6. Laser Frequency Measurements, the Speed of Light, and the Meter*

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With 5 Figures

The spectral characteristics of electromagnetic radiation are determined by either its vacuum wavelength or its frequency (and, of course, the speed of light is the product of the two). Before the advent of lasers, infrared and visible spectra were measured using wavelength techniques. Lasers have fractional linewidths approaching those of radio and microwave oscillators and have many orders of magnitude more spectral radiance than incoherent sources, as shown in Fig. 6.1; thus, direct frequency measuring techniques as well as wavelength techniques can be used and the frequency techniques provide much more resolution and accuracy in measuring the spectral characteristics of the radiation. Frequency measuring techniques are limited only by the accuracy of the fundamental standard and the stabilities of the sources available and, as a result, are better by several orders of magnitude. Hence, lasers which provide intense coherent sources of electromagnetic radiation extending from the microwave through the visible to the ultraviolet portion of the electromagnetic spectrum (see Fig. 6.2) can be considered as either wavelength or frequency sources.

In spite of the fact that lasers provided coherent frequency sources in the infrared and visible, frequencies could not immediately be measured because no device capable of generating frequencies of a few THz from harmonics of cw sources was known to exist. Secondly, the laser frequency was not very stable; that is, in the case of the gas laser although its short term linewidth was a few hundred hertz, over a long period, its frequency could vary within the Doppler and pressure broadened gain curve of the laser. This gain curve might vary from less than a hundred to several thousand megahertz depending on the laser. Therefore, even though the instantaneous frequency of the laser could be measured, there was no reference point other than the broad gain curve whose center could not be located very precisely. Happily, solutions to both of these problems were found: for the first, the extension of frequency measurements into the infrared by means of the metal-on-metal point contact diode [6.1], and for the second, the development of the technique of

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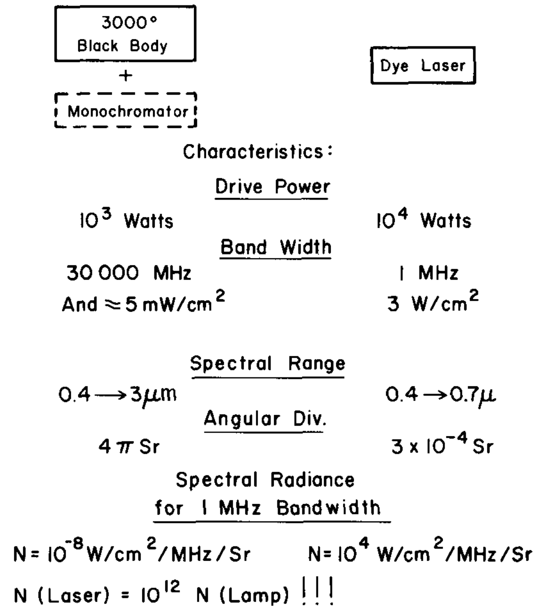

Fig. 6.1. Comparison of tunable light sources. The laser is characterized by its small spectral band width and angular divergence resulting in a large spectral radiance per unit band width. The narrow tuning-range disadvantage of a typical gas laser is to a large extent being removed by the development of the dye laser

saturated absorption [6.2] (see e.g. Subsect. 1.4.2). These two developments meant that coherent, highly stable, short wavelength sources of radiation existed whose frequency and wavelength could be directly related to the primary frequency and wavelength standards.

With the perfection of highly reproducible and stable lasers, their wavelength-frequency duality becomes of wider interest. We begin to think of lasers as frequency references for certain kinds of problems such as high resolution optical heterodyne spectroscopy [6.3]. The extension of absolute frequency measurements, linking the cesium standard (accurate to about 2×10^{-13}) [6.4] to these lasers, provides accuracy as well as resolution to the absolute frequencies involved. At the same time, we use the wavelength aspect of the radiation, for example, in precision long-path interferometry [6.5]. Indeed, the increasing resolution which these new spectroscopic techniques provide may very well usher in an era of precision and accuracy in frequency and length measurements undreamed of a few years ago.

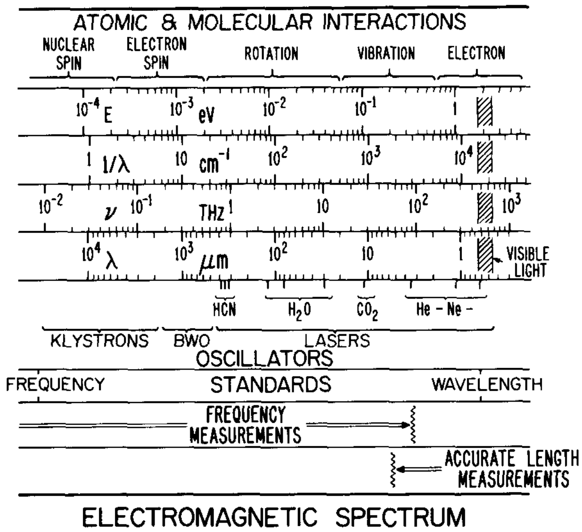

Fig. 6.2. The electromagnetic spectrum showing oscillators, frequency and wavelength standards, and measurement regions. The extension of frequency measurements into the infrared has produced an overlap of the accurate ($<4\times10^{-9}$) wavelength measurement region and the frequency measurement region for the first time. The frequency standard is the zero field hyperfine structure separation in the ground state of ^{133}Cs which is defined to be 9 192 631 770 Hz. The wavelength standard is the transition between the $2p_{10}$ and $5d_5$ levels of ^{86}Kr with the vacuum wavelength of this radiation defined to be 1/1650763.73 m.

Recent advances in stabilizations with saturated absorption techniques (see Chapter 1) have produced lasers with one-second fractional frequency instabilities [6.2] as small as 5×10^{-13}. Although the fractional uncertainty in frequency reproducibility is somewhat larger, stabilized lasers are already excellent secondary frequency standards. With additional development in laser stabilization and infrared frequency synthesis some of these devices can be considered as contenders for the primary frequency standard role; the 3.39 μm He–Ne laser, for example, currently has a fractional frequency uncertainty in reproducibility [6.2] of less than one part in 10^{11}. The duality implies that the radiation must have a similar wavelength characteristics, i.e., $\Delta\lambda/\lambda\approx10^{-11}$ which is more than 100 times better than the current length standard [6.6]. Hence, the stabilized laser must be considered to have tremendous potential in wavelength as well as frequency standards applications and perhaps in both [6.7].

It has been clear since the early days of lasers that this wavelength-frequency duality could form the basis of a powerful method to measure the speed of light. However, the laser's optical frequency was much too high for conventional frequency measurement methods. This fact led to the invention of a variety of modulation or differential schemes, basically conceived to preserve the small interferometric errors associated with the short optical wavelength, while utilizing microwave frequencies which were still readily manipulated and measured. These microwave frequencies were to be modulated onto the laser output or realized as a difference frequency between two separate laser transitions [6.8]. Indeed, a proposed major long-path interferometric experiment [6.9] based on the latter idea has been made obsolete by the recent high-precision direct frequency measurement [6.10]. An ingenious modulation scheme, generally applicable to any laser transition, has recently produced successfully an improved value for the speed of light [6.11]. While this method can undoubtedly be perfected further, its differential nature leads to limitations which are not operative in direct frequency measurements.

Recent ultrahigh resolution measurements of both the frequency and wavelength of the methane stabilized He–Ne laser yielded a value of the speed of light 100 times more accurate [6.12] than that of the previously accepted value [6.13]. This significant increase in accuracy was made possible by the extension of frequency measurements to the region of the electromagnetic spectrum where wavelength measurements can be made with high accuracy and by the use of very stable lasers.

It is the purpose of this chapter to describe the stabilization of lasers by saturated absorption, laser frequency measuring techniques, experimental details of the speed of light measurement, and some possibilities for a new standard of length.

6.1. Stabilization of Lasers by Saturated Absorption

Homogeneous as well as inhomogeneous broadening in gas lasers results in gain curves which are many MHz wide while cavity linewidths are of the order of only 1 MHz. Therefore, the frequency of a gas laser is determined within the confines of the gain curve largely by the optical path length between the mirrors. The fractional frequency instability is equal to the fractional change in optical path length, and since it is difficult to keep this parameter less than one part in 10^{-7}, passively stabilized lasers have in general been free to drift many MHz over long periods of time.

The best short term stability is obtained by taking steps to control the optical path length between the mirrors. These steps have included use of cavity materials with near zero expansion coefficients, cavity

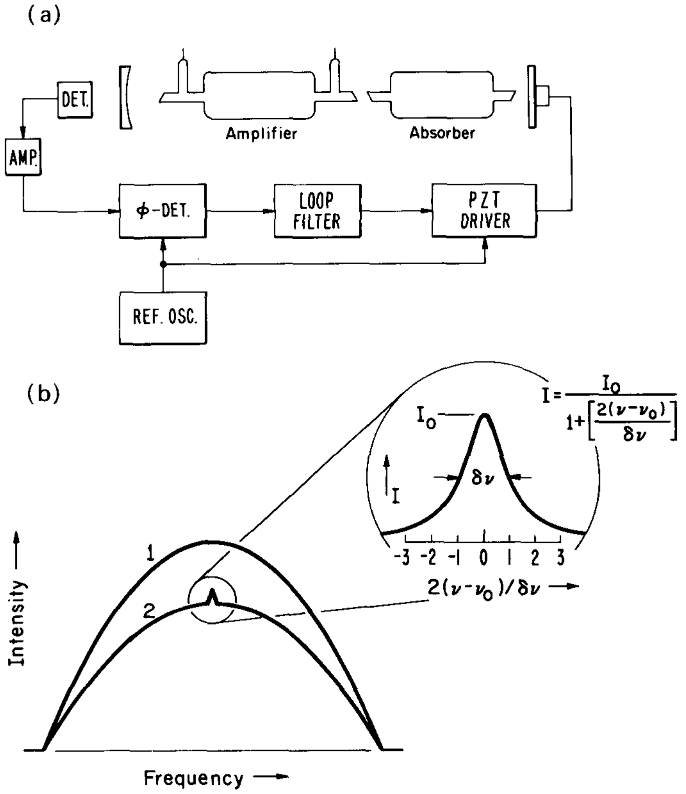

Fig. 6.3a and b. Schematic for laser stabilization by the technique of molecular saturated absorption. Diagram (a) shows the servo-controlled laser with an internal molecular absorption cell. Diagram (b) shows 1) the gain curve of the laser without absorber, and 2) the gain curve of the amplifier-absorber combination. The frequency of the laser is locked to the peak of the narrow "emission-type" feature shown on curve *2*

temperature control, isolation from mechanical and acoustic disturbances, as well as other ingenious ideas and devices. Also in a discharge excited gas laser, it is necessary to use a highly stabilized power supply in order to maintain a constant index of refraction. Some of the most sophisticated passively stabilized gas lasers have been designed by FREED and the interested reader is referred there [6.14] for more details. The observed spectral width is always controlled by environmental perturbations giving rise to frequency modulation. However, with care, lasers with short term spectral linewidths of the order of a kHz can be constructed.

Long term stability of laser oscillators can be attained by servo controlling the frequency to some more stable reference device. For example, long term stability may be provided by locking the laser to the resonant frequency of a temperature controlled, mechanically and thermally stable, passive cavity. However, for good resetability a molecular reference which is less subject to environmental perturbations is more suitable, provided that Doppler and pressure broadening can be eliminated or at least greatly reduced. Molecular beam type devices suggest themselves. However, the molecular saturated absorption technique attains nearly the same goal and yet avoids most of the experimental complications of beam devices. With lasers, the technique was first demonstrated by LEE and SKOLNICK [6.15] with the 6328 Å laser and a ^{20}Ne absorption cell excited by a dc gas discharge. Later a similar technique was developed by BARGER and HALL [6.16] with the 3.39 μm He–Ne laser to the point where one second fractional frequency instabilities are now only a few parts in 10^{13}. A schematic for laser stabilization by the technique of saturated absorption is shown in Fig. 6.3a + b. Since the linewidths are inversely proportional to the molecular transit time across the laser beam, HALL and BORDE [6.3], by increasing the diameter of the laser beam and cooling the absorption cell, have observed saturated absorption lines which are only 7 kHz wide. This refinement represents a resolution greater than 10^{10} and is narrow enough for observation of the methane hyperfine structure. Other lasers of interest here wich have been stabilized by saturated absorption include the 6328 Å laser which has been locked to various iodine absorption lines [6.17] and all of the lines in both the 9 and 10 μm bands of the CO_2 laser which have been stabilized to CO_2 itself [6.18, 19].

Since the wavelength of the radiation coming from an oscillator is simply related to the frequency through the velocity of propagation, it is reasonable to assume that the wavelength stability will be the same as the frequency stability. Moreover, since the coherence length is inversely proportional to the spectral linewidth of the radiation source, lasers are excellent wavelength standards. Thus we have laser oscillators which are excellent secondary frequency and wavelength standards at a number of convenient points in the electromagnetic spectrum. The frequencies of all the aforementioned molecular stabilizing transitions except those at 6328 Å have been measured absolutely [6.10, 20] to an accuracy exceeding that of the length standard.

6.2. Frequency Measurement Techniques

Direct frequency measurements require counting the number of cycles of electromagnetic radiation in a given period. Modern electronic circuitry permits direct cycle counting up to about 500 MHz with the timing generally provided by a quartz crystal oscillator, or for the highest accuracy, directly by a cesium clock. A measurement of a higher frequency requires a heterodyne technique in which two oscillators (one whose frequency is known) are mixed together so that a countable frequency difference is generated. The known frequency may be synthesized as an exact harmonic of a directly countable lower frequency by irradiating an appropriate nonlinear device. To synthesize microwave frequencies, oscillators of about a hundred MHz irradiating a silicon diode will generate useful harmonics as high as 40 GHz. The desired harmonic is generally mixed with the unknown frequency in the same diode so that the heterodyne beat note of a few MHz is finally generated and can be directly counted.

The above process may be illustrated in the following equation

$$\nu_x = l\nu_a \pm \nu_b , \tag{6.1}$$

where ν_x is the unknown frequency, ν_a the reference frequency, and ν_b the countable beat note frequency. The harmonic number l is generally determined by making an approximate frequency determination from a wavelength measurement. At frequencies from about 40 GHz to 1000 GHz (1 THz), the silicon diode is still operable; however, several steps are usually required in a frequency measurement chain extending from some countable reference frequency. For this purpose, klystrons between 60 and 80 GHz are often phase locked to a lower frequency klystron and these are used to cover the range between 200 and 1000 GHz with less than 15 harmonics in each step. The harmonic number is kept below 15 because at frequencies above a few hundred gigahertz the overall harmonic generation-mixing process is less efficient and consequently, one must use a lower harmonic number.

6.3. High-Frequency Diodes

In addition to the silicon diode already mentioned, another type of harmonic generator mixer, the point contact Josephson junction, is a much more efficient diode in the generation of high harmonics than is the silicon diode. Its use has been extended a little higher in frequency than [6.21] the silicon diode to 3.8 THz by the direct generation of the 401*st* harmonic from an X-band source. Work is continuing on this device to determine its high frequency limit.

A third type of harmonic generator-mixer, the metal-metal diode, is the only device which has been used at frequencies above 3.8 THz. This metal-metal point contact diode has been the most useful at laser frequencies, and has, thus far [6.22], operated to 88 THz (3.39 μm). High frequency applications of this diode were first demonstrated in Javan's laboratory [6.1] by generating and mixing the third harmonic of a pulsed water vapor laser with a CO_2 laser. Specifically, the tungsten-nickel diode has been more useful than many other metal-metal combinations which were tested. At these laser frequencies, harmonic generation, sideband generation, and mixing occur in the same diode, that is, the harmonics or sidebands are not actually propagated from diode to diode, but a single diode is radiated with all of the necessary frequencies. As an example, one of the steps in measuring the frequency of a CO_2 laser is to compare the frequency of its 9.3 μm $R(10)$ line with the third harmonic of a water vapor laser.

In this case,

$$\nu_{\mathrm{CO_2},R(10)} = 3\nu_{\mathrm{H_2O}} - \nu_{\mathrm{kly}} + \nu_{\mathrm{beat}}, \tag{6.2}$$

where $\nu_{\mathrm{CO_2},R(10)}$ is the unknown frequency (32.134267 THz), and $\nu_{\mathrm{H_2O}} = 10.718069$ THz, $\nu_{\mathrm{kly}} = 0.019958$ THz, $\nu_{\mathrm{beat}} = 0.000020$ THz. In this heterodyning, the radiation from all three sources simultaneously irradiates the diode and the resulting 20 MHz beat note is amplified and measured in a counter or spectrum analyzer.

Some characteristics of this type of diode have been measured [6.23], and so far, attempts at extending its range to the visible have shown that it mixes at frequencies as high as 583 THz (5145 Å). However, harmonic generation beyond 88 THz has not been demonstrated. Although the exact physical mechanism by which the harmonic generation-mixing occurs is not yet understood, there are at least three different possible explanations for the phenomena. One is a tunneling process through an oxide layer [6.24], another is a field emission process [6.25], and a third is a quantum mechanical scattering model [6.26].

To illustrate the way in which the diode is used in laser frequency measurement, a direct measurement of the methane transition used to stabilize the 3.39 μm He–Ne laser will be described. It is this frequency which is multiplied by the precisely determined methane wavelength to yield a definitive value of the speed of light.

6.4. The Speed of Light

The speed of light, c, is possibly the most important of all the fundamental constants [6.27]. It enters into the conversion between electrostatic and electromagnetic units; it relates the mass of a particle to its energy in the well known equation $E = mc^2$; and it is used as well in many relationships connecting other physical constants. In ranging measurements, very accurately measured transit times for electromagnetic waves are converted to distance by multiplying by the speed of light. Examples are geophysical distance measurements which use modulated electromagnetic radiation [6.28], and astronomical measurements such as microwave planetary radar and laser lunar ranging [6.29]. Recent experiments have set very restrictive limits on any possible speed dependence on direction [6.30] or frequency [6.31].

Because of its importance, more time and effort have been devoted to the measurement of c than any other fundamental constant. In spite of this fact, a highly accurate result has remained elusive even in recent times—mainly because of ever present systematic errors which have been difficult to properly evaluate. Indeed, the probable value of c has changed, and the suggestion has been made that the real value may be changing linearly or even periodically with time [6.32]. However, in view of recent electro-optical measurements, microwave interferometer measurements, spectroscopic measurements, and the laser measurement to be described here, it appears that the probable value of c is converging to a constant within the stated errors and that the changing nature of c in the past was related to unaccounted inaccuracy in previous experiments.

Three different techniques have been used to measure the speed of light: 1) time of flight techniques; 2) ratio of electrostatic to electromagnetic units; and 3) frequency and wavelength measurements ($\lambda\nu = c$). The first quantitative measurement of c was an astronomical one in which the time of flight of light across the earth's orbit around the sun was measured by ROEMER in 1676. Early time-of-flight terrestrial measurements utilized long accurately-measured base lines and either rotating toothed wheels or mirrors for measuring the time interval. One of the most accurate early measurements of c was an electrostatic to electromagnetic ratio experiment by ROSA and DORSEY [6.33] in 1906.

Measurements of c in which both the wavelength and frequency of an oscillator were measured played a significant role in proving that radio and light radiation were electromagnetic in nature. This method was used by FROOME [6.13] to obtain the accepted value of c in use since 1958. His method used a moving reflector type of microwave interferometer operating at 72 GHz which was used to measure the microwave wavelength in terms of the length standard. The vacuum wavelength thus obtained when corrected for diffraction and other systematic effects was multiplied by the measured frequency to give a value for the speed of light. The frequency could be related to the primary standard with good accuracy, but the major estimated experimental error was connected with uncertainties in the wavelength measurement. At these long wavelengths the diffraction problem forced the use of a long air path which resulted in uncertainties in the measurement of the path length and in the index of refraction.

Speed of light determinations from wavelength and frequency measurements have traditionally suffered from the problems illustrated by FROOME's experiment. To measure the frequency, it is best to do the experiment at a frequency not too far removed from the primary Cs frequency where extremely stable oscillators can be made and where frequencies are easily measurable. However, to measure the wavelength, it is best to do the experiment close to the visible ^{86}Kr wavelength standard where wavelengths can be more easily compared and where diffraction problems are not as severe. The extension of frequency measurements into the infrared portion of the electromagnetic spectrum has in a sense solved this dilemma, and has been responsible for the 100 fold increase in the accuracy in the value of c. The frequency of the methane stabilized helium-neon laser is over 1000 times higher in frequency than that of the oscillator used in FROOME's measurement of c. Direct frequency measurements were recently extended to this frequency [6.22] and subsequently refined [6.10] to the present accuracy of 6 parts in 10^{10}. The wavelength of this stabilized laser has been compared [6.34–37] with the krypton-86 length standard to the limit of the usefulness of the length standard (approximately 4 parts in 10^9) [6.6]. The product of the measured frequency and the wavelength yields a new, definitive value for the speed of light, c. That measurement will now be described.

6.5. Methane Frequency Measurement

To measure the frequency of methane, a chain of oscillators extending from the cesium frequency standard to the methane stabilized helium-neon laser was used. The chain is shown in Fig. 6.4. The three saturated-absorption-stabilized lasers are exhibited in the upper right-hand section, the transfer chain oscillators are in the center column, and the cesium frequency standard is in the lower right-hand corner. The He–Ne and CO_2 lasers in the transfer chain were offset locked [6.16], that is, they were locked at a frequency a few megahertz different from the stabilized lasers. This offset-locking procedure produced He–Ne and CO_2 transfer oscillators without the frequency modulation used in the molecular-stabilized lasers. The measurements of the frequencies in the entire chain were made in three steps shown on the right-hand side, by using standard heterodyne techniques [6.22, 38–40].

Conventional silicon point-contact harmonic generator-mixers were used up to the frequency of the HCN laser. Above this frequency, tungsten-

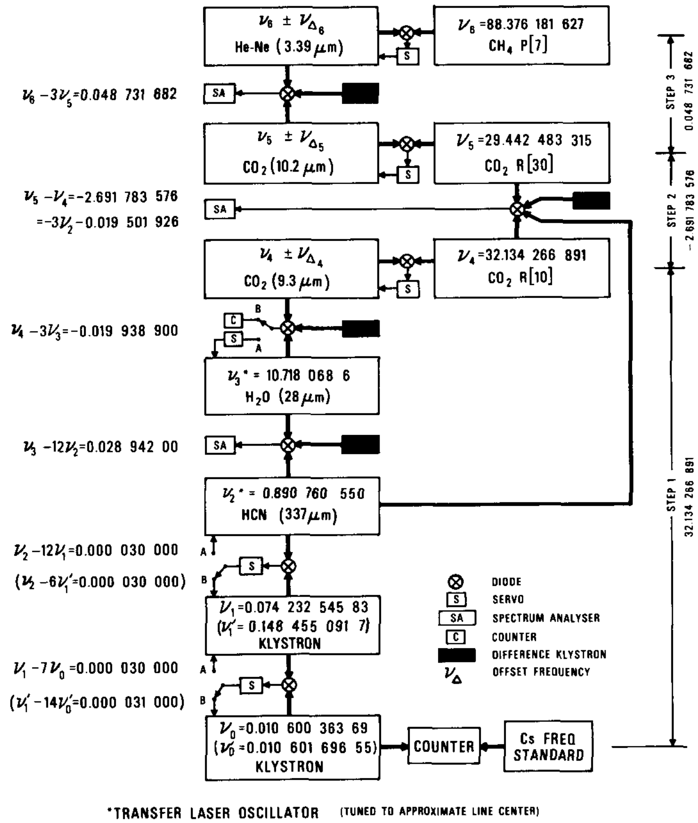

Fig. 6.4. Stabilized laser frequency synthesis chain. All frequencies are given in THz; those marked with an asterisk were measured with a transfer laser oscillator tuned to approximate line center

on-nickel diodes were used as harmonic generator-mixers. These metal-metal diodes required 50 or more mW of power from the lasers to obtain optimum signals. The 2-mm-long, 25 μm-diam. tungsten antenna, with a sharpened tip which lightly contacted the nickel surface, seemed to couple to the radiation in two separate manners. At 0.89 and 10.7 THz it acted like a long wire antenna [6.41, 42], while at 29–88 THz its concial tip behaved like one-half of a biconical antenna [6.42]. Conventional detectors were used in the offset-locking steps.

The methane-stabilized He–Ne laser used in these experiments is quite similar in size and construction to the device described by HALL

[6.2]. The gain tube was dc excited, and slightly higher reflectivity mirrors were employed. The latter resulted in a higher energy density inside the resonator and consequently a somewhat broader saturated absorption. Pressure in the internal methane absorption cell was about 0.01 Torr (1 Torr = 133.3 N/m^2).

The two 1.2-m-long CO_2 lasers used in the experiments contained internal absorption cells and dc-excited sealed gain tubes. A grating was employed on one end for line selection, and frequency modulation was achieved by dithering the 4-m-radius-of-curvature mirror on the opposite end. CO_2 pressure in the internal absorption cell was 0.020 Torr. The laser frequency was locked to the zero-slope point on the dip in the 4.3 μm fluorescent radiation [6.18]. The 0.89-, 10.7-, and 88-THz transfer lasers were 8-m-long linearly polarized cw oscillators with single-mode output power greater than 50 mW. The Michelson HCN laser has been described [6.43]. The H_2O laser used a double-silicon-disk partially transmitting end mirror, and a 0.5-mil polyethylene internal Brewster-angle membrane polarized the laser beam. The 8-m He–Ne laser oscillated in a single mode without any mode selectors because of a 4-Torr pressure with a 7:1 ratio of helium to neon. The resultant pressure width was approximately equal to the Doppler width, and a high degree of saturation allowed only one mode to oscillate.

Conventional klystrons used to generate the four difference frequencies between the lasers were all stabilized by standard phase-lock-techniques, and their frequencies were determined by cycle counting at X-band.

An interpolating counter controlled by a cesium frequency standard of the NBS Atomic Time Scale [6.44, 45] counted the 10.6-GHz klystron in the transfer chain. This same standard was used to calibrate the other counters and the spectrum-analyzer tracking-generator.

In step 1, a frequency synthesis chain was completed from the cesium standard to the stabilized $R(10)$ CO_2 laser. All difference frequencies in this chain were either measured simultaneously or held constant. Each main chain oscillator had its radiation divided so that all beat notes in the chain could be measured simultaneously. For example, a silicon-disk beam splitter divided the 10.7-THz beam into two parts: one part was focused on the diode which generated the 12th harmonic of the HCN laser frequency, the remaining part irradiated another diode which mixed the third harmonic of 10.7-THz with the output from the 9.3 μm CO_2 laser and the 20-GHz klystron.

Figure 6.4 shows the two different ways in which the experiment was carried out. In the first scheme (output from mixers in position A), the HCN laser was frequency locked to a quartz crystal oscillator via the 148- and 10.6-GHz klystrons, and the frequency of the 10.6-GHz klystron was counted. The H_2O laser was frequency locked to the stabilized CO_2 laser, and the beat frequency between the H_2O and HCN lasers was measured on the spectrum analyzer. In the second scheme (output from mixers in position B), the 10.6-GHz klystron was phase locked to the 74-GHz klystron, which in turn was phase locked to the free-running HCN laser. The 10.6-GHz klystron frequency was again counted. The free-running H_2O laser frequency was monitored relative to the stabilized CO_2 laser frequency, and the beat frequency between the H_2O and HCN lasers was measured as before on the spectrum analyzer.

In step 2, the difference between the two CO_2 lines was measured. The HCN laser remained focused on the diode used in step 1, which now also had two CO_2 laser beams focused on it. The sum of the third harmonic of the HCN frequency, plus a microwave frequency, plus the measured rf beat signal is the difference frequency between these two CO_2 lines. The two molecular-absorption-stabilized CO_2 lasers were used directly, and the relative phase and amplitudes of the modulating voltages were adjusted to minimize the width of the beat note. The beat note was again measured on a combination spectrum analyzer and tracking-generator-counter. The roles of the CO_2 lasers were interchanged to detect possible systematic differences in the two laser-stabilization systems.

In step 3, the frequency of the $P(7)$ line in methane was measured relative to the 10.18 μm $R(30)$ line of CO_2. Both the 8-m 3.39 μm laser and the CO_2 laser were offset locked from saturated-absorption-stabilized lasers and thereby not modulated. The 10- to 100-MHz beat note was again measured either on a spectrum analyzer and tracking generator, or in the final measurement when the S/N ratio of the beat note was large enough (about 100), directly on a counter.

The measurements were chronologically divided into four runs, and values for each of the steps and for ν_4, ν_5, and ν_6 were obtained by weighting the results of all runs inversely proportional to the square of the standard deviations. The largest uncertainty came in step 1; however, a recent measurement by NPL [6.46] gave a value of the $R(12)$ line which was only 2×10^{-10} (7 kHz) different from the number obtained by adding the $R(12)$–$R(10)$ difference [6.20] to the present $R(10)$ value. Thus, the first step of the experiment has been verified.

The final result is:

Molecule	Line	λ [μm]	Frequency [THz]
$^{12}C^{16}O_2$	$R(30)$	10.18	29.442483315(25)
$^{12}C^{16}O_2$	$R(10)$	9.3	32.134266891(24)
$^{12}CH_4$	$P(7)$	3.39	88.376181627(50)

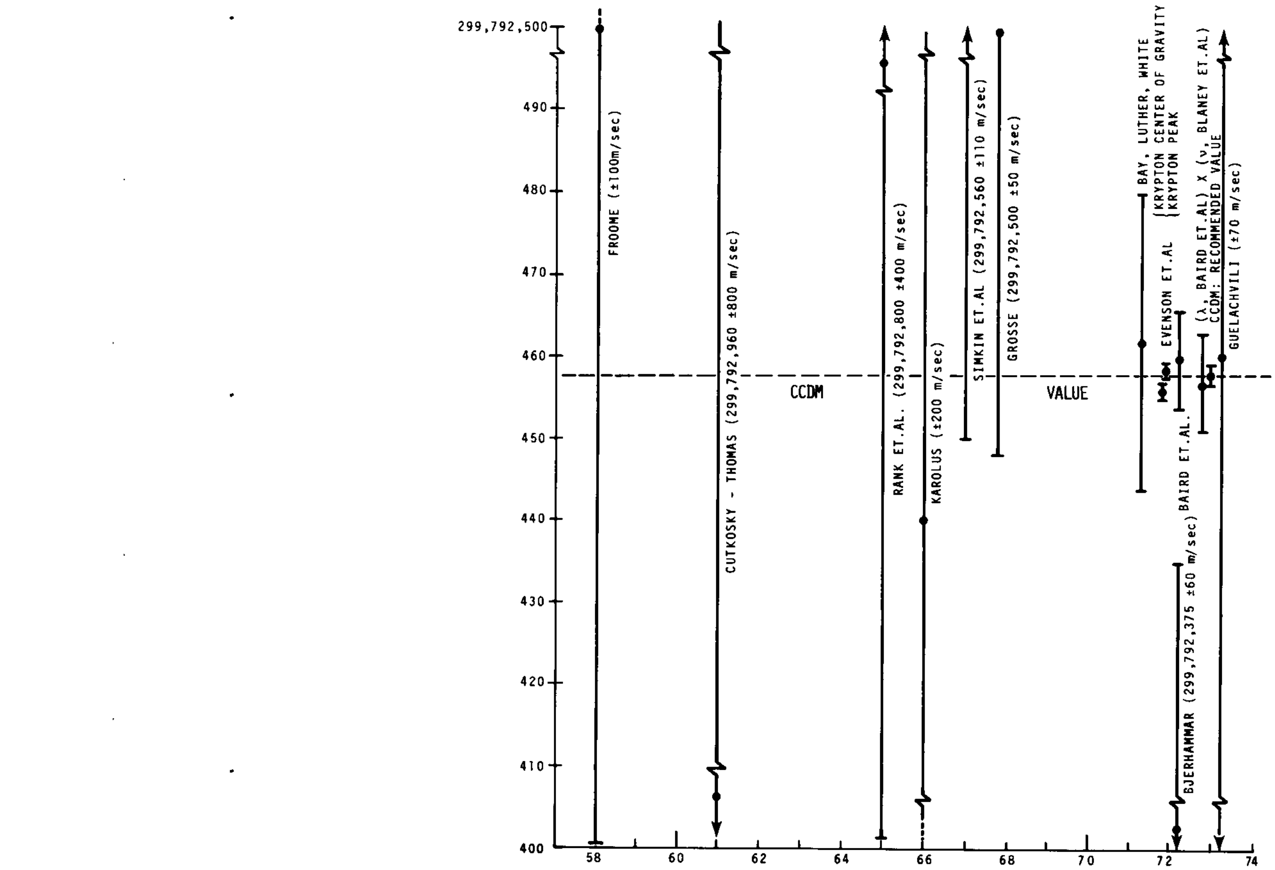

Fig. 6.5. Accurate speed of light values in meters per second since 1958. The value "recommended" by CCDM is 299792.458 m/s with an uncertainty of about 4 parts in 10^9. This value maintains continuity in the meter and may be used when the meter is redefined

The numbers in parentheses of the right column are 1-standard-deviation-type errors indicating uncertainties in the last two digits.

In a coordinated effort, the wavelength of the 3.39 μm line of methane was measured with respect to the ^{86}Kr 6058 Å primary standard of length by BARGER and HALL [6.34]. Using a frequency-controlled Fabry-Perot interferometer with a pointing precision of about 2×10^{-5} orders, a detailed search for systematic offsets inherent in the experiment, including effects due to the asymmetry of the Kr standard line, was made. Offsets due to various experimental effects (such as beam misalignments, mirror curvatures and phase shifts, phase shift over the exit aperture,

Table 6.1. Speed of light measurements since 1958

Year	Author	Ref.	Method	c [km/s]	δc [km/s]
1958	Froome	[6.13]	Radio interferometer	299792.5	0.1
1961	Cutkosky and Thomas	[6.48]	Ratio of units	299791.96	0.8
1965	Kolibayev	[6.49]	Electro-optical	299792.6	0.06
1965	Rank et al.	[6.50]	Spectroscopic	299792.8	0.4
1966	Karolus	[6.51]	Electro-optical	299792.44	0.2
1967	Grosse	[6.52]	Electro-optical	299792.5	0.05
1967	Simkin et al.	[6.53]	Radio interferometer	299792.56	0.11
1971	Bjerhammar	[6.54]	Electro-optical	299792.375	0.060
1972	Bay et al.	[6.11]	He–Ne $\lambda\nu$ (0.633 μm)	299792.462	0.018
1972	Baird et al.	[6.47]	CO_2 $\lambda\nu$ (9 and 10 μm, avg.)	299792.460	0.006
1972	Evenson et al.	[6.12]	He–Ne $\lambda\nu$ (3.39 μm) c.g.	299792.4562	0.0011
			peak	299792.4587	0.0011
1973	Guelachvili	[6.55]	Spectroscopic	299792.46	0.07
1973	Baird and Blaney et al.	[6.47, 46]	CO_2 $\lambda\nu$ (9.32 μm)	299792.457	0.006
1973	CCDM	[6.6, 10]	He–Ne $\lambda\nu$ (3.39 μm)	299792.458	0.0012

diffraction, etc.) were carefully measured and then removed from the data with an uncertainty of about 2 parts in 10^9. Their results indicate an asymmetry in the krypton line which resulted in two different values of λ_{CH_4}. One value arises if the center of gravity of the krypton line is used to define the meter, and another if the peak value is used. This reproducibility for a single wavelength measurement illustrates the high precision which is available using the frequency-controlled interferometer.

At the 5th session of the consultative committee on the definition of the meter (CCDM) [6.6], results of Barger and Hall as well as measurements made at the International Bureau of Weights and Measures [6.36], the National Research Council [6.37], and the National Bureau of Standards at Gaithersburg [6.35] were all combined to give a "recommended" value for the wavelength of the transition of methane used to stabilize the He–Ne laser. The recommended value is

$$\lambda_{CH_4[P(7),\,\mathrm{band}\,\nu_3]} = 3\,392\,231.40 \times 10^{-2}\,\mathrm{m}\,. \tag{6.3}$$

Multiplying this recommended wavelength of methane by the measured frequency yields the value for the speed of light:

$$c = 299\,792\,458\ \mathrm{m/sec}\ (\Delta c/c = \pm 4 \times 10^{-9})\,, \tag{6.4}$$

which was also recommended by the CCDM [6.6] to be used in distance measurements where time-of-flight is converted to length and for converting frequency to wavelength and vice versa.

This result is in agreement with the previously accepted value of $c = 299\,792\,500(100)$ m/sec and is about 100 times more accurate. A recent differential measurement of the speed of light has been made by BAY et al. [6.11]; their value is 299792462(18) m/sec, which is also in agreement with the presently determined value. A third recent, highly accurate value may be obtained by multiplying the frequency of the $R(12)$, 9.3 μm line of CO_2 measured by BLANEY et al. [6.46] by the wavelength measured by BAIRD et al. [6.47] which yields the value of 299 792 458 (6) m/sec for c. Also shown is another value by BAIRD [6.47], however, it used the CO_2 frequencies which were measured in this experiment, and hence, does not represent an independent value.

The fractional uncertainty in this value for the speed of light, $\pm 4 \times 10^{-9}$, arises from the interferometric measurements with the incoherent krypton radiation which defines the international meter. This limitation is indicative of the remarkable growth in optical physics in recent years; the present krypton-based length definition was adopted only in 1960.

Various measurements of c since FROOME's work are listed in Table 6.1 and are plotted in Fig. 6.5. One sees a remarkable convergence of the values of c for the first time in history!

6.6. Possible New Standard of Length

In addition to the "recommended" values of the wavelength of methane and the value of the speed of light made at the 5th CCDM meeting [6.6], a value for the wavelength of iodine was also recommended:

$$\lambda_{^{127}I_2[R(127),\text{band } 11-5, i \text{ component}]} = 632991.399 \times 10^{-12}\,\text{m}\,.$$

These "recommended" values are in agreement with wavelength measurements to the limits possible with the krypton length standard (that is, about $\pm 4 \times 10^{-9}$). It is "recommended" that either of these values be used to make length measurements using these stabilized lasers in the interim before the meter is redefined.

It is also significant that no further work was recommended on the present length standard, the krypton lamp, which is far inferior to a laser and will probably soon be replaced by one.

As a result of the recommendations made by CCDM, two different definitions of a new length standard must be considered. First, we can continue as before with separate standards for the second and meter, but with the meter defined as the length equal to $1/\lambda$ wavelengths in vacuum of the radiation from a stabilized laser instead of from a ^{86}Kr lamp. Either the methane-stabilized [6.2, 16] He–Ne laser at 3.39 μm (88 THz) or the I_2-stabilized [6.17] He–Ne laser at 0.633 μm (474 THz) appear to be suitable candidates. The 3.39 μm laser is already a secondary frequency standard in the infrared, and hopefully, direct measurements of the frequency of the 0.633 μm radiation will give the latter laser the same status in the visible. The 3.39 μm laser frequency is presently known to within 6 parts in 10^{10}, and the reproducibility and long term stability have been demonstrated to be better by more than two orders of magnitude. Hence, frequency measurements with improved apparatus in the next year or two are expected to reduce this uncertainty to a few parts in 10^{11}. A new value of the speed of light with this accuracy would thus be achievable if the standard of length were redefined in terms of the wavelength of this laser.

Alternately, one can consider defining the meter as a specified fraction of the distance light travels in one second in vacuum (that is, one can fix the value of the speed of light). The meter would thus be defined in terms of the second and, hence, a single unified standard would be used for frequency, time, and length. What at first sounds like a rather radical and new approach to defining the meter is actually nearly one hundred years old. It was first proposed by Lord Kelvin in 1879 [6.56]. With this definition, the wavelength of all stabilized lasers would be known to the same accuracy with which their frequencies can be measured. Stabilized lasers would thus provide secondary standards of both frequency and length for laboratory measurements, with the accuracy being limited only by the reproducibility, measurability, and long term stability. It should be noted that an adopted nominal value for the speed of light is already in use for high-accuracy astronomical measurements [6.57], thus, there are currently two different standards of length in existence: one for terrestrial measurement and one for astronomical measurements. A definition which fixes c and unites these two values of c would certainly be desirable from a philosophical point of view.

Independent of which type of definition is chosen we believe that research on simplified frequency synthesis chains bridging the microwave-optical gap will be of great interest, as will refined experiments directed toward an understanding of the factors that limit optical frequency reproducibility. No matter how such research may turn out, it is clear that ultraprecise physical measurements made in the interim can be preserved through wavelength or frequency comparison with a suitably stabilized laser such as the 3.39 μm methane device.

Frequencies are currently measurable to parts in 10^{13}, and hence the over-all error of about six parts in 10^{10} for the frequency measurement can be reduced. This measurement was performed fairly quickly to obtain a frequency of better accuracy than the wavelength. It should be possible to obtain considerably more accuracy by using tighter locks on the lasers. For example, the 8-m HCN laser has recently been phase locked [6.58, 59] to a multiplied microwave reference which currently determines the HCN laser linewidths. An improved microwave reference could be a superconducting cavity stabilized oscillator [6.60] for best stability in short term (narrowest linewidth) coupled with a primary cesium beam standard for good long term stability.

The relative ease with which these laser harmonic signals were obtained in these frequency measurements indicates that the measurement of the frequencies of visible radiation now appears very near at hand. Even if the point contact metal-on-metal diode is inoperable above 88 THz, conventional nonlinear optical techniques (i.e., 2nd harmonic generation in crystals) could still be used to extend direct frequency measurements to the visible. Such measurements should greatly facilitate one's ability to accurately utilize the visible and infrared portion of the electromagnetic spectrum.

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