accuracy capability in that the ^{202}Hg laser

contains no discharge. Consequently, it may be a quiescent and extremely stable medium which should be conducive to improved short-term frequency stability performance. Still another laser absorber system of the accidental overlap type that has been studied recently is the He-Xe laser at 3.5 μm which saturates a strong line in formaldehyde (*43*).

Stabilized CO_2 Lasers

The second general class of stabilized lasers is primarily represented by the CO_2 family. In this system there are a number of different rotational lines within two vibrational bands on which laser action can be obtained. As has been shown by Freed and Javan (*44*), strong narrow saturated fluorescence peaks can be observed in a separate CO_2-containing cell exposed to a standing wave laser field. As there is spectral overlap guaranteed by the identity of the laser amplifier and laser absorber molecules, one has the prospect of many, many lines for frequency standards.

The CO_2 laser systems have a number of interesting properties. First, the approximately 50 consecutive transitions have a spacing of about 50 GHz and provide a rather extended coverage in the 9.6- and 10.2-μm range. Second, differences and sums of the frequencies may be taken to synthesize other frequencies. Finally, even considering the high accuracy of the measurements of the frequencies of these stabilized laser lines, it proved possible to represent their frequencies (to within $\simeq$ 3 kHz) by a simple formula (*45*). Nine molecular constants were derived for each band. In addition, similar measurements have been made on isotope-substituted CO_2 lasers, notably by Freed and his coworkers (*46*). The substitution of ^{13}C for ^{12}C and ^{18}O for ^{16}O provides laser lines that fall in between the usual $^{12}C^{16}O_2$ laser lines. Thus one is never more than about 10 GHz away from one of these reference transitions. Since optical heterodyne techniques can cover frequency intervals of this magnitude, with readily available diodes, one is in the situation of having a usable, known reference line anywhere within a 2.5-THz window at approximately 30 THz.

Although the use of sums and simple differences of these frequencies may be readily imagined by workers in the field, a new and audacious scheme to connect from microwaves to the 10-μm region, using only CO_2 lasers, has recently been demonstrated by Baird at NRC (*47*). In this work, difference frequency currents between CO_2 laser lines are intense enough in the diodes to generate harmonics, so that the difference frequency between two lines, multiplied by a harmonic multiple, is within a microwave frequency of the difference between another pair of CO_2 lines. With five CO_2 lasers and iteration of this bootstrap method, these workers have now managed to reach the 3.39-μm transition without the use of any of the troublesome auxiliary lasers employed in more conventional frequency multiplication setups. Another recent discovery by Reid and Siemsen (*48*) is that it is straightforward to encourage the CO_2 laser to oscillate on the $v = 2$ to $v = 1$ "sequence" band rather than the usual $v = 1$ to $v = 0$ band simply by providing a heated absorption cell within the laser resonator. (The extra population in the $v = 0$ level essentially inhibits oscillation on the usual transition from 1 to 0.) The sequence bands also fall in the 10-μm region and so may also be used as known frequency markers. By going to small capillary bore (wave guide) laser designs, it has proved possible to increase the CO_2 gas pressures sufficiently to provide tuning over frequency intervals of approximately 1 GHz (*49*). In spite of the short length, about 10 cm, such a wave guide laser can produce a power of $\sim$ 1 watt. This wide tuning capability does not yet provide continuous coverage in the 10-μm region, but the windows occupy only about 90 percent of the space now.

The CO_2 lasers also appear favorable for highly refined stabilization techniques since they are powerful lasers and are spectrally quiet. With specially designed and isolated lasers, Freed has obtained CO_2 beat spectra as narrow as $\sim$ 10 Hz (*50*). In the 10-μm spectral region there is a large number of molecules available for saturated absorption studies, notably SF_6, SiF_4, PF_5, NH_4, and NH_3Cl. Perhaps the most interesting ultimate possibility is OsO_4. Kompanetz and Letokhov and their associates have investigated some of these OsO_4 transitions with separated isotopes and identified some of the hyperfine spectra observed (*51*).

A frequency-controlled laser spectrometer with exceptionally high resolving power has been built at the Université de Paris-Nord by Bordé and his colleagues (see Fig. 1). In this apparatus the saturating and retroreflected probe beams are 30 cm in diameter [this was done in an effort to reduce the transit broadening to very low levels ($<$ 1 kHz)]. Spectral resolution below 5 kHz has already been obtained (*52*). Both wave guide and conventional CO_2 lasers are used in this frequency-controlled spectrometer. The optically pumped dimer lasers may provide some of the multiline, self-stabilizing properties of the CO_2 laser in the visible region (*53*).

Continuously Tunable Lasers (Dye Lasers and F-Center Lasers)

Although much interesting spectroscopy has been done based on the very narrow tuning range of gas lasers, restricted by their Doppler line width to a few parts per million, it is clearly attractive to have a more general coherent source which can be tuned to an arbitrary transition wavelength of some particular atom or molecule. Such versatile and general sources form a third class of lasers and are approximated in the visible region by continuous dye lasers, pumped by powerful Ar^+ or Kr^+ lasers. A newly available analog for the near-infrared ($\lambda < 3.3$ μm) is based on Kr^+ laser pumping of appropriate color centers in alkali halide crystals (*54*). The most interesting sources for precision measurements are operated in the single mode: by placing extra frequency-selective elements in the dye laser's optical cavity, the oscillation is constrained to a single frequency. Power conversion efficiency in a single-mode operation may typically be 5 to 10 percent. As a result, rather substantial input power ($\sim$ 2 to 5 watts) is necessary to obtain dye laser output levels in the interesting range of 10 to 100 milliwatts, which provides access to the nonlinear high-resolution techniques such as saturation spectroscopy and two-photon Doppler-free absorption. At present, two major vendors offer tunable single-frequency dye lasers, and one of them (*55*) also provides active servo control circuitry to reduce the instantaneous spectral width of the laser to the neighborhood of 2 MHz ($\Delta\nu/\nu = 4 \times 10^{-9}$). Both laser systems can be electronically swept over frequency intervals $\approx$ 1 cm^{-1} (30 GHz), thus providing coverage of a few dozen typical Doppler line widths. The article in this issue by Schawlow reports many novel and interesting applications of this kind of dye laser technology. Of particular significance for this article are the high-precision measurements of the Rydberg constant and ground-state hydrogenic Lamb shift carried out by Hänsch and his group at Stanford University. Using a pulsed laser, they have already achieved an accuracy of 1×10^{-8} in the determination of the Rydberg constant (*56*), the fundamental constant which expresses the scale of atomic energy levels in terms of the macroscopic

Système International d'Unités (SI units). The Lamb shift of $n = 1$ and 2 in H and D atoms has recently been measured with a continuous wave laser source; pulsed dye amplifiers were used to reach the intensity necessary to excite the two-photon transition from 1*s* to 2*s* (*57*). For the future a more benign environment for the H atoms will be necessary, perhaps an atomic beam, coupled with known spectroscopic and interferometric techniques of improved accuracy. Certainly improved values of the Lamb shift will be determined, along with a further-improved Rydberg constant limited, most likely, by the inadequate present definition of the meter. It seems quite possible that these advanced measurements, when carried out for both H and D atoms, can also lead to an improved value for the ratio of the electron mass to the proton mass.

From the viewpoint of generality, the dye lasers are ideal. We can cover 500 angstroms with a single dye, and enough dyes are available to totally cover the wavelength interval from 440 to 900 nm. But from the viewpoint of stability and precision measurements generally, it is madness to include a liquid dye cell or free-flowing jet in an optical resonator: the thickness or density variations will be transformed into frequency noise in the laser output. For dye lasers of moderate output (> 50 mW), the necessary high input power will lead us to be interested mainly in jet stream lasers (to avoid damage to the cell windows). In this case frequency variations of perhaps 30 MHz may be expected, due primarily to low-frequency modulation of the upstream pressure of the jet. With suitable hydraulic filtering and passive stabilization of the laser resonator, line widths in the range from 5 to 1 MHz may be expected. Alternatively, a frequency servo of modest bandwidth (10 kHz) may be used to achieve the same 1-MHz resultant line width. Such a laser system is now commercially available (see above). However, to narrow the laser line width further becomes a more interesting and more difficult problem because of the high Fourier frequency at which the thickness variations in the jet can occur. For example, if we assume a servo bandwidth of 10 kHz, the frequencies above 10 kHz will not be suppressed by the servo and the laser line width will likely be 1 MHz. If we assume a servo bandwidth of 100 kHz (which can be achieved with suitably designed miniature piezoelectric transducers), the dye laser line width can be about 250 kHz.

Another technique for reaching the same kind of bandwidth is the use of an acousto-optical frequency shifter outside the laser resonator to perform a posteriori correction of the laser frequency (*58*). The output of this system is taken, for example, as the first-order Bragg side band, upshifted in frequency by the r-f applied to the acousto-optic transducer. Thus, deliberate variation of the r-f frequency can compensate for unplanned laser frequency changes such that the sum frequency is constant. The bandwidth of this system, and consequently the laser spectral width, is similar to that obtainable with sophisticated piezoelectric transducers operating on one of the laser cavity mirrors. However, for some purposes the acousto-optic stabilizer is more attractive in that variation of the intensity of the r-f drive applied to the transducer maps into intensity variations of the utilized first-order Bragg side band. It is thus possible for the one device to simultaneously stabilize the laser's frequency and intensity. Useful optical isolation is also provided by the frequency shift.

Superstable Dye Lasers

Although for some purposes the 0.25-megacycle line width obtainable this way is quite satisfactory, for the high-precision experiments of interest in this article a more rapid servo is required to further spectrally narrow the laser. The best technique presently known is the use of an intracavity laser phase modulator, based, for example, on the crystal ammonium dihydrogen phosphate in a transverse cut which is free of piezoelectric resonances. With appropriately designed, fast, low-noise amplifiers, it has proved possible to reach frequency servo-controlled bandwidths of ~ 1 MHz giving a ~ 10-kHz dye laser line width (*59*) and more recently ~ 3-MHz bandwidth giving approximately a ~ 2-kHz line width for the dye laser (*60*). It seems quite possible to reach a control bandwidth of about 5 MHz, in which case the dye laser line width should be around 800 Hz. This will be essentially a limiting value for this type of stabilization because the shot noise in the laser signal monitored will be interpreted by the control system as a frequency variation of this magnitude. The continuous wave dye laser systems producing high power and having spectral widths below this approximately 1-kHz limit will most likely be based on frequency measurements of the power dye laser relative to a low-power but vastly more stable dye laser or perhaps an optically pumped gas laser. Experiments along these lines are being considered at JILA and in Garching, West Germany.

The present general concept of laser stabilization is to use a passive, high-finesse Fabry-Perot resonator which is constructed so well that its eigenfrequency will not rapidly change. The dye laser is controlled to the side of the transmission fringe of the interferometer so as to transduce a frequency variation into an intensity variation. A comparison intensity is provided to the servo electronics through an optical circuit containing only an attenuator. This servo drives the laser frequency to produce equal light signals through the attenuator and through the resonator so as to lock, say, at the 50 percent transmission level of the resonator. When the laser is thus locked to this cavity, it has a spectral width, dependent on the speed of the control system, which can be as narrow as 2 kHz with contemporary designs.

Now we must address the issue of tuning this cavity and thereby the dye laser and of suppressing its long-term drift. In some special cases the investigated line itself can provide information on how to do this (*61*), but in general we must rely on another source of stability and tuning control. The best method known at present makes use of a stabilized laser based on either CH_4 or I_2. For example, the He-^{22}Ne laser locked on the B peak of $^{129}I_2$ gives a nice saturated absorption peak with a signal-to-noise ratio of about 500 in a 10-millisecond integrating time. The 4-MHz third derivative line width of this peak gives us a stability of about 1 kHz for a 1-second integrating time. With this radiation we can also lock the dye laser's reference cavity and consequently stabilize the dye laser to essentially this precision. Unfortunately, we also want to tune the dye laser and it is thus necessary to introduce another laser into this scheme. The simpler choice is to introduce another gas laser operating, say, on ^{20}Ne which is heterodyned with the I_2-stabilized laser and controlled such that the beat frequency must track the output frequency of a programmable frequency synthesizer. The output wavelength of this auxiliary laser is used to control the dye laser's reference cavity or an auxiliary resonator. Thus, as the programmable synthesizer is stepped from one frequency to the next, the local oscillator laser changes its frequency and the resonator in turn changes its length, thus scanning the dye laser. The frequency steps introduced into the dye laser are modified by the wavelength ratio of the dye laser and the local oscillator laser, but this is a well-known quantity. Although this concept is rather elaborate

and expensive, it provides performance which cannot be obtained by any other method at the present time.

An alternative technique makes use of a second dye laser rather than a second gas laser. In this scheme one locks the transfer cavity to the I_2-stabilized laser and the auxiliary dye laser to the transfer cavity. The powerful dye laser is then controlled by its optical heterodyne with the stabilized dye laser. This system has the advantage of direct calibration of the frequency scan in megahertz, but by the same token it requires a very expensive frequency synthesizer with a wide tuning range for the scan.

Dye Laser Wavelength Readout

One of the essential problems in dye laser spectroscopy is knowledge of the laser wavelengths. The laser can tune perhaps 500 Å in the visible, and within each angstrom are something like 100 typical Doppler line widths of a gas sample. Thus, if one is looking for a narrow weak resonance, some type of high-accuracy wavelength readout will be an essential tool. At first, spectrometers were used in conjunction with wavelength calibration lines from suitable spectral lines, but instruments of adequate resolving power are very large and expensive. Thus almost every laboratory seriously concerned with dye laser spectroscopy has addressed the wavelength readout problem, and there are nearly a dozen resulting schemes (*62*). One interesting technique (*63*) works with either a continuous or a pulsed laser in the accuracy domain up to approximately 10^{-7}. This instrument views in reflection wedge fringes formed by two closely spaced uncoated interferometer flats. The fringes are imaged onto a multielement solid-state photodiode array. A minicomputer processes the fringe period to give the integer fringe order in the interferometer and processes the fringe phase to refine the wavelength value. Another ingenious instrument, called a sigma-meter (*64*), measures optical wave numbers by a polarization-sensitive interferometer. A clever mixture of analog and digital processing allows one fringe, representing perhaps 500 MHz, to be subdivided while fringe multiples may be totaled in a suitable counter. This instrument can be used for real-time laser control as well as readout. Another popular type of interferometer is based on a scanning Michelson design where "cat's eyes" or retroreflectors are used to obviate the alignment problems. For a resolution of about $\delta\lambda/\lambda \simeq 10^{-6}$, a convenient design can be based on the use of an air track so that no rolling friction and vibration problems need be addressed (*65*). For much higher resolution, a technique of optical r-f phase-locking was introduced to provide an electrical analog of the optical fringes but with 100 times higher resolution (*66*). This lambda meter design has recently been shown to provide accuracy of a few parts in 10^8, and it seems possible that an improvement by an order of magnitude could be rather directly realized.

An experiment that shows the accuracy of the lambda meter in a convincing way was based on two-photon excitation of Rydberg levels in rubidium (*67*). In this experiment Lee *et al.* measured the wavelengths at which two photons of the dye laser excited rubidium atoms from *5s* to *ns* Rydberg levels. These transition wavelengths were measured for principal quantum members between $n = 13$ and $n = 50$. It may be expected that this one electron spectrum can be well represented by the quantum defect formulation, and we found that this was indeed true even at a precision level of three parts in 10^8. It was found necessary to include two energy-dependent terms in the quantum defect in order to adequately represent these levels. From one point of view it is rather surprising that four constants can serve to represent the energies of an atom with such a high precision: two digits specifying the principal quantum number punched into a hand-held calculator can result in an eight-digit wavelength display accurate to within our present wavelength measurement capability of $\sim 3 \times 10^{-8}$. This is clearly an attractive case of information condensation. It would be interesting in future experiments to measure the *D* levels of rubidium and, by using optical second harmonic generation, to also measure the *P* level positions. One can in this way derive an unambiguous value for the ionization potential of the alkali rubidium.

Ultrahigh-Resolution Dye Laser Spectroscopy

Another interesting current application of these Doppler-free, two-photon transitions to Rydberg levels is as a proving ground for various extremely high-resolution techniques, notably the optical Ramsey fringe method (*68*). The basic idea is similar to Ramsey's suggestion in the microwave domain. An atom is exposed to two radiation fields, separated in time. Each interaction produces a quantum-mechanical amplitude for reaching the excited state. The field ionization process used for detection is sensitive only to highly excited atoms. In consequence of the two separated interactions, the wave function of the atom has an excited state component produced by each of these interaction channels: in the excited state probability we thus expect to observe interference terms between the first and second interactions. Essentially after the first interaction we may view the isolated atomic system as an atomic clock precessing at its own natural frequency, while the laboratory oscillator is developing phase at a rate defined by its frequency. When the atom comes into the second radiation field, it may be again in phase with the driving field and so be further driven toward the excited state, or it may be out of phase and so returned to the ground state. The tuning sensitivity of the phase comparison is enhanced by the number of cycles that have elapsed while the atom was in the darkness. By increasing the separation of the light beams to large values, it is expected that very narrow Ramsey fringes ($\approx$ kilohertz) can be produced. At the present time the Rydberg levels of atoms form a good testing ground for this concept as we may vary the contributions of the decay processes to the Ramsey fringe width using the known $(n^*)^3$ lifetime dependence. Two-photon Ramsey fringe (full) widths of 17 kHz have been observed (*69*). Interesting future applications of the two-photon Ramsey method may be to two-photon transitions with very long lifetimes such as those in Bi, Ag, and Hg^+ (*70*). Some good (transit-limited) two-photon signals have already been obtained in Bi (*71*).

Analogous "Ramsey" interference fringes are expected (*72*) and have been observed (*73*) in saturation spectroscopy. Additional considerations relating to spatial phase and Doppler frequency shifts give rise to the necessity for at least three equally spaced excitation zones in saturation spectroscopy. Figure 3 shows these Ramsey fringes observed with a cw dye laser exciting the Ne 588-nm transition from $1s_5$ to $2p_2$ in a fast atomic beam (*73*). Trace a shows most of the beam Doppler profile with the Lamb dip at its center, with Ramsey fringes superposed. Use of only two excitation regions (trace b) gives a Lamb dip only. With three illuminated zones (trace c) the Ramsey fringes are clearly visible. Trace d corresponds to the use of four equally spaced interaction regions. Although high resolution is not expected in these demonstration experiments with a short-lifetime Ne transition, the principle and techniques are directly applicable to

very-high-resolution studies. The results are themselves interesting in connection with a relativistic time dilation experiment described below.

Probably the best presently known candidate for an optical frequency standard is the Ca intercombination transition at 6573 Å (*74*). Using three-zone Ramsey excitation (*72, 73*) in saturation spectroscopy of a Ca atomic beam, Barger and his colleagues have recently totally resolved the recoil splitting (23 kHz) (*75*). A line width of $\simeq$ 9 kHz was obtained. The second-order Doppler shift can be estimated from the shape of the secondary Ramsey maxima, so that an absolute accuracy capability of $\sim 10^{-14}$ may be confidently expected.

A provocative recent experiment (*76*) with two illuminated zones showed useful optical Ramsey fringes in the linear interaction domain. Basically a photolithographic grid with a period of $\lambda/2$ was used to block the flight of molecular beam CH_4 molecules that would otherwise contribute Ramsey fringes of reversed polarity. Thus it may be feasible to use mechanical rather than nonlinear optical techniques at the longer wavelengths to obtain nonzero net fringes after averaging.

In the more distant future, the use of Penning magnetic ion traps and ionic species may prove to be the method of choice. The Ramsey optical excitation pulses will then be separated in time. The interesting possibility for the long term is that the isolation attainable with the trapping technique may make it feasible to use radiative interactions to modify the velocity distribution, in particular, to cool the ions so as to lower the second-order Doppler shift ($1/2\ v^2/c^2$). Although several investigators have considered radiative cooling processes (*77*), it is only recently that definitive experimental cooling has been demonstrated. In this case Mg^+ ions were cooled to about 10 K (*78*).

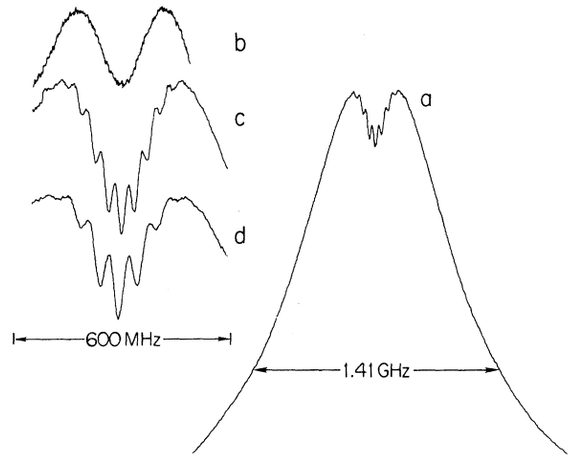

Fig. 3. Ramsey interference fringes, viewed in fluorescence from a fast Ne beam: (a) Most of the beam Doppler profile (full width at half maximum = 1.41 GHz), showing saturation dip and Ramsey fringes; voltage, 19.5 kV; fringe contrast, ~3.8 percent. (b) Saturation dip observed with two separated laser beams. (c) Ramsey fringes and saturation dips at 35 kV with three beams. (d) Ramsey fringes and saturation dips at 35 kV with four beams.

Relativity Experiments with Stabilized Lasers

As I mentioned at the beginning of this article, special relativity has provided a strong stimulation for the development of stabilized laser techniques. We perhaps are now coming full circle whereby these laser techniques may be used for modern experimental tests of the postulates of special relativity. In fact, three such experiments are under way now. In the relativistic time dilation experiment at JILA, the Ramsey fringe technique is being used to provide high-resolution information about the proper frequency of moving atomic clocks. In this experiment a Ne transition from $1s_5$ to $2p_2$ forms the atomic clock, and the Ne atoms can be accelerated to velocities of $\leq 3 \times 10^{-3}$ of c. (These high velocities are produced with good precision by accelerating Ne^+ from a suitable ion source and focusing the ion beam through a charge-transfer oven containing Na vapor.) Basically this experiment measures the relativistic time dilation, or it may be alternatively viewed as measuring the second-order Doppler shift. Our present knowledge of the validity of the relativistic Doppler shift formula is based on experiments with optical (*79*), Mössbauer (*80*), meson-beam (*81*), and meson-storage (*82*) techniques. Although the Mössbauer experiment had high resolution, the velocity was rather small. The meson experiments measured a decay lifetime increase with velocity. Their accuracy was limited by counting statistics and other factors. Each of the first three experiments provides about 0.5 percent accuracy checks of the dilation term. The storage ring experiment (*82*) checked the relativistic increase of the μ-meson lifetime at an accuracy of 0.1 percent. The accuracy achieved in the first laser measurement (*83*) was ~ 0.5 percent. (We had a natural line width of about 5 MHz and a relativistic time dilation shift of almost 1400 MHz.) Using the Ramsey fringe technique (*72, 73*), we now have a measurement precision at each beam accelerating voltage of better than 100 parts per 10^6 and we are optimistic that a significant improvement in our knowledge of the relativistic time dilation will be obtained from these experiments.

Another very interesting research area is large-scale spatial anisotropy. For example, Smoot (*84*) and his colleagues have recently shown that the solar system is apparently not at rest with respect to the cosmic blackbody radiation. Early in the evolution of the universe, a stage of expansion (or critical density) was reached beyond which the radiation bath was no longer tightly coupled to the matter. By continuing expansion this radiation has been frequency-shifted down to the microwave domain. It seems reasonable to wonder if the isotropy of the presently observed blackbody radiation (after correction for our motion) may perhaps carry information about a preferred inertial reference frame. Thus it is interesting to apply the highest-sensitivity techniques to look for small preferred frame effects or other breakdowns of isotropy. One ingenious experiment of this type being pursued by J. G. Small and P. Franken at the University of Arizona uses two CH_4-stabilized lasers on a rotating table. They look in the r-f domain for a phase shift which could arise from a one-way anisotropy in the speed of light. Basically the optical phases of the two independently stabilized lasers are compared in two photodiodes at the ends of a reciprocal 1-m transmission path. The differences in these two phases will then carry the spatial signature of a cosmic anisotropy in the speed of light (*85*).

At JILA, A. Brillet and I are making a new measurement of the Michelson-Morley type. In our experiment a 3-μm He-Ne laser is tightly locked to a very stable isolated Fabry-Perot resonator. A length change of this length etalon—whether cosmic or accidental—gives a laser frequency shift. This stable reference interferometer, the laser, and all its optical and electronic accessories are mounted on a shock-isolated table rotating once every 10 seconds. Electrical power and diagnostic signals are communicated through pins dipping into mercury-filled circular channels at the base of the rotating table. We use frequency metrology to read out the wavelength of

the stabilized laser: a portion of its output is diverted up along the rotation axis of the table and is directed over to a large floating table on which our "in-house CH_4-stabilized frequency standard" is constructed. The stability of this laser is approximately 30 Hz for a second of averaging time. The same stability is reached by our cavity-stabilized laser on the rotating table. The experiment consists of recording as a function of sidereal time the beat frequency between the "length-stabilized" laser and the "atomic physics–stabilized" laser. Each frequency measurement is triggered from the angular position of the table and is totally resynchronized once each turn. At present, we see a small spurious signal with an amplitude of ~ 500 Hz and a frequency of once per turn which is evidently associated with some laboratory-fixed environmental factor. The cosmic signal is expected to exhibit two cycles per table revolution [$P_2(\cos\theta)$]. At present, we see no signals as large as 10 Hz carrying this signature. With the recent improvements in the rigidity of the rotating structure, we expect our data acquisition periods to be lengthened to several weeks at a time, thus making possible much more sensitive measurements. The sensitivity of this experiment, even in its rather early present form, is an improvement of nearly 100 times over the useful sensitivity of the MIT Michelson-Morley experiments of 1964. Although nearly 15 years have passed since these classic experiments were published, the interval has provided time for the conceptual and technical development of new laser techniques which will enable the high promise of this early time to be realized in many precision physical measurements.

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86. In a summary article of this type it is nearly impossible to avoid some parochialism of interest, and I apologize to those whose work I have omitted or presented in an inadequate manner. I am indebted to the following colleagues for discussions and collaboration: R. L. Barger, P. L. Bender, C. J. Bordé, K. Uehara, S. A. Lee, J. C. Bergquist, and J. Helmcke.