CHAPTER 7

ACCURATE FREQUENCY MEASUREMENTS: RELEVANCE TO SOME OTHER AREAS OF METROLOGY*●

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Contents

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"Time present and time past
Are both perhaps present in time future,
And time future contained in time past."

Thomas Stearns Eliot

Accurate frequency measurements in the microwave through the infrared regions as well as the imminent realization of accurate frequency measurements in the near infrared and visible regions are surveyed, and their significance on the system of basic standards and fundamental constants is discussed. An exceedingly accurate redetermination of the speed of light, and a single primary unified standard for frequency, time, and length are imminent possibilities. The further possibility of one primary standard for many (if not all) of the base units exists. Traditional beam techniques, storage methods, and infrared or visible radiation molecular absorptions appear as the most promising candidates for the primary (frequency) standard.

Key words: Cesium beam; frequency standards; frequency/time metrology; fundamental constants; International System of Units; length standards; speed of light; unified standard; units of measurements.

7.1. INTRODUCTION

The present International System of Units of Measurement (SI) is built on six base units[1] which are related—with one exception (mass)—to fundamental properties of nature: time, length, mass, temperature, electrical current, and luminous intensity[2] [1].[3] Of these the unit of time, or more exactly the unit of time interval, the second, has been in modern times the most accurately[4] known and internationally accepted unit. The simple reason for this is that we are provided by nature with a unit of time interval: the duration of one day due to the rotation of the earth. Up to the recent past the definition of the second was based on the rotation of the earth and more recently on the revolution of the earth around the sun [2]. The accuracy of the second which can be realized by the definition approaches one part in 10^9 for extremely long observation periods (many years) [2, 3]. For shorter observation periods the accuracy is correspondingly worse. Figure 7.1 depicts the development of the accuracy capability of time interval standards since the advent of atomic clocks. Accuracy capability is here expressed as the one sigma combined uncertainty of all bias corrections. The bias corrections are the result of a theoretical and experimental evaluation of each particular standard, whose actual performance always deviates to some degree from the idealized conditions which are adopted in a definition of a base unit.

[1] In October 1971 the General Conference on Weights and Measures (CGPM) voted to adopt the mole as a base unit in the SI, thereby increasing the number of base units from six to seven (see footnote 2). The mole is a measure of the quantity of matter [59].
[2] Of these, only the first four are represented by independent primary base standards. See footnote 17.
[3] Figures in brackets indicate the literature references at the end of this chapter.
[4] By accuracy, we mean the degree to which a physical measurement or its measuring device conforms to a specified definition.

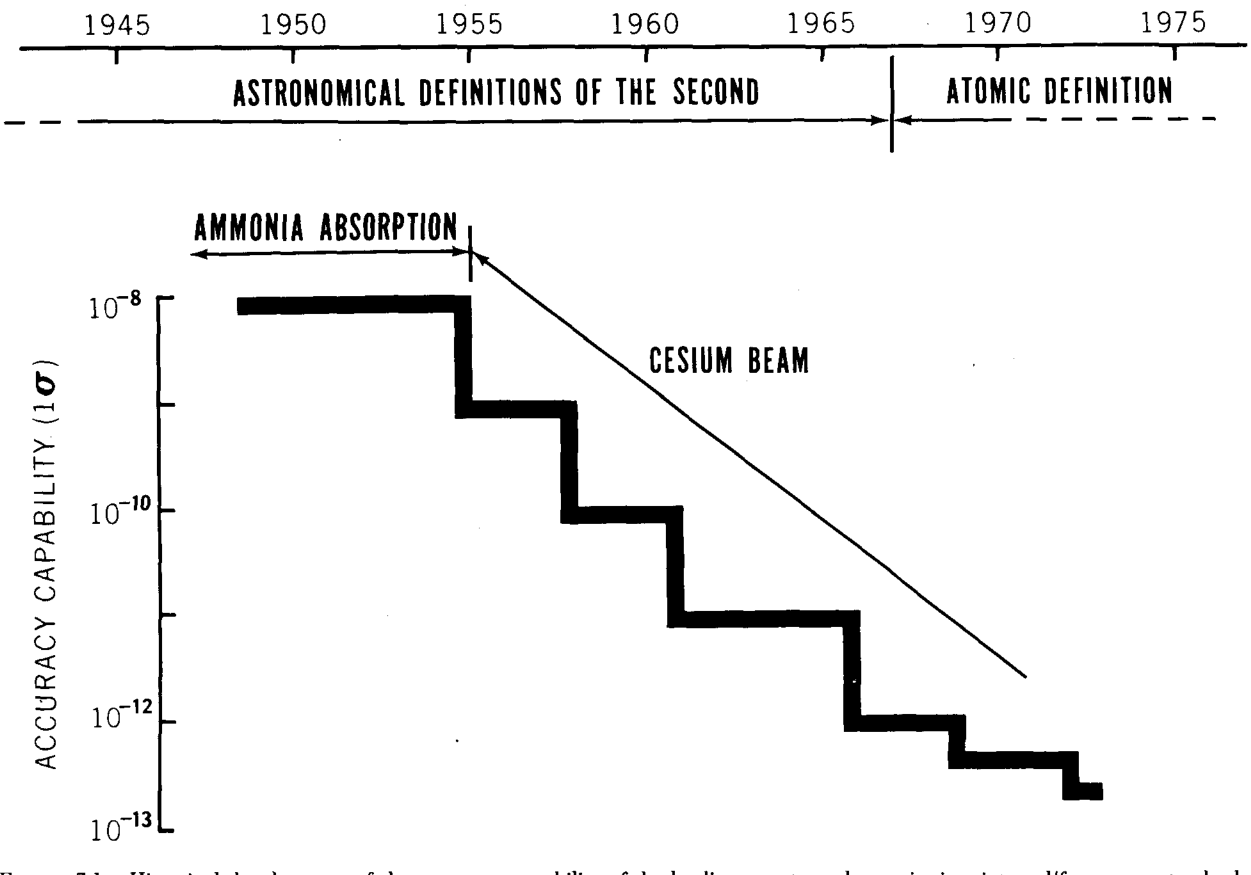

FIGURE 7.1. Historical development of the accuracy capability of the leading quantum electronic time interval/frequency standards, up to early 1973 (for recent values for time interval see ref. [70, 71]).

Figure 7.1 shows that the astronomical definition held its place exclusively until 1948. In that year the first ammonia clock was operated by H. Lyons at the National Bureau of Standards [4]. This clock's performance did not yet surpass that of the astronomical one. However, the advent of the ammonia clock is important for two reasons: Firstly, the unit of time interval could be related for the first time to an (assumed) invariant physical constant, here to the inversion transition in the ammonia molecule, instead of being based solely on the movements of macroscopic celestial bodies which are known to have secular changes (it is possible to correct for some but not all of the secular changes). Secondly, a frequency standard was used to aid in the definition of time interval; i.e., one used the relationship

$$\tau \equiv b\nu^{-1}, \tag{7.1}$$

and $b \equiv 1$, with τ and ν being the period and frequency of the radiation which is associated with the quantum transition. The unit of time interval, the second, can thus be defined as a certain number of periods of this radiation.[5]

A complete atomic clock system based on a hyperfine transition in cesium was operated and evaluated in 1955 by Essen at the National Physical Laboratory [5] and exceeded the performance of previous standards by one order of magnitude. As indicated in figure 7.1, further improvements in the cesium atomic clock at several laboratories around the world [3], [6–15] pushed its accuracy capability to its current value of better than 10^{-12} [16–19]. This performance of cesium clocks led the 13th General Conference on Weights and Measures in 1967 to accept the following definition: "The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom." The unit of frequency, the hertz, is then defined by eq (1) with $b \equiv 1$ Hz·s.

7.2. ACCURATE FREQUENCY MEASUREMENTS: PRINCIPLES AND METHODS

The base standard for time interval, the cesium atomic beam apparatus, is not only the most accurate frequency source, but also the most accurate of all base standards by a considerable margin as is illustrated in figure 7.2. This graph depicts the accuracy capability for all six (see footnote 1) units of the SI Base Units [1, 20]. The values for time, length, current, temperature, and luminous intensity describe the ability of actual instruments to realize the definition of the corresponding base unit. They

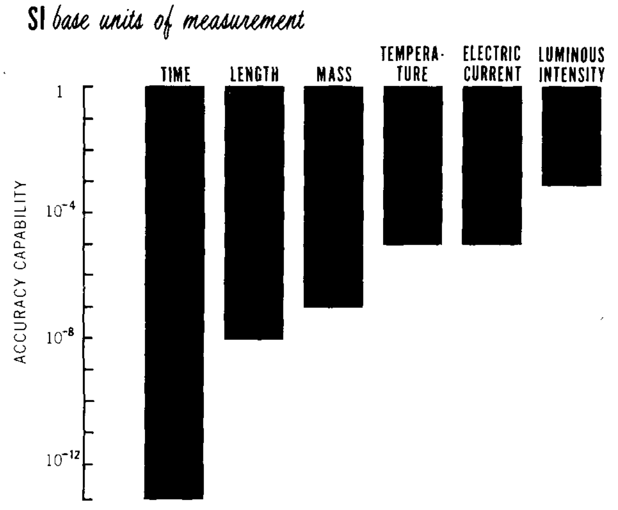

FIGURE 7.2. Comparison of the current accuracy in the realizations of the six base units of the International System of Units (SI) up to early 1973 rounded to orders of magnitude. (See footnote 1.)

were obtained from theoretical and experimental evaluations of bias corrections and from national and international intercomparisons. The only base unit which is still defined by an artifact is the kilogram. Here the accuracy capability is the ability to compare masses with this artifact and to preserve it unchanged. It must be noted that the precision[6] of relative measurements in any of these base units may be considerably better than the quoted accuracy capability of the corresponding base standards. In addition to being the most accurate kind, frequency/time metrology is the most precise of the many kinds of metrology (e.g., length, mass, force, pressure, resistance, current). Accurate and precise frequency measurements can be easily instrumented and can be highly automated. The versatility of frequency measurement techniques has led to their wide usage in metrology in general. Radio broadcasts of accurate frequency and time signals are available worldwide.

It is obvious from figure 7.2 that measurements which are based on time interval or frequency determinations have the potential of exceeding by far the accuracy of any measurement involving the five other base units (see footnote 1). Some physical constants can therefore be measured with extreme accuracy by using time interval and frequency methods. In particular this is true for the measurement of quantum transitions in atoms and molecules.

The availability of an exceedingly accurate standard is, however, only one prerequisite for an accurate measurement. In order to utilize the high accuracy capability of a time interval/frequency

[5] There could be separate standards for time interval and for frequency. The constant b in eq (7.1) would then be a fundamental constant in a sense quite similar to the speed of light, and b would have the dimension Hz · s.

[6] By precision, we mean here the reproducibility, within a set, of specified measurements taken as a time series.

standard, the system which is to be measured has to be brought under such experimental control that its measurement yields an accuracy which approaches that of the standard. In the limit, the system under study will have to show properties which are characteristics of a time interval/frequency standard itself. Therefore, the very systems which yield the most accurate measurements are simultaneously candidates for new time interval/frequency standards. We will discuss this aspect later in this chapter.

A system intended for the measurement of a transition frequency of an atom or molecule involves several steps of physical and technical processing which lead to bias corrections and corresponding uncertainties. These steps can be classified into three groups: (1) particle preparation, (2) particle confinement, and (3) particle interrogation [21].

There is no fundamental necessity to prepare the particles. However, often it is desirable to select only certain energy states or to achieve a desired population distribution of the energy levels. This can be done by spatial state selection, optical pumping, etc. Care must be taken to minimize perturbing effects.

A fundamental aim of precise measurements is an observation time as large as possible. Particle confinement is used to achieve coherent interaction times between the particles and the interrogating radiation which are as long as possible without introducing undue perturbations or excessive loss of signal. The confinement technique also is of considerable importance in the reduction of the Doppler effect, which is the most severe limitation in simple gas cell absorption measurements. Various confinement techniques such as a storage vessel with coated walls, ion storage, the storage in a cell filled with buffer gases, or the traveling particle beam are possible.

The particles have to be interrogated. Usually a resonant structure (e.g., cavity or interferometer) is used to enhance the interaction and to provide a spatially well-defined interaction region. The interrogation process itself may introduce perturbations such as the Bloch-Siegert effect [22] and photon recoil [21, 23].

We will now discuss the three methods [7] which stand out as leading to the most accurate measurements. It is not surprising that all three have in common a significant reduction of the Doppler effect limitation.

7.2.1. Particle Beams

In a particle beam apparatus, particles emerge from a source, forming a beam which travels through vacuum as indicated in figure 7.3. A polarizer (spatial state selector, optical pump, . . .) creates a certain, more desirable population distribution of the energy levels. The beam then enters the region of interrogation and is "confined" there for the duration of the transit time. The interrogation by radiation of suitable intensity and a suitable frequency which is compared to the frequency standard results in a change of the population distribution and a change of the intensity of the transmitted or reflected radiation. Two modes of detection are therefore possible. One is the analysis of the population distribution by counting the number of particles in a selected energy state. An analyzer, similar to the polarizer, and a particle detector are then necessary. An example of this mode of detection is shown in figure 7.3 [24]. The other mode of detection, which is not shown in figure 7.3, involves the monitoring of the radiation intensity [25, 26]. Under certain conditions, particularly at sufficiently high beam intensity, the system converts to a frequency generator (maser, laser oscillator) [25]. The output frequency is then detected and measured by comparison with a frequency standard.

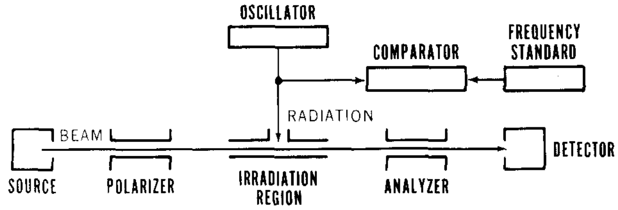

FIGURE 7.3. Accurate frequency measurements: particle beam method.

In the particle beam the Doppler effect is greatly reduced by the narrow, unidirectional beam. If care is taken in the design of the resonance structure so that the beam does not encounter net radiation power traveling parallel to the beam direction, the limitations due to the first-order Doppler effect can be virtually eliminated [24]. The second-order Doppler effect can be measured, or can be calculated, if the particle speed is adequately known. Particle preparation does not introduce frequency bias if it is spatially separated from the interrogation region.

7.2.2. Storage of Particles

In a storage device, particles are stored in a vessel which is located within the resonance structure as shown in figure 7.4. Particle preparation may be done simultaneously with the interrogation, e.g., by optical pumping and monitoring the intensity of the transmitted pump radiation as indicated in figure 7.4 [27]. However, this introduces frequency shifts which are difficult to evaluate [28].

[7] A more detailed discussion of these methods is given in Chapter 6.

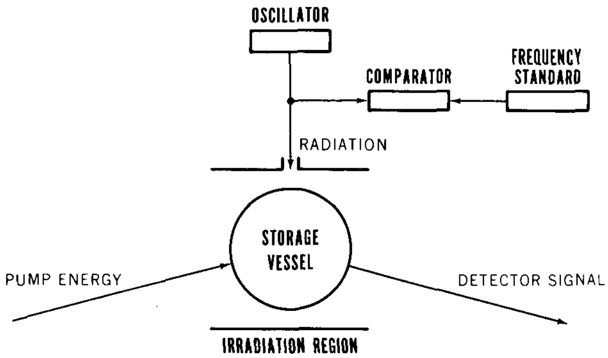

FIGURE 7.4. Accurate frequency measurements: particle storage method.

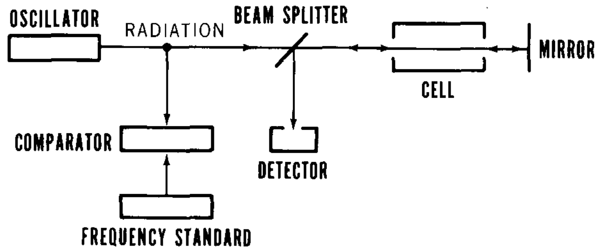

FIGURE 7.5. Accurate frequency measurements: saturated absorption method.

It is therefore advantageous to separate the preparation and interrogation regions and to use the storage principle in connection with the polarizing and analyzing technique of figure 7.3. In other words, the storage device of figure 7.4 is inserted between polarizer and analyzer of the system in figure 7.3 thus forming a storage beam device [29, 30]. Again we have the option to adjust the system parameters (beam intensity, pumping strength, . . .) such that self-oscillations are possible [28, 31].

The advantage of the storage technique is the increase in the confinement time leading to a very sharp line. The first-order Doppler effect also can be virtually eliminated if the movement of the particles is confined to a region of less than half the wavelength of the interrogating radiation. This is easy for the case of microwave frequencies but is more difficult at very short wavelengths. However, buffer gases can sufficiently restrict the particle movements. Also, buffer gases [28] and coating of the walls of the storage vessel [31] are used to reduce frequency shifts and relaxation processes due to wall collisions. The second-order Doppler shift can be calculated to a high degree of accuracy from the temperature of the storage vessel since the kinetic energy of the stored particles is in thermal equilibrium with the storage vessel.

7.2.3. Saturated Absorption

As shown in figure 7.5, in a saturated absorption device, the radiation of an oscillator is passed in opposite directions through a cell which is filled with the particles under study. The transmitted radiation intensity is monitored. Those particles with a near-zero velocity component parallel to the radiation propagation vector experience a nonlinear, enhanced interaction with the radiation field ("Lamb dip") [32, 33]. The system parameters can be adjusted so that those particles which have a significant velocity component parallel to the radiation beam are not interrogated. This reduces considerably the first-order Doppler effect and also excludes from the interrogation most of the particles which suffered a collision with other particles.[8] The line width is thus ultimately given by the transit time of particles across the radiation beam. The second-order Doppler correction can be obtained from the gas cell temperature. At higher frequencies the saturated absorption method may be limited by photon recoil effects which cause the emitted frequency ν_E to be different from the absorbed frequency ν_A by the fractional amount [21, 23]

$$(\nu_A - \nu_E)/\nu = h\nu/mc^2, \tag{7.2}$$

where ν is the average of ν_A and ν_E, m is the mass of the particle, h is Planck's constant, and c is the speed of light.

7.3. SURVEY OF ACCURATE FREQUENCY MEASUREMENTS

For figure 7.6 we have selected the most significant of the many published accurate frequency measurements and have plotted the published one sigma accuracy versus the location of the transition in the electromagnetic spectrum. The dashed bar in the case of I_2 indicates that its frequency has not yet been measured.[9] This is because frequency synthesis[10] has not yet succeeded in reaching to this frequency. However, advances by several groups, in particular by K. Evenson of NBS [34] and A. Javan of MIT [35], indicate that success is immi-

[8] Particle collisions lead to changes in particle speed and direction. A strong collision removes the particle from the interrogation process because the collision introduces, with high probability, a significant velocity component parallel to the radiation beam.

[9] The first measurement by frequency metrology of the 88 THz frequency of CH_4 was achieved on 11 November 1971 at NBS [60]. In 1972, the accuracy of the frequency measurement was improved to 6 parts in 10^{10} yielding 88.376 181 627 THz [61]. As of late 1972, the 474 THz frequency of I_2 has not yet been measured by frequency metrology, although the frequency is being determined via length metrology (unpublished work of H. Layer and R. D. Deslattes). To the best of our knowledge, the highest frequency yet synthesized from the frequency of cesium is 177 THz (unpublished work of G. W. Day and H. Hellwig).

[10] For a survey of infrared frequency synthesis, see reference [62].

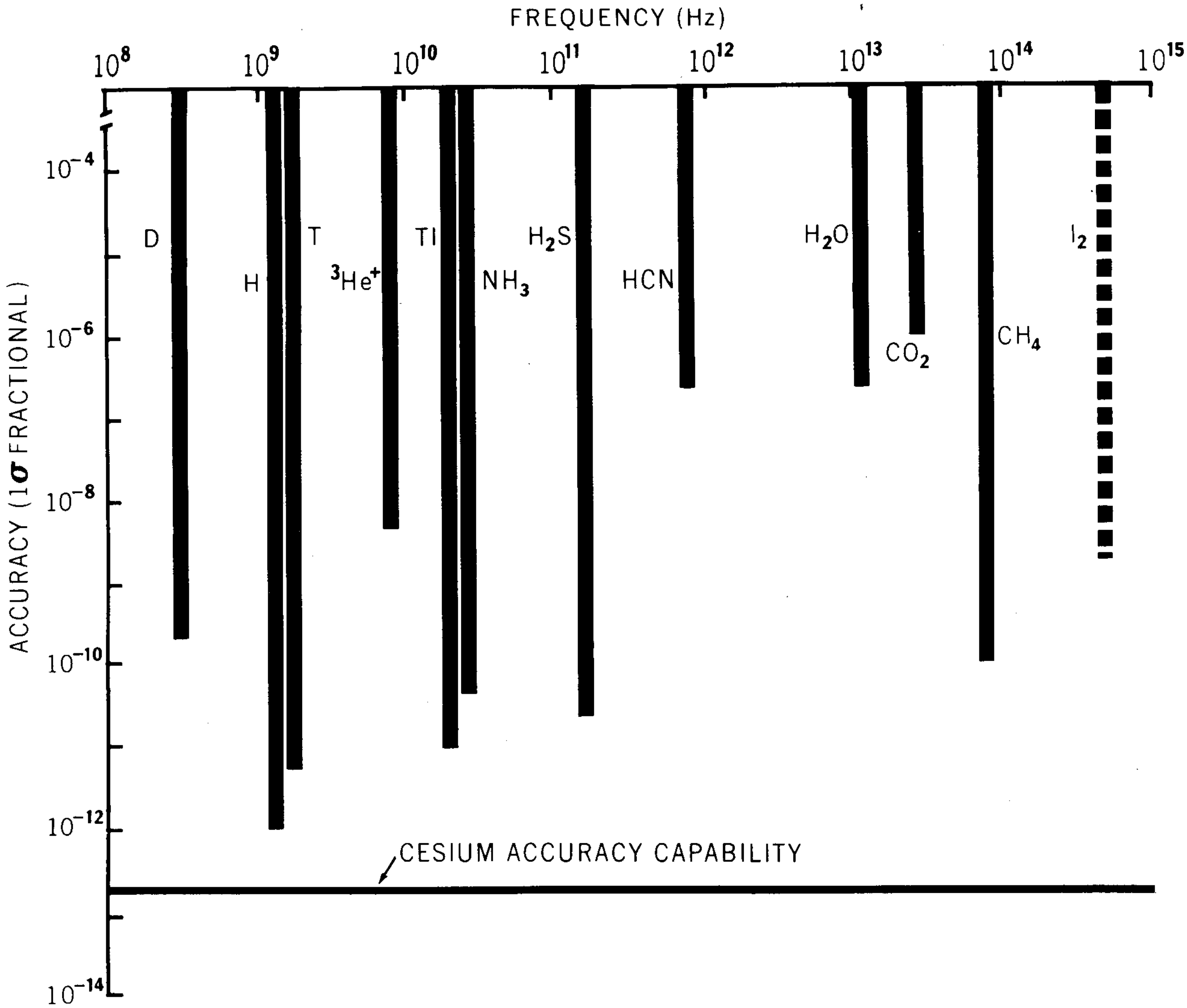

FIGURE 7.6. A survey of selected accurate frequency measurements throughout the electromagnetic spectrum. The accuracies reflect the state of the art as of early 1973. For I_2 the anticipated value is indicated (see text).

nent.[9] The value indicated for the accuracy of the anticipated measurement of I_2 is based on the evaluation of the beat frequency between two lasers which were independently frequency-locked to the I_2 transition together with absolute wavelength measurements [33]. Table 7.1 contains information supplementary to figure 7.6.

The measurements of HCN, H_2O, and CO_2 were made by frequency multiplication in a metal-metal point contact diode. The comparatively low accuracy of these values is due mainly to the fact that the molecular transition was investigated in a laser oscillator. This technique introduces large uncertainties because of Doppler effects, pressure effects, resonator frequency pulling, etc. Application of the saturated absorption method would considerably increase the measurement accuracy as is demonstrated by the CH_4 and I_2 experiments.

The storage of ions is a powerful and very promising spectroscopic tool as is demonstrated by the $^3He^+$ measurement. However, several experimental parameters are not yet fully understood, and they need further investigation, especially the kinetic energy of the stored ions (Doppler effect) [36].[11]

The methods on which the most accurate measurements are based were already discussed. They are the saturated absorption (CH_4, I_2), the storage vessel (H, D, T), and particle beams (Tl, NH_3, H_2S, Cs). The cesium particle beam tube serves as the primary standard for the base unit of time interval and frequency. It has been the most accurate measuring device since 1955 (fig. 7.1). Its present accuracy capability, shown as the horizontal line across the bottom of figure 7.6, is 2 parts in 10^{13} [15, 17, 18, 19, 70, 71 (see chap. 5B)].

[11] References [63] and [64] give discussions of the ion storage techniques as related to frequency standards.

TABLE 7.1. *Survey of accurate frequency measurements*

Particle	Transition	Technique	Frequency [a]	Accuracy	References
D	$F, m_F = \frac{3}{2}, \frac{1}{2} \leftrightarrow \frac{1}{2}, -\frac{1}{2}$	Storage maser	327 384 352.51 Hz	2×10^{-10}	[37].
H	$F, m_F = 1, 0 \leftrightarrow 0, 0$	Storage maser	1 420 405 751.768 Hz	1×10^{-12}	[38], [39].
T	$F, m_F = 1, 0 \leftrightarrow 0, 0$	Storage maser	1 516 701 470.809 Hz	5×10^{-12}	[40].
$^3He^+$	$F, m_F = 0, 0 \leftrightarrow 1, 0$	Ion storage	8 665 649 905 Hz	6×10^{-9}	[41].
^{205}Tl	$F, m_F = 1, 0 \leftrightarrow 0, 0$	Particle beam	21 310 833 945.9 Hz	1×10^{-11}	[42], [43].
$^{15}NH_3$	$J, K = 3, 3$ inversion	Beam maser	22 789 421 731 Hz	5×10^{-11}	[44].
$H_2^{32}S$	$1_{-1} \leftrightarrow 1_1$	Particle beam	168 762 762 373 Hz	2×10^{-10}	[45].
$H^{12}C^{14}N$	$110 \leftrightarrow 040$	Laser	0.890 7606 THz	2×10^{-7}	[46], [47].
$H_2^{16}O$ [b]	$001 \leftrightarrow 020$	Laser	10.718 073 THz	2×10^{-7}	[47].
$^{12}C^{16}O_2$	P(18), $001 \leftrightarrow 100$	Laser	28.359 800 THz	1×10^{-6}	[34].
$^{12}C^{16}O_2$	R(12), $001 \leftrightarrow 020$	Laser	32.176 085 THz	6×10^{-7}	[50].
$^{12}CH_4$	P(7), ν_3 band	Saturated absorption	$\approx$ 88 THz	(1×10^{-11})	[32].
I_2	R(127), 11–5 band of electr. trans. $B^3\Pi^+_{0g} \leftrightarrow X^1\Sigma^+_{0u}$	Saturated absorption	$\approx$ 474 THz	(2×10^{-9})	[33].

[a] By definition, $\nu_{Cs} \equiv$ 9 192 631 770 Hz. See text for recent results on CH_4.

[b] The frequencies of several other transitions in water vapor lasers have been measured such as the 2.5–THz (118 μm) line in H_2O [48] and the 3.6–THz (84 μm) line in D_2O [49].

7.4 SIGNIFICANCE AND IMPACT OF ACCURATE FREQUENCY MEASUREMENTS

We can identify four general areas where accurate frequency measurements are significant and where some impact on future scientific and technological developments is foreseen. These are summarized in table 7.2. Within the scope of this chapter only the last area, fundamental constants and basic standards, is of importance; we will discuss it in detail and only briefly explain the first three items.

Metrology and applications include radar ranging especially over long (planetary) distances; planetary exploration in general; earth and space navigation, where timekeeping over weeks, months, or even years without resynchronization is vital; telecommunication aspects including high bit rates and better usage of the electromagnetic spectrum; and aircraft collision avoidance systems which can be based, perhaps with advantage, on time domain techniques which employ accurate clocks.

Accurate frequency measurements throughout the infrared and visible region will greatly increase our knowledge of the structure of atoms and molecules. Spectroscopic constants such as transition frequencies, g-factors, Stark coefficients, rotational distortions, etc., will be accessible to measurements of unprecedented precision and accuracy.

Tests of the general theory of relativity involving differences of coordinate time and frequency at locations of different gravitational potential will be made with clocks placed in satellites or on other celestial bodies. An improvement in accuracy of about one order of magnitude over our present accuracy capability will permit some tests to be conducted on the earth's surface.

TABLE 7.2. *Areas of impact*

Metrology and Applications to Technology
Spectroscopic Constants
General Theory of Relativity
Fundamental Constants and Basic Standards

The ability to perform accurate frequency measurements throughout the electromagnetic spectrum may have a considerable impact on the system of fundamental constants and basic standards. Figure 7.6 illustrates that frequency measurements have already been made in the terahertz region and that the ability to compare directly the frequencies of the standard of time interval/frequency (currently ^{133}Cs) and of the standard of length (currently ^{86}Kr) will soon be a reality.[12] The relationship between these standards involves the speed of light c,

$$\lambda = c\nu^{-1}, \tag{7.3}$$

where λ is the vacuum wavelength and ν is the frequency of the radiation. Equation (7.3), as applied to the direct comparison of length and frequency (time interval), will lead to a determination of the speed of light with unprecedented accuracy [34], which will be limited only by the ability to perform an interferometric length measurement (compare fig. 7.2).[12]

[12] This has been partially achieved in 1972. See reference [61].

Equation (7.3) is not the only "simple" relationship between basic standards involving a fundamental constant. The Josephson phenomenon [51] provides us with a relationship between the electrical potential difference V (relating to the standard of electrical current) across a superconducting weak link and the corresponding Josephson oscillation frequency ν

$$V = (h/2e)\nu. \qquad (7.4)$$

Equation (7.4) has already served to determine Planck's constant h divided by the electronic charge e with unprecedented accuracy [52, 53] which led to a refitting of the whole system of fundamental constants [54].[13] We can imagine further simple relationships between basic standards and the time interval/frequency standard involving fundamental constants, such as a relationship for the mass m

$$m = f(\nu), \qquad (7.5)$$

or for the temperature[14] T

$$T = g(\nu). \qquad (7.6)$$

Accurate frequency measurements based on eqs (7.3) to (7.6) could therefore lead to a more accurate knowledge of the fundamental constants. This increased accuracy in turn would allow a more sensitive search for possible spatial and secular variations of the fundamental constants [55].

It is a consequence of historical development and experimental expertise that we have a set of base units and corresponding standards such as the SI; no fundamental physical principle is involved in this choice. It is already possible to compare spectroscopic data in the infrared or visible regions using frequency measurement techniques with a precision far exceeding that of interferometric (length measurement) techniques.

In view of the success of frequency multiplication from the microwave region into the infrared region and its imminent extension into the visible region it seems to be in order to question, at least philosophically, the need for a separate standard of length. Length measurements could be related to the base unit for time interval and frequency via eq (7.3). The speed of light would then be a defined constant[15] [56, 57, 58]. The defined value of c would be chosen to be compatible with its previous best experimental value, and the most accurate frequency standard would serve as a *Unified Standard* for frequency, time, and length.[16]

In the limit this philosophy would lead to a base set of fundamental constants with defined values. The most accurate standard, which is today the cesium beam frequency standard, would then serve as *The Standard*, and all other units of measurement could be derived using relationships such as eqs (7.3) to (7.6) with c, $h/(2e)$, and some yet undetermined function like $f(\nu)$ and $g(\nu)$ (see footnote 14) as defined entities.[17] These possibilities add excitement to the work which is being done on frequency standards.

7.5. SUMMARY

In the preceding sections, we pointed out that frequency/time metrology is currently the most precise and accurate kind of metrology, and we outlined the significance of accurate frequency measurements and their impact on technology and physics, and in particular on the system of fundamental constants and basic standards. Possibly being the *Unified Standard* or even *The Standard* in some future system of units of measurement, the primary frequency standard should get special attention. At present we see several ways [21] of pushing its accuracy capability beyond the present one sigma performance of 2×10^{-13} of the laboratory cesium beam tube [70, 71].

We discussed the three most promising methods which allow the most accurate frequency measurements: particle beam, particle storage, and saturated absorption. We also mentioned that naturally these very same methods are the most promising ones for the development of future standards of even better accuracy.

In table 7.3, experimental realizations of these methods are listed together with evaluated accuracy capabilities and projected performances. Each projected performance is listed as better than some quoted value. This value is believed to represent a minimum performance which almost certainly can be surpassed based on our present experimental and theoretical knowledge; however, we cannot predict with sureness if and by how far. In this sense, a technique quoted as "better than 10^{-11}" could well surpass one quoted as "better than 10^{-12}." For a more detailed discussion we recommend the cited literature, and we suggest reference [21] for a critical comparison and prognostic.

Perhaps a uniquely superior method of accurate frequency measurement will be singled out by additional experimental and theoretical work, or perhaps these three methods will each improve significantly so as to remain mutually competitive. Very likely, in the continuing progress of knowledge and technical abilities, new possibilities will continue to appear.

[13] It is now possible with the Josephson junction to create an operational substitute for the traditional bank of saturated cells used to maintain the NBS calibrated secondary working voltage standard ("Legal Volt"). Such an operational system was formally established in NBS on 1 July 1972 [65].

[14] Such a relationship has been used recently for temperature measurements in the millikelvin range [66, 67]. The method is based on the measurement of frequency fluctuations in a Josephson junction caused by voltage fluctuations which in turn are caused by thermal noise corresponding to the temperature of a resistor shunting the junction.

[15] Compare with footnote 5.

[16] These considerations are discussed in more detail in reference [68].

[17] Although there are seven base units in the SI (see footnote1), there are at present only four independent primary base standards in the SI [69]; water for temperature (kelvin), prototype kilogram for mass (kilogram), atomic krypton for length (meter), and atomic cesium for time (second). Consequently, to go from four independent primary base standards to only one (*The Standard*) would require adoption of a suitable set of three such definitions, one of which would be the value of the round trip speed of light c.

TABLE 7.3. *Promising candidates for primary frequency standards*

Method	Device	ν(Hz)	Accuracy capability (one sigma)	
			Present performance	Projected performance
Particle beam	Cesium beam	9.2×10^{9}	2×10^{-13} [70, 71]	Better than 10^{-13}.
	Iodine beam	5.8×10^{14}	.... [26]	Better than 10^{-12}.
Particle storage	Hydrogen Maser	1.4×10^{9}	1×10^{-12} [38]	Better than 10^{-12}.
	Hydrogen storage beam	1.4×10^{9}	.... [30]	Better than 10^{-12}.
	$^3He^+$ Ion storage (or heavy ions)	8.7×10^{9}	6×10^{-9} [27]	Better than 10^{-11}.
Saturated absorption	Methane cell	8.8×10^{13}	1×10^{-11} [32]	Better than 10^{-12}.
	Iodine cell	4.7×10^{14}	2×10^{-9} [33]	Better than 10^{-11}.

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