ATOMIC FREQUENCY STANDARDS: A SURVEY*

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Abstract

The last comprehensive survey on atomic frequency standards was given by A. O. McCoubrey in 1966 (Proc. IEEE 54, p.116). This survey reviews the more recent historical background of atomic frequency standards leading to the present developments. A discussion of the underlying physical and engineering principles is given. Modern atomic frequency standards, including their performance, are compared quantitatively,and projections are attempted at likely future developments and performance characteristics.

As in 1966, the standards principally used in technical and scientific applications are rubidium gas cell devices, cesium beam tubes, and hydrogen maser oscillators. However, substantial advances in physical and performance characteristics can be reported.

New developments include passive hydrogen devices, saturated absorption stabilized lasers, ion storage devices, and atomic beams in the far infrared and infrared region, as well as new techniques to evaluate frequency biases such as those encountered in cesium and hydrogen standards.

The survey includes a discussion of the effects of past and current developments in atomic frequency standards on the technical and scientific user community.

Introduction

The last comprehensive survey of atomic frequency standards was done eight years ago by A. O. McCoubrey [1]. Since then, considerable changes have taken place in the field. Companies who were manufacturing atomic standards at that time are not doing so any more, and a number of new companies have come up with new devices. This survey is intended to be as complete as possible including commercial manufacturers, as well as companies who are known to work on the development of atomic standards. In addition, a listing, as exhaustive as possible, of all non-commercial laboratories is given, including their main activities. An apology is in order at this point because being totally exhaustive is an elusive goal.This paper is therefore bound to suffer from the omission of some places where important work may go on. The reader is encouraged to supply the author with information which may remove as much as possible this shortcoming, so that some later revised version of this survey may include such information.

Two restrictions had to be applied: The first restriction refers to the inclusion of only those laboratories or companies which either have publicly announced their intention to develop or contribute to the development of frequency standards, or which have participated in relevant meetings and conferences, or which are typically referenced in relevant papers on our subject. The second restriction is the omission of the efforts in eastern European countries. We shall however attempt a brief sketch of this effort. Within a cesium standards program in Poland a laboratory type cesium standard has been built for service in connection with the standard time and frequency broadcasts of this country (private comm. A. Chachulski). Also, a research effort on a silver atomic beam has been reported. In the USSR, we believe that a sizable hydrogen maser effort is in progress; in fact, the time and frequency dissemination services of the USSR rely on an ensemble of hydrogen masers. Other efforts in the USSR include rubidium gas cell studies, saturated absorption for laser stabilization, in particular, the methane-stabilized helium-neon laser,and cesium devices.

In this survey, no attempt is made at discussing in any depth the physical principles underlying the functions of atomic frequency standards. The 1966 survey of McCoubrey and other more recent articles [2,3,4,5,6] adequately cover the subject. The data which are reported in this paper rely on values which are either taken from manufacturer's specifications and/or scientific publications, and/or information obtained at scientific conferences and meetings; not on NBS measurements.

Developments Since 1966

The types of standards which are in actual use as frequency standards and clocks in science and industry have not changed since 1966. We still find hydrogen masers, cesium beam tubes, and rubidium gas cells. However, considerable technology advances have significantly improved the performance and other physical characteristics of these standards. A detailed discussion of these developments is given in the next Chapter.

A number of known principles have been developed into concepts bearing all the characteristics of high performance atomic frequency standards. Following and paralleling the pioneering efforts of Dehmelt at the University of Washington on ion storage [7], three new efforts came to life at the Texas A&M University under H.Schüssler concentrating on light ions [8], under

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F. Major at NASA, Goddard Space Flight Center using heavy ions [9], and under C. Audoin at the Laboratoire de l'Horloge Atomique in Orsay, France (also on heavy ions) [10]. One of these efforts, the activity at the Goddard Space Flight Center, has been discontinued as of 1973.

Lasers alone have never been considered very good candidates for frequency standards of high accuracy. However, because of their rather high short term stability, i.e., spectral purity, lasers can serve as high quality local oscillators in roles very much like those of quartz crystal oscillators. Thus, atomic or molecular systems can be used as the frequency reference and can be used to stabilize a laser oscillator. One of the techniques which have emerged as being highly promising is the saturated absorption in molecules pioneered by Hall and Barger at NBS(JILA) in 1969 [11] with the saturated absorption in methane used to stabilize a helium-neon laser at 3.39 μm (88THz). This new atomic frequency standard concept has stimulated a desire to measure the frequency of such a system. Pioneering work of K. Evenson and his coworkers at NBS led ultimately to the successful measurement of the 88 THz transition in methane [12]. It is important to realize that in order to do such a precision measurement, it is absolutely essential to have a device at each end of the frequency synthesis chain which has frequency standards characteristics [13], since to assign a specific frequency requires a well defined, narrow resonance line, such as in methane. Another system with very promising stability and accuracy aspects is the iodine saturated absorption stabilized helium-neon laser at 633 nm in the visible region pioneered by C. Baird and his group at the NRC in Canada [14]. Also important is the stabilization of the CO_2 laser by saturated absorption in CO_2 first done by Freed of MIT [15], and in SF_4 as demonstrated by Petersen of NBS [16], and in other molecules. Another promising method to stabilize a laser oscillator has been proposed and experimentally tried with success by S. Ezekiel of MIT [17]. He uses a beam of iodine molecules to stabilize the frequency of an argon-ion laser. A common problem of all the infrared and visible region based frequency standards is that in order to make them usable for technical applications, they must be able to also serve as clocks, i.e., they must allow a division of their frequency down to pulses per second. In principle, this has been successfully executed up to the methane resonance at 88 THz. What is still needed is a precision adequate for the 10^{-13} to 10^{-14} capability of the existing devices, and a frequency synthesis or a frequency divider chain with more practical physical and cost characteristics.

Another proposal made by Strumia of the University of Pisa in 1972 [18] has aroused considerable interest. It involves resonances in magnesium (600 GHz) or calcium (1.5 THz) in an atomic beam machine. The local oscillator in this concept can, in principle, be based in the microwave region because reasonable frequency synthesis techniques do already exist such as the use of the Josephson junction [19] and diode structures. It was experimentally tried with promising first results.

The use of hydrogen atoms in systems other than the hydrogen maser oscillator was proposed by Peters at NASA in 1970 [20], and in the same year by Hellwig at NBS [21]. The NASA proposal encompasses a straight hydrogen beam going through a Ramsey type structure being detected by a detector capable of counting hydrogen atoms. The NBS proposal retains the storage principle of the maser oscillator, but uses a passive approach with either detection of the microwave signal or a detection of hydrogen atoms. All of these new approaches with hydrogen have been tried experimentally with quite promising results [20,22].

The substitution of cesium for rubidium while retaining a buffer gas cell leads to the proposal for an optically pumped cesium gas cell or cesium maser oscillator made by Strumia of the University of Pisa and Leschiutta from the IEN in Torino, Italy. Both of the concepts have been experimentally tried, but no published results are available at the time of this writing. Finally, research on a free rubidium beam has been done by Arditi at the Laboratoire d'Electronique Fondamentale in Orsay, France [23]. It involves a beam machine featuring a Ramsey cavity and state selection and detection by optical pumping.

Traditional Atomic Frequency Standards: Present Status

A. General

For the purpose of this paper, we consider the following as traditional frequency standards: cesium beam tube devices, hydrogen maser devices, rubidium gas cell devices, and rubidium maser devices. It appears to be of advantage to classify these standards into sub-categories. This also avoids the possibility that qualitative and quanitative comparisons between different devices of different manufacturers can be inferred from this paper which certainly is not its intent. The following Tables 1 and 2 list these sub-categories ranging from the small commercial rubidium standard to the evaluable laboratory cesium standard. We shall now discuss some general aspects common to all traditional frequency standards. Most important to any user whether he is a metrologist, scientist, or systems designer is probably the stability characteristics of the particular standard. Stability can be characterized in the frequency domain or in the time domain. We shall restrict our discussion here to time domain stability and use the Allan variance σ_y as the quantity of interest [24]. A stability plot of a frequency standard typically always shows the characteristic as shown in Fig. 1. The first part, "I", with $\sigma_y \sim \tau^{-1}$ (white or flicker of phase noise), or $\sigma_y \sim \tau^{-1/2}$ (white frequency noise) reflects the fundamental noise properties of the standard. These may be shot noise in the beam of cesium atoms or photon shot noise in the photo cell of a rubidium device or additive noise due to the microwave receiver of a hydrogen maser, etc. This behavior continues with increasing averaging time until the so called flicker "floor" is reached where σ_y is independent of the averaging time (flicker of frequency noise). This behavior is found in all frequency standards; it depends on the particular frequency standard and is not fully understood in its physical basis. Examples for probable causes for the flicker "floor" are power supply voltage fluctuations, magnetic field fluctuations, changes in components of the standard, microwave power changes, etc. Finally, in the third section of the generalized curve, the stability deteriorates with increasing averaging time. This occurs typically at times ranging from hours to days, again depending on the particular category of the standard. A behavior $\sigma_y \sim \tau^{+1}$ corresponds to pure frequency drift or linear aging. Usually, the slope is between τ^0 and τ^{+1}, but cannot be determined too accurately because of the long averaging times needed in order to get statistical confidence in the values. Also, the power law of this noise is often not stable. Probably a quite general statement may suffice at this point. This deterioration of the stability with increasing long averaging times is due to some physical changes within the standard, such as a change in the magnetic shielding capability, in the beam alignment, in the optical properties of the optical pumping process, etc. Also, environmental influences may be responsible, like daily, monthly, or yearly phenomena or manmade events due to the particular environment of the particular laboratory in which the standard is located. Thus, the third part of the curve can be improved by better control of the standard in the laboratory or its protection against environmental influences. Linear aging appears as a deterioration of frequency stability with longer averaging times, which sometimes is misleading since a linear frequency drift is measurable and usually does not affect the usable stability of the standard, even over very long averaging times. Because of this, the third portion of the curve is omitted in the graphic representation of Fig. 2. In this graph we have only seven distinctly different curves due to the fact that the small and the regular commercial cesium standards perform about the same and the two different hydrogen maser categories differ largely in size, but not in performance.

B. Cesium Standards

The basic design of a cesium standard is shown in Fig. 3. The cesium beam emerges from an oven into a vacuum, passes a first state selecting magnet, traverses a Ramsey type cavity where it interacts with a microwave signal derived from a slave oscillator. The microwave signal changes the distribution of states in the atomic beam which is then analyzed and detected by means of the second state selector magnet and the atom detector. The detector signal is used in a feedback loop to automatically keep the slave oscillator tuned. The line-Q is determined by the interaction time between the atoms and the microwave cavity. Thus, a beam of slow atoms and a long cavity leads to a high line-Q. Commercial devices which for obvious reasons are restricted in total size have line-Q's of a few 10^7, whereas, high performance laboratory standards with an overall device length of up to 6m feature line-Q's of up to 3×10^8.

As summarized in Table 3, over the past years, several design alternatives have been developed. The cavity can either be a single Rabi type conventional cavity or a separated cavity of the Ramsey type. All existing cesium beam tubes feature the Ramsey [25] cavity because of its advantages in reducing first-order Doppler effects, magnetic field problems, and cavity phase shifts. However, the possibility of a single cavity remains; it has been tried by several laboratories and it may still be of some attractiveness in standards of very small design.

In the beam optics the choice is to use dipole magnets or hexapole magnets or a combination of these. All of these systems are presently in use in various standards with the dipole approach probably dominating. To the author's knowledge, a hexapole optic is featured only in the primary standard of the Physikalisch-Technische Bundesanstalt (PTB) in Germany [26], and in an experimental tube designed by the Laboratoire Suisse de Recherche Horlogeres (LSRH) [27]. With regard to accuracy and very long term stability there is probably an advantage to the hexapole design; we will come back to this later.

The beam tube can be either a single conventional beam or a multiple beam as has been developed recently in some commercial beam tubes. This allows a high beam intensity without too much sacrifice in the ability of the designer to control and predict the functions of the beam optics.

In the magnetic field design, either an axial magnetic field or a transverse magnetic field can be used which require a corresponding axial or transverse orientation of the rf magnetic field component in the cavity. Again, only the PTB features an axial magnetic field design which has the advantage of the long magnetic coil with its inherent homogeneity of field and simplicity in construction [26]. However, it is also a demonstrated fact, especially by the other primary standards laboratories [28,29] that, although in principle inferior, the transverse magnetic field design is quite adequate, limiting the accuracy of a primary standard to not worse than 2×10^{-14}.

As shown in Table 4, one basic accuracy limitation of a cesium device is due to the phase difference between the two parts of a Ramsey cavity. Even with the most advanced manufacturing tolerances, and manufacturing controls, parts in 10^{12} are typical in its effect on the frequency of the standard. The other accuracy limitation is due to the second-order Doppler effect which relates to the absolute speed of the atoms with respect to the observer (cavity). The second-order Doppler effect is typically of the order of parts in 10^{13} depending on the velocity range being used. Actually, in order to measure the second-order Doppler effect to the precision desired (1 x 10^{-14}), it is necessary to not only know some mean velocity of the atoms but to know the whole velocity distribution in order to arrive at the mean squared velocity. This is not trivial because the velocity distribution of any cesium standard is highly determined by the alignment and design of the beam optics, and reflects very little the temperature of the cesium oven. Thus, as shown in Table 5, the second-order Doppler effect requires either a very narrow velocity distribution and a measurement of the linewidth of this narrow velocity distribution (then just the linewidth gives adequate information on the mean velocity), or the velocity distribution must be inferred from the microwave (Ramsey) spectrum [30,31,32], or the velocity distribution must be measured directly which is possible with a recently developed technique [33,34] applying the exciting microwave power in pulses, spaced in such a way that the atoms are strobed. Then a variation of the pulse setting will scan the velocity distribution. All of these techniques are able to produce information on the second-order Doppler effect which reduce its contribution to the inaccuracy to parts in 10^{14}. For the cavity phase difference a frequency measurement has to be made because the cavity phase difference will cause a frequency shift which depends on the velocity of the interrogated atoms. A change in the mean velocity of the interrogated atoms can be effected by: (a) beam reversal which nominally retains the absolute value of the velocity but changes the sign [35,36]. This method has the disadvantage that it is not quite possible to ascertain that the beam retraces its original trajectory when the beam reversal is executed. (b) The beam optics can actually be changed. This has been done by switching magnets of a different strength which select different velocities [26]. This is again a very powerful method if it can be assured that the trajectory is essentially the same. (c) The microwave power picks a certain velocity subset out of the available velocity distribution by virtue of the fact that the transition probability is dependent on the interaction time and power between the microwave field and the atoms [28,30,33,34,37]. An analysis of the frequency shifts encountered in changing the microwave interrogation power can lead to data on the cavity phase difference. An evaluation of this effect requires a knowledge of the velocity distribution, (d) Finally, we can pick a certain velocity very much in analogy to the beam optics change discussed above by applying the microwave power in pulses, i.e., strobing the beam [28,33,34]. The only disadvantage in this method is that because of the pulsed operation a certain loss in signal-tonoise must be tolerated.

All of these methods have been used. Some were even used with preliminary results on commercial standards (the microwave power shift and the pulsed operation) [34]. The results obtained by the three laboratories which currently operate evaluated cesium beam devices for the purpose of the definition of the second are summarized in Table 6 as of the fall, 1973. The common stable reference used by all three laboratories is the International Atomic Time Scale (TAI). The measurement of TAI in terms of the evaluated primary standard of each of the laboratories is listed in the first column [37,38,39]. The individually assigned 1σ uncertainty is listed in the second column, and in the third column we find a listing of the methods used by each laboratory to do the evaluation. We see from this that the evaluation methods and the different laboratories have very nice agreement in the ultimate results. The conclusion is that the International Atomic Time Scale is about 1 part in 10^{12} too high in its frequency, i.e., the second as communicated to the user via TAI is 1 part in 10^{12} too short.

We now should go back to the question of the hexapole beam optics. It is essential to have the capability of retracing the trajectory of the original beam when a change is made in the mean velocity of the beam, by either beam reversal, beam optic switching, microwave power, or pulsed operation. Dipole optics have the very fundamental problem that they do not only state-select, but also produce a spatial velocity spectrum, i.e, they act like an optical prism, whereas, the hexapole optic acts more like a lens focussing along an optical axis. Thus, if a change in velocity is effected, the hexapole beam optic will, in first order, still project the atomic beam along the optical axis of the system, whereas in the dipole case, the beam would have a different spatial location. Since the cavity is not fully characterized by a unique cavity phase shift (but in the next order of approximation must also be characterized by the distribution of phases across the opening and along the axis in one of the cavity sections) the atomic beam will sample a different phase shift depending on the particular spatial location of the beam within the cavity. This limits the ability to assign a cavity phase shift correction [34]. Such limitation will incidentally be the worse the shorter the cavity length. Thus, for future high performance cesium standards the hexapole optics may be the optics of choice. Another advantage of the hexapole optics which relates to this cavity phase shift problem, is that a high intensity is realized while the beam is kept fairly narrow allowing small cavity openings and less critical sampling of a distributed phase shift across and along the cavity opening. Since accuracy is for all practical purposes related to very long term stability some of these considerations might influence the design of future commercial standards.

C. Hydrogen Maser Standards

Hydrogen masers are rather simple devices as shown in Fig. 4. The hydrogen is produced usually by a radio frequency discharge from molecular hydrogen. The beam then emerges in a vacuum, passes a state selecting hexapole magnet, and enters a quartz vessel whose inside is lined with a fluorocarbon coating. This storage bulb is located inside of a microwave cavity. If the cavity losses are low enough and the intensity of the state selected hydrogen beam high enough, self-sustained oscillations occur and a microwave output is generated. This microwave output is used to lock a crystal oscillator to the hydrogen transition frequency via a frequency synthesizer and a phase comparator. Storage times of up to 1 second can be realized ultimately limited by recombination of hydrogen and relaxation of the state selected hydrogen atoms after too many wall bounces. The Q-values of hydrogen masers are the highest of all the traditional frequency standards and are typically 2×10^{9} which accounts for the excellent stability of hydrogen masers as listed in Table 1 and Figure 2.

Design options which have been available over the past years are the following (see Table 5): The basic design of the vacuum chamber was traditionally a two-chamber design one chamber containing the beam system, the second containing the storage bulb and, in some cases, the cavity [40]. A one-chamber design has made it possible to significantly reduce the size of the hydrogen maser as shown in Table 2 [41].

For the basic design of the cavity one has two choices and both were realized over the past years with success. The total temperature coefficient of the cavity (including the dielectric temperature dependence of the storage bulb) is designed as close to zero as possible adding a very precise temperature control [40,42]. This design has the advantage that it assures a low temperature coefficient in a well controlled environment. It has the potential problem of mechanical stresses and strains due to temperature gradients in the low heat conductivity materials used for the cavity. For this reason, the other, all metal design was pursued [43]. A good temperature control is added, and a servo is used to keep the cavity tuned. This leads to the next point, the cavity control:Either a thermostat, is used, or a tuning servo which senses changes in the cavity resonance and corrects as necessary. All combinations of cavity design and cavity control have been tried successfully with results which do not differ very significantly from each other.

The fundamental limitation in accuracy of the hydrogen maser (or of any device using the hydrogen storage principle) are the wall collisions and the second-order Doppler effect. The second-order Doppler effect is of the order of 1.4×10^{-13} per degree kelvin, thus, a control to 1×10^{-14} in long term requires a temperature stability of slightly better than a tenth of a degree. In order to apply an absolute correction with regard to the second-order Doppler effect one has to know the absolute temperature to a corresponding precision. If an absolute accuracy of parts in 10^{14} is desired it means the ability to determine the absolute temperature of the hydrogen atom ensemble to better than a tenth of a degree at about 300^{o}K which is by no means a trivial task. Also, one has to assume that the ensemble of hydrogen atoms in the storage bulb is in adequate thermal equilibrium with the storage bulb wall. (Experiments by H. E. Peters support the validity of this assumption).

Wall collisions cause a phase shift in each collision of a radiating atom with the surface of the storage bulb. The accumulated phase shift during the lifetime of a radiating atom in the storage bulb results in a frequency shift. For typical bulb sizes, the related frequency shift is of the order of 2×10^{-11}.

Many wallshift experiments have been carried out during the existence of hydrogen maser devices [44]. New developments in the understanding of hydrogen masers, of wall coating problems, and better cesium beam standards as references have led to a number of recent measurements with improved precision. Table 7 lists eight such measurements since 1970 [44,45,46,47,48,49,50]. With the exception of the Harvard measurement of 1974, all other measurements rely on the traditional technique of equipping a given hydrogen maser with a series of storage bulbs of different sizes. This allows an extrapolation to infinite diameter equivalent to zero wallshift. These multiple bulb measurements rely on the assumption that the resettability of the hydrogen maser is adequate to a precision much better than the desired wallshift value, and also on the ability to produce the same wall properties from bulb to bulb. The Harvard measurement involves the so called "big-box" hydrogen maser [49,51] (a large storage container outside of the cavity) and a change in its surface to volume ratio by means of a flexible wall of the storage bulb. The two efforts marked with an asterisk do not rely on unique multiple bulb measurements but take the results of other efforts.

The present accuracy of the hydrogen maser is limited by the wall collision effect to 1×10^{-12} and is thus considerably worse than that of cesium; however, more thorough use of new evaluation techniques such as the variable or flexible storage bulb [49,52,53] (applied also to small bulbs), and use of the temperature dependence of the wall shift [54] are likely to yield better results. A special incentive towards this goal lies in the documented fact that the wallshift appears to be highly stable in the well controlled environment inside of the vacuum of a hydrogen maser. Masers have run over many years with at most 1×10^{-13} drift per year [55]. This estimate is actually the measurement limit of the systems employed. Thus, hydrogen masers are very good candidates indeed for clocks and accurate primary frequency standards.

D. Rubidium Standards

The basic design of a passive rubidium gas cell standard is depicted in Fig. 5. Rubidium and some buffer gas is contained within a storage cell located within a microwave cavity. The storage cell is completely sealed off. A lamp emits light at an optical transition of the rubidium. It is transmitted through a filter which contains a rubidium isotope, then through the rubidium cell to a photo-detector. If the signal injected from a slave oscillator into the cavity coincides with the microwave transition, the light intensity is changed due to the simultaneous action of the microwave radiation and the light radiation on the same energy level. Thus the detector signal can be used in a feedback network to keep the slave oscillator on the rubidium resonance frequency. If the cavity is of sufficiently low loss, and the rubidium content and the lamp intensity are sufficiently high, the system is capable of self-sustained oscillations. Rubidium maser oscillators (Fig.6) have been built [56] with an output frequency equivalent to the rubidium transition frequency. As in the case of a hydrogen maser, a crystal oscillator can be locked to the rubidium resonance via a frequency synthesis chain and phase detector.

The system can be built rather compactly and thus has led, especially in its passive version, to several commercial devices of rather small size, weight, and low cost as compared to the other available frequency standards.

The only significant design option which has evolved over the past years is the optical microwave package design. The traditional design is shown in Fig.5 and 6 where we have physically separated lamp, filter, and gas cell. The other alternative is a "distributed filter" by using suitable isotope mixtures in lamp and gas cell which will yield the desired filtering without the necessity of having a separate filter [57]. This allows an even higher degree of compactness of the fundamental optical package.

One accuracy limitation of a rubidium gas cell is due to the use of buffer gas mixtures in addition to rubidium in the gas cell which introduces frequency shifts of potentially larger than 10^{-10}. These frequency shifts are difficult to evaluate since they would require a knowledge of the precise composition and physical action of the gases in the cell. In view of the size of the effect it is rather obvious that this is a difficult task if we are talking about accuracies of 10^{-13} or better. The other serious shortcoming, as far as accuracy is concerned, is the simultaneity of the light and the microwave interaction. Two radiation fields of different frequency which couple to the same atomic state influence each other. In other words, the exact microwave resonance depends on the intensity and the spectral distribution of the optical light. Again, these effects are of the order of 10^{-10} and thus very difficult to evaluate accurately. For these reasons, rubidium gas cells do not take part in the considerations about an independent, primary frequency standard capable of being evaluated. For the same reasons, rubidium standards exhibit a long term performance including aging and drift which is considerably inferior to that of the other standards. It is likely that this behavior is due to small changes in buffer gas composition, rubidium density, light intensity, spectral distribution of the light, etc., as the standard ages. This demonstrates the already stated link between accuracy and long term stability. However, new developments appear to yield some better handling of these long term processes.

New Concepts and Principles

We included here only those concepts and principles which have demonstrated in the laboratory with adequate theoretical analysis their likelihood of being used in an atomic frequency standard device. In the following, we will discuss in more detail the basic principles of these new devices.

A. Hydrogen Atomic Beam

One variety of this concept is very analagous to that of cesium shown in Fig.3 Atomic hydrogen is generated by radio frequency discharge from molecular hydrogen. It passes a state selector which may or may not be a hexapole magnet and then enters a cavity which in the case of the hydrogen resonance would be of considerably different design than for cesium. The beam passes through a second state selector and reaches a detector. If sufficient beam intensities are available, universal detectors such as a pressure gauge type detector,or an electron bombardment ionizer detector possibly followed by a mass spectrometer can be used.A complete system of this configuration has been demonstrated [20]. The line-Q in this system is given by the interaction time of the atoms with the microwave field and thus depends on the speed of the hydrogen beam which, because it is a light atom, is very fast. Velocity selection and cooling in addition to state selection has been employed to reduce the mean velocity. Line-Q's of several 10^6 have been reported [20], and further increases in the line-Q appear possible.

The second variety of the passive hydrogen principle is depicted in Fig.7 [21]. We see here a mixture of the basic cesium principle of Fig. 3 and the basic hydrogen principle of Fig. 4. The atomic hydrogen beam, after passing the state selector, enters a storage container, and is allowed to spend some time in the storage bulb. After leaving the storage bulb the atoms pass a second state selector and finally are detected. The arrangement in Fig. 7 of a beam stop and input and output at opposite ends of the storage bulb is actually not desirable, but is shown here for simplicity of the Figure. The line-Q can be as high as in the hydrogen maser oscillator because of the storage principle.The detector has to be highly selective and low noise, and thus poses an even bigger problem as in the previously discussed hydrogen variety, because the re-formation of a focussed atomic beam will be accompanied by a significant loss in particles. An efficient, selective atomic hydrogen detector does not exist at present. Thus, the realization of this principle is crucially dependent on the development of such a detector. Its advantages are, that it features a stability which is equivalent to that of a hydrogen maser for short and medium term and may have an even better long term stability,or, at least, less technical problems with achieving very excellent long term stability. The cavity pulling effect can be reduced to insignificance, thus relaxing temperature stability, cavity tuning and cavity design problems. The evaluation of the wallshift is here still a necessity but may be eased by the ability to vary bulb parameters in a much wider range and with less effect via cavity pulling than in the case of the active maser oscillator. A compromise between the desire for a passive device and the unavailability of an efficient detector is a passive hydrogen maser device as depicted in Fig.4. A microwave signal is injected into the cavity which has a very low Q-value so that self-oscillations are not possible. The response of the hydrogen system is then detected by looking at the amplitude or phase change due to the presence of atomic hydrogen. Stabilities of 10^{-13} and a line-Q of 10^{9} have been achieved using that principle [22].

B. Ion Storage

Figure 8 gives a crude schematic of a possible ion storage configuration [7]. Because of the great variety of not fully explored possibilities of injecting a microwave signal into the ion ensemble, of interrogating this ion ensemble, and of state selection, these features are omitted in the schematic. Ion storage is capable of featuring very high line-Q's of 10^{10} or more [58]. Resonance frequencies correspond to hyperfine transitions in atomic ions and thus lie in the GHz region. No working frequency standards have yet been constructed based on this principle. Its basic advantage, aside from the very high line-Q's is the use of electromagnetic fields to create containing potential walls. An analysis of the corresponding effects has shown their influence is less than 1×10^{-14}[59]. The main drawback of this method is the difficulty in determining the speed of the ions (Doppler effects). Also, the signal-to-noise ratio of this configuration has been a problem due to the limited number of ions which can be stored at one time within the trap.

C. Saturated Molecular Absorption

The basic principle is shown in Fig. 9. A laser acts as the slave oscillator which interrogates gas at low pressure contained in a suitable cell. The light is transmitted through the cell in one direction and back in the opposite direction. With a proper choice of laser power we obtain the effect of saturated absorption which has been described in detail elsewhere [60,61]. In saturated absorption, preferential interaction with the light field occurs for those atoms with vanishing velocity components in the direction of light propagation. First order Doppler effect and Doppler broadening is largely avoided, and we obtain very narrow lines. The signal is detected by a suitable light-sensitive detector and used to steer the laser to the molecular resonance. Line-Q's of 10^{9} have routinely been achieved and line-Q's of 10^{11} have already been reported [62]. The best results in terms of frequency standard performance have been obtained with the methane/helium-neon combination [63,64,65].Stabilities of 2×10^{-13} for 1 s averaging time have been reported by several laboratories, and flicker "floors" of parts in 10^{14} have been achieved. No reliable long term data beyond the order of one hour exist. In certain configurations which tend to be on the low Q side (approx. 10^{9}), very small, simple, and rugged designs appear possible. Thus, these devices have the potential of not only being very high precision laboratory devices, but also of being user oriented. The study of the accuracy potential of these devices is still incomplete with no full experimental data available at the present time to support accuracy claims beyond 10^{11}. However, analysis of the underlying principles allow a projection of a potential accuracy and of a related long term stability of much better than this figure. The practical drawback of this device is not its own fault; it lies in the fact that it is still not easy to link its frequency to the microwave region. First, it has not yet been demonstrated that frequencies can be translated between the traditional frequency regions and the upper THz region with a precision allowing the full exploitation of the potential of devices on both sides, i.e., cesium and hydrogen on one side, and saturated absorption stabilized lasers on the other. Secondly, the methods used are not yet simple enough to be truly practical. This situation is expected to change in the future.

D. Submillimeter Beams

The submillimeter beam concept has only recently been proposed as an atomic frequency standard, and its experimental realization is in its early stage. The basic concept [18] is shown in Fig. 10. A beam of magnesium is generated which after leaving the oven is subjected to an electron discharge creating metastable magnesium atoms. A transition at about 0.6 THz can be stimulated in this metastable state by subjecting the atoms to radiation from a slave oscillator at this frequency in a suitable resonator. As a result, the magnesium atoms are transferred to a state from which a radiative optical transition is possible, which can be detected as fluorescence of the beam after the beam has passed the resonator. Thus, the degree of light from the beam as picked up by a photo detector can be used to steer the slave oscillator. The magnesium beam and the generation of the metastable state has been successfully demonstrated at this time [66]. However, a suitable, spectrally pure source for the 0.6 THz (or the 1.5 THz, in the case of calcium) has not yet been realized. There are several technical possibilities to this end. One promising multiplier is the Josephson junction as a harmonic generator]19],and spectrally pure frequency sources in the microwave region may include crystal oscillators of improved short term stability [67,68],as well as superconducting cavities [69,70]. The advantages of this beam concept as compared to microwave beam concepts, such as cesium, lies in the much higher frequency which reduces, fractionally, most effects except for Doppler effects. Also, very high beam intensities which promise very excellent short-term stabilities (exceeding 10^{-13} for 1 s), and high line-Q's in the 10^9 region appear possible. Technical problems, besides the generation of the high resonance frequency, include phase shifts in the resonator which are not easy to avoid (though possible) in view of the rather short wavelength.

E. Optical Beams

The basic principle is depicted in Fig. 11. An atomic or molecular beam is interrogated at right angles with the light from a laser oscillator. The right angle arrangement can avoid to high order Doppler shifts of first order and Doppler broadening. Thus, we can achieve narrow lines and correspondingly line-Q's of the order of 10^9. The combination of an iodine beam with an argon ion laser has experimentally and successfully been tried [17].Stabilities of the order of 10^{-13} from one second to one hour have been reported [71]. The detection can be done by monitoring the laser light which contains the resonance of the iodine molecule. This has the disadvantage that the small signal rides on the large laser photon background, which causes excessive shot noise. If the fluorescence in the beam is detected, this background is avoided but the efficient collection of the radiation may pose problems. The system is conceptually and experimentally rather simple. The biggest problem in the particular combination discussed, is the spectral purity and stability behavior of the slave oscillator. The system has considerable potential for very competitive accuracy and short and long-term stability. It shares with the saturated molecular absorption the problem of having an optical frequency which at present prohibits its use as true time and frequency standard.

F. Rubidium Beam

The rubidium beam concept is depicted in Fig. 12. It is very much like the cesium beam concept shown in Fig. 3, except that state selection and detection is done by optical pumping [23]. Since optical pumping is less efficient in the state selection as well as the detection of particles, the system may have signal-to-noise problems, although wide beams could be used. However, it is a free rubidium beam and thus allows the measurement of the unperturbed rubidium resonance frequency with very good accuracy. It may thus play a role in the whole system of rubidium standards of various designs in developing more stable and more accurate rubidium devices.

G. Cesium Gas Cell

The design principles are very similar to those shown in Figs.5 and 6 for rubidium [72]. Both principles have been researched and are in an experimental stage; however, no full frequency standard has been built or tested at this time. One of the main differences to rubidium is that isotope filters are not possible. Magnetic effects are used for the filter which allows an efficient optical pumping [73]. One advantage of this principle is that, although the filter from a designer's viewpoint is more complicated than an isotope filter, it allows a stable and controllable spectral distribution of the light. It thus may have advantages as far as the evaluation and long-term stability of the light frequency shift is concerned.

Summary of the International Effort on Atomic Frequency Standards

It has become much more attractive in recent years to consider the use of systems in order to achieve excellence in short-term stability, medium-term stability, and long-term stability as well as accuracy. Frequency standards, which are excellent for certain averaging times, can be combined to systems which then are excellent throughout all averaging times. As an example, the ultimate in accuracy, which is presently realized by a laboratory type cesium standard, needs only a stability which allows the exploitation of its accuracy potential within a reasonable time--e.g., one day. The stability for times longer than one day can be realized by stable devices such as commercial cesium standards or hydrogen masers. For shorter time periods, one would resort to very stable devices which do not necessarily need to be accurate or long-term stable, such as rubidium standards or crystal oscillators. Several laboratories employ such composite systems as their basic time and frequency reference.

We should also not forget that, for some designs, principle physical limitations in short-term stability do exist. Short-term stability is linked to the available signal-to-noise and to the linewidth; e.g., in a rubidium standard, these two quantities become coupled. If one wants to increase the signal-to-noise (that is, the output power of a rubidium maser oscillator) one has to interrogate more rubidium atoms.This can be done by raising the rubidium gas density in the bulb and/or more pumping light. Both will have the effect of broadening the line. This line broadening has the effect of reducing the overall stability of the total standard. We find a similar, related phenomenon in hydrogen storage devices, such as the hydrogen maser, where an increase in signal-to-noise would mean a larger input of hydrogen atoms into the storage bulb. At some point, this increased input of hydrogen atoms will defeat the power related increase in stability due to broadening of the line because of spin exchange collisions of the hydrogen atoms with each other. In both devices, rubidium and hydrogen, this effect has been estimated to limit the short-term stability to about 1 part in 10^{13} for 1 s averaging time. We realize that the actual devices are very close to this theoretical potential. Corresponding limitations can be found for practically all existing or proposed designs.

The following tables, 8 through 11, are essentially self-explanatory. For any listed type in Tables 8, 9, and 10, the reader may use as a cross reference Tables 1 and 2, in order to find the corresponding stability and physical characteristics. We also have assumed that all devices feature at least a 5MHz output. In Table 8, we list the manufacturers of commercially available frequency standards with their basic address and the types of standards which they manufacture. Table 9 is arranged in very much the same way as Table 8 but lists those commercial efforts which the author knows exist and which may lead in the future to the availability of devices of the indicated type. The comments here relate mainly to the likelihood of availability. Finally in Table 10, a list is found of non-commercial efforts throughout the world with the exclusion of eastern Europe. Indicated is the area of activity of each laboratory. Again, the author is bound to have omitted a few important efforts and would appreciate having any such omissions brought to his attention. In Table 11, a probably interesting numerical summary of the content of Tables 8 through 10 is given. The number of laboratories or companies is listed which mount an effort in any of the five selected fields: cesium beams, hydrogen maser oscillator, rubidium gas cell (including maser), saturated absorption stabilized laser, and the remaining other, more research oriented efforts. The active efforts are separated into non-commercial and commercial efforts. We see from this table that the biggest effort, numerically, concentrates on hydrogen maser oscillators followed by about similar efforts on cesium, rubidium, and saturated absorption stabilized lasers. The total number of laboratories working on all other approaches amounts to only eight.

Photographs of all commercially available frequency standards (compare Table 8) are depicted in Fig. 13 and 14, of maser devices and other laboratory devices in Fig. 15 and 16. The four operational and two near-operational primary cesium standards are shown in Fig. 17.

Impact of Atomic Frequency Standards

A. Science

The history of atomic frequency standards is intimately related to the development of atomic physics, and significant contributions have been made both ways between these related areas. For more information, the reader is referred to the surveys by McCoubrey [1], Ramsey [74], and Hellwig/Halford [13]. Table 12 lists five specific areas where significant impact of the atomic frequency standards has been felt. The first two areas relate to scientific metrology. The definition of the second, of course, has been related since 1967 to the transition frequency in cesium by the international agreement at the 13th General Conference on Weights and Measures. Since then, the cesium second was not always used by the time services of the world. The length of their second was adapted to the astronomical needs (i.e., to the rotation angle of the earth) with occasional adjustments in its length. Only since January 1972, by international agreement, the cesium second is used by most time services. The needs of navigators, who demand the rotation angle of the earth, are accommodated by inserting or leaving out leap seconds, as the need arises [75]. Very recently, however, a more accurate determination of the second by three laboratories in three different countries (see Table 6) has shown that even this international second (the second of the International Atomic Time, TAI) is not as good as it could be, and deviates by 1 part in 10^{12} from the "true" second.

In another area of metrology, the meter is increasingly related to atomic frequency standard devices. The meter is still internationally defined by the wavelength of the krypton lamp. Recently, however, practical definitions of the meter are proposed which are tied to frequencies of atomic frequency standards, such as methane and iodine stabilized helium-neon lasers [76,77]. In addition, it has been proposed and officially recommended that the meter may be defined by defining the speed of light, and thus eliminating an independent standard for the meter [78]. Length (wavelength) would then simply be determined by dividing by the defined number for the speed of light the measured frequency. Frequency is measured in terms of the cesium second. In a related move, the practical voltage standard is already tied to the frequency standard by an accepted ratio of $\frac{e}{h}$ making use of the Josephson effect [79]. One volt corresponds to a certain standard frequency multiplied by $^{h}/2e$ [80].

A very significant scientific application for atomic frequency standards of utmost stability has been very long baseline interferometry. Frequency standards with stabilities of 10^{-14} or better are needed to fully exploit the capability of VLBI [81,82], allowing the taking of astronomical data and constants. More recently an interesting earth application has developed. Position on earth or distances on the earth's surface can be measured very precisely by utilizing VLBI and high stability frequency standards. Position precisions of centimeters are being considered almost a reality for practical applications. Thus, it becomes possible to monitor and measure very precisely geophysical phenomena such as continental drift and changes in crustal strain. The latter one is likely to give insight into the mechanism of earthquakes and may even be used to predict earthquakes from unusual changes in the strain conditions in certain areas on earth [83].

Relativity is an obvious candidate for experiments using high performance atomic frequency standards. Relativistic effects have been observed using atomic frequency standards [84]. For example, the frequency of a standard changes by a little more than 1 part in 10^{13} for 1 km altitude change. The corresponding effect of 1.8×10^{-13} for the location of the U.S. National Bureau of Standards with respect to sea level has been included in Table 6. A very accurate measurement of this effect is now in preparation at the Smithsonian Astrophysical Observatory with support from NASA [85] and scheduled for 1975. It involves sending a high performance hydrogen maser oscillator in a probe into space for a several hour flight. The expected accuracy of this measurement may be as high as 10^{-5} of the effect. Effects due to the rotating earth have been experimentally demonstrated by Haefele and Keating [84], in which ensembles of clocks were carried on commercial airline flights around the earth in easterly and westerly directions. A theoretical analysis shows that even with an infinitesimal slow movement of one clock in an easterly direction and of another clock in a westerly direction, staying on the surface of the earth, the time difference between ideal clocks would be 200 ns due to their movement in a rotating frame with respect to the stars [86].

B. Technology

For technical applications and systems usage of atomic frequency standards, it is usually of advantage to talk about time or time interval. We have to remember that one nanosecond per day approximately corresponds to a fractional frequency stability of 1×10^{-14}. Table 13 lists two major areas: navigation and communication. Navigation has historically played a tremendous role in the development of clocks. Clocks and frequency standards have, in turn, advanced the state-of-the-art of navigation. The interest in the exploration of the world starting with the discovery of the New World by Columbus followed by a succession of famous voyages of explorers led naturally to a demand for good clocks. The first clocks which incorporate the modern principle of frequency standards were developed in the 17th century based at that time, of course, on mechanical devices such as the balance wheel and the gravitational pendulum. Navigators need time since the determination of an unknown position on earth from a table plus an observation of celestial objects requires a time reference. In modern times, artificial aids were developed for more precise navigation on sea, land, and in the air, and more recently in space. They depend for a position determination basically on the speed of light. Thus, we find another translation: a position determination with an accuracy of 1 m requires a time accuracy of 3 nanoseconds. Clocks may be needed in vehicles, ships, aircraft, or spacecraft for navigational purposes with a quality depending on the accuracy requirement and on the ability or desirability of resetting those clocks. A very good frequency standard with an excellent long-term stability will be needed if high accuracy is required but at the same time resynchronization is either only infrequently possible or is to be avoided for security or reliability reasons; or it is impossible because of the location of the clock carrier.

Navigational aids [87] which are available to a large class of users include standard frequency and time broadcasts of many nations, the Loran-C system with a capability of about a tenth of a microsecond, and, for space navigation, the NASA tracking stations. Characteristically, we find high performance atomic frequency standards or groups of such standards as the signal source at corresponding stations. For the future, even more sophisticated networks are proposed, such as aircraft collision avoidance systems [88] which may allow a three dimensional navigation of aircraft to accuracies of meters near airports and hundreds of meters in intercontinental flights. Another example is a navigational system based on satellites. Satellites will carry clocks and ground stations will be equipped with clocks. Systems such as these two proposed ones require clocks which are at least state-of-the-art, if not beyond.

Communication has traditionally used standard frequencies to allocate frequency bands in the electromagnetic spectrum. The required accuracy was state-of-the-art in the beginning of the era of radio broadcasts but these demands can now be fulfilled rather easily. However, new demands in communication, mainly the coupling of computers over large distances, requires networks which are able to handle extremely high bit rates. In a synchronous mode, independent clocks at the ends of such a communication network are needed. If megabits are to be handled, we need clock accuracies in the sub-microsecond region. If such a communication has to be continually maintained for extended time periods, it taxes the capability of even the best frequency standards available. Networks are in a state of implementation which utilize atomic clock ensembles as their base clock, such as the new Bell System facilities [89]. Television networks routinely use atomic frequency standards to assure adequate phase stability of the color subcarrier signals. As a result, the color subcarrier can be used as a standard frequency source [90].

Future Outlook

A. Traditional Standards

The following is the author's guess at the future: It is likely that rubidium standards with significantly reduced aging and a somewhat reduced flicker noise "floor" can be designed. A "floor" of better than 1×10^{-13} appears likely and a reduction in the aging of at least one order of magnitude. Smaller and cheaper rubidium devices are already being developed and will come on the market. Prices of $2000 in larger quantities for "low" performance units do not seem unreasonable. Lifetimes are likely to be extended for all three standards by the development of better vacuum technology, gas handling, and component reliability. Rubidium standards are likely to reach volumes of less than 1 liter and weights of less than 1 kilogram. There is no reason to believe that accuracy of rubidium standards can ever become competitive with that of the other two traditional standards which is expected to become better than 1×10^{-13}. Hydrogen masers will probably further lower their flicker "floor", possibly to below the 10^{-15} level. Similar developments may take place in the case of cesium devices. New approaches to interrogate the atoms, and more advanced engineering may lead to long-term stabilities which are better than 10^{-14}. Whether the hydrogen maser can be further reduced in size beyond the present maser for space application appears doubtful. However, cesium devices are likely to become significantly smaller, and a device with a total volume of 10 liters and a weight of 10 kilograms seems quite realistic. Prices of hydrogen masers are very difficult to assess and as long as they are not manufactured in significant numbers commercially, an estimate of the price seems to be too risky. In the case of cesium standards, $7000 appears to be an achievable figure. Advances in electronics and packaging are also likely to reduce the overall power consumption of devices.

B. New Concepts

We have taken an earlier guess at the basic capabilities of the seven discussed techniques and shall not repeat this here. Of interest for the future may be an assessment of the device capabilities of such standards. Saturated absorption, passive hydrogen devices, and sub-mm and optical beams are very likely candidates with regard to their potential as primary frequency standards. Such a usage appears doubtful in the case of ion storage. The optically pumped cesium and the rubidium beam are considered unlikely to be truly competitive.

With regard to frequency stability, ion storage is at present an unlikely competitor because of signal-to-noise problems of the device. The optically pumped rubidium beam and optical beams are considered as possible competitors capable of matching the performance of present atomic standards. However, saturated absorption, passive hydrogen, and sub-millimeter beams offer stabilities considerably superior to those realized with today's standards.

The commercial device potential includes the consideration whether a device can be built small enough or priced low enough to be commercially attractive. Here, saturated absorption and passive hydrogen are likely candidates. Ion storage and optically pumped cesium have some possibility because they are intrinsically relatively small devices. Unlikely candidates are all new beam concepts because a very excellent beam device (cesium) already exists featuring attractive characteristics in volume, length, weight, cost, etc.

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NOTE:

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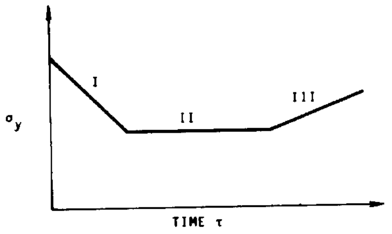
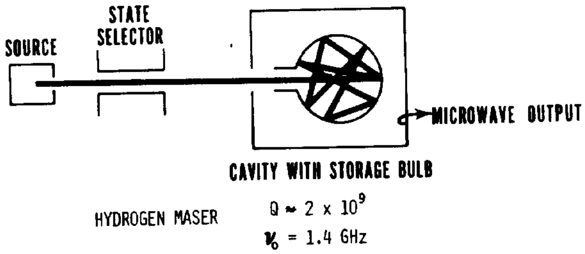


I.	$\sigma_y \sim \tau^{-1}$	WHITE OR FLICKER OF PHASE NOISE
	$\sigma_y \sim \tau^{-1/2}$	WHITE FREQUENCY NOISE
II.	σ_y = CONSTANT	FLICKER "FLOOR" (FLICKER OF FREQUENCY)
III.	$\sigma_y \sim \tau^{\alpha}$	$0 \le \alpha \le 1$ TYPICAL
		$\alpha = 1$ PURE FREQUENCY DRIFT (AGING)

Fig. 1 General frequency stability characteristic.

FIGURE 4



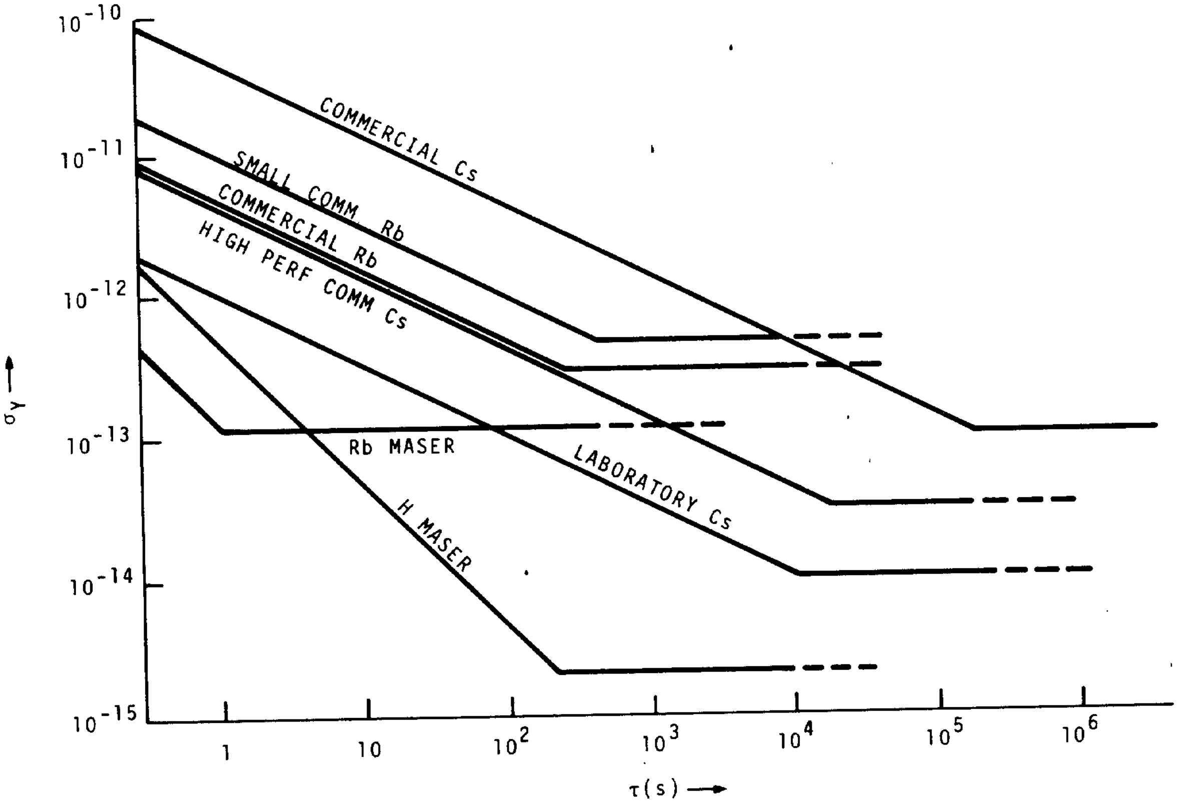


Fig. 2 Measured frequency stabilities of various types of atomic frequency standards.

FIGURE 3

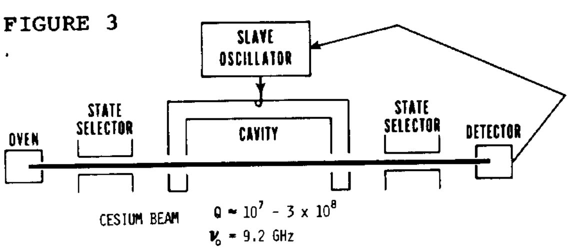


FIGURE 5

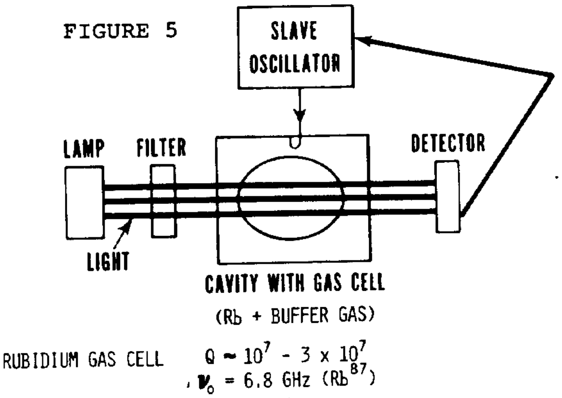
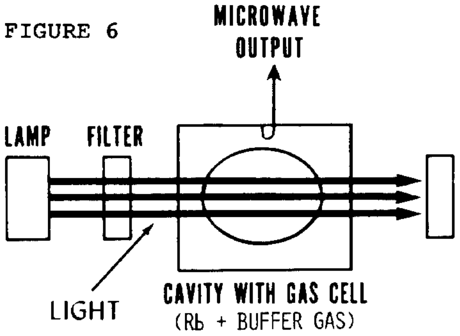
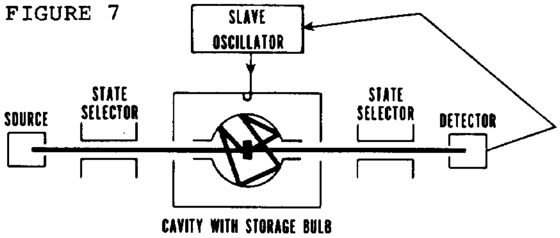


FIGURE 6



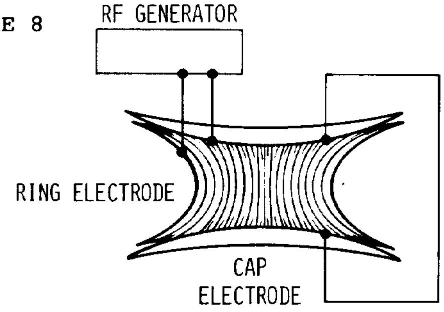
RUBIDIUM MASER $Q \approx 10^7$
$\nu_0 = 6.8$ GHz (Rb^{87})
$= 3.0$ GHz (Rb^{85})

FIGURE 7



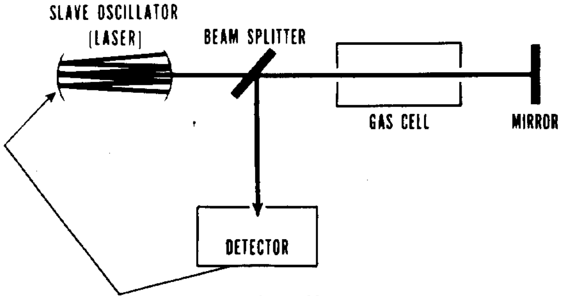
HYDROGEN STORAGE BEAM $Q \approx 2 \times 10^9$
$\nu_0 = 1.4$ GHz

FIGURE 8



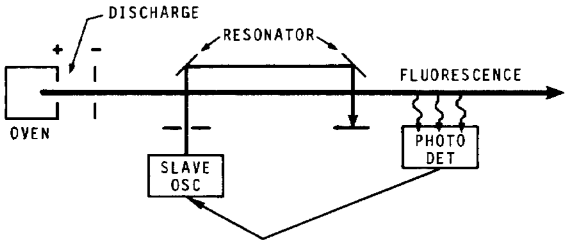
ION STORAGE $Q \approx 10^8 - 10^{10}$
ν_0 = GHz REGION

FIGURE 9



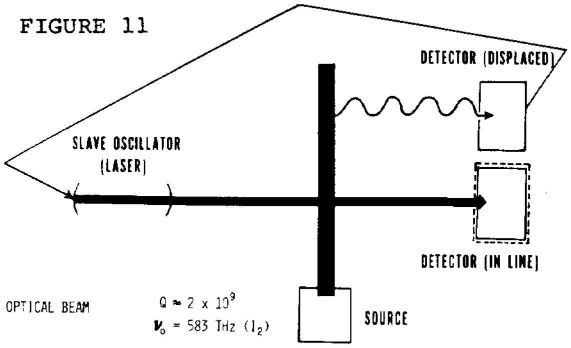
SATURATED ABSORPTION $Q \approx 10^9 - 10^{11}$
ν_0 = THz REGION

FIGURE 10



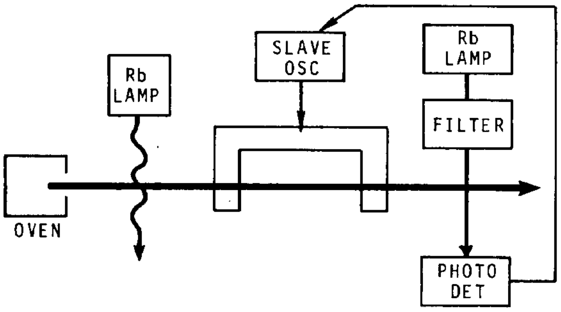
SUB-MM BEAM $Q \approx 5 \times 10^9$
$\nu_0 = 0.6$ THz (Mg)

FIGURE 11

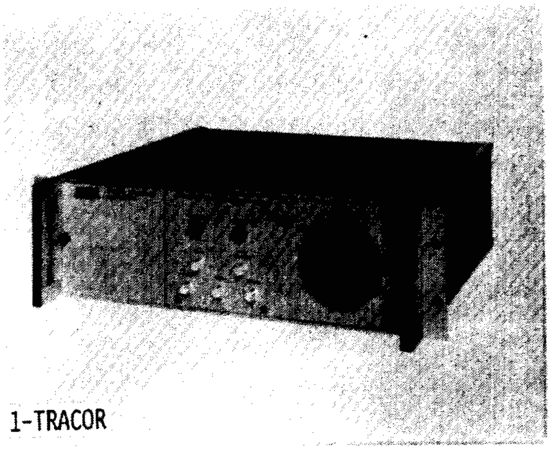


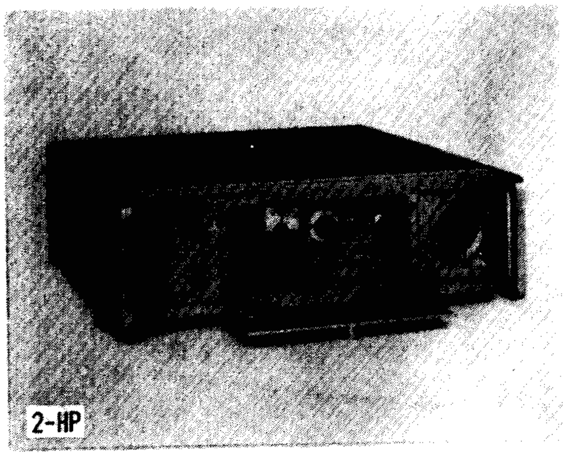
OPTICAL BEAM $Q \approx 2 \times 10^9$
$\nu_0 = 583$ THz (I_2)

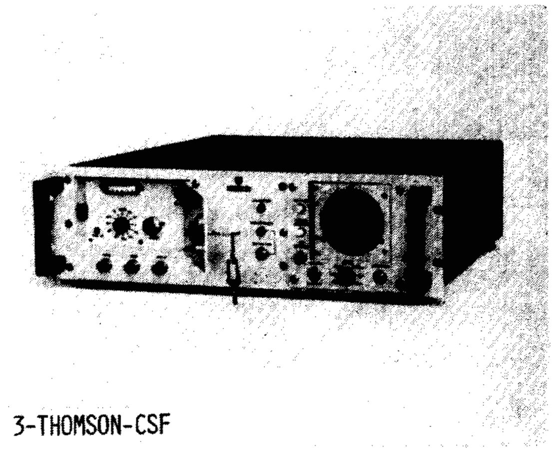
FIGURE 12

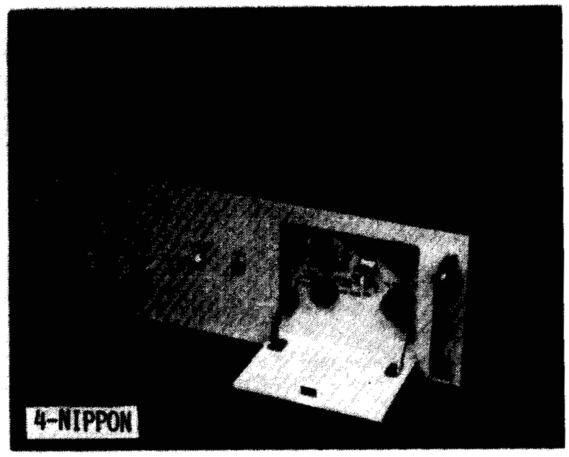


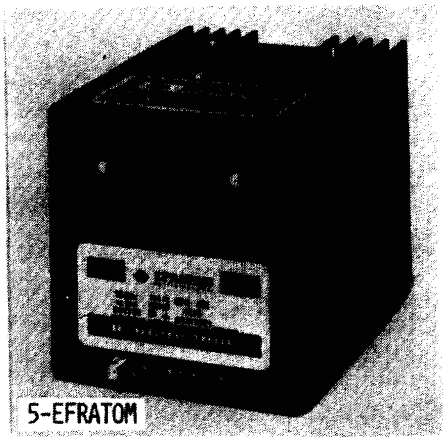
RUBIDIUM BEAM $Q \approx 10^7$
$\nu_0 = 6.8$ GHz (Rb^{87})


1-TRACOR


2-HP


3-THOMSON-CSF


4-NIPPON


5-EFRATOM

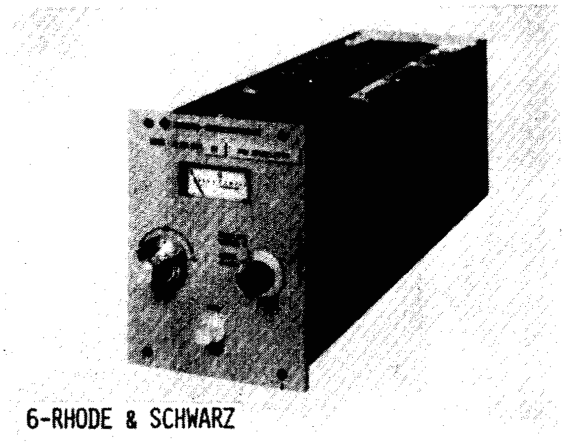
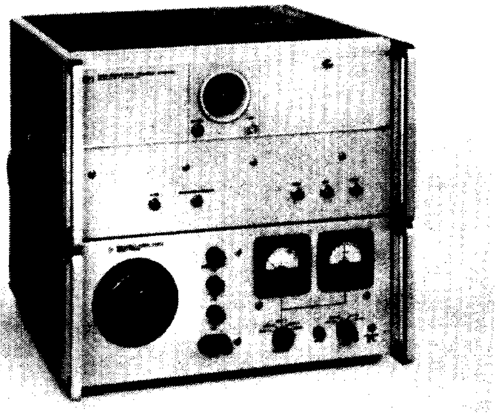
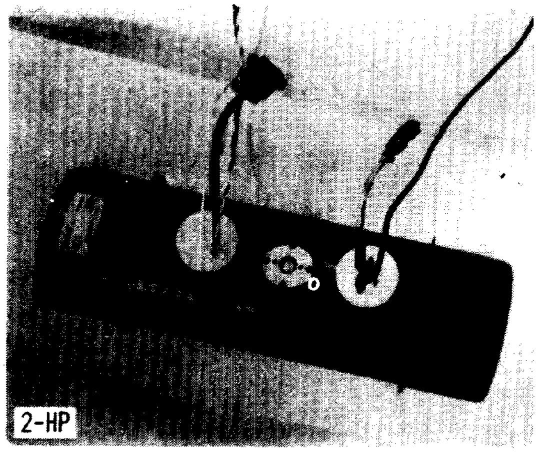
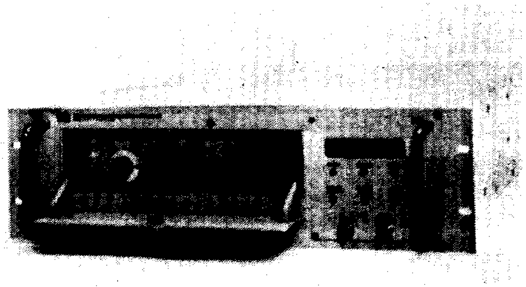
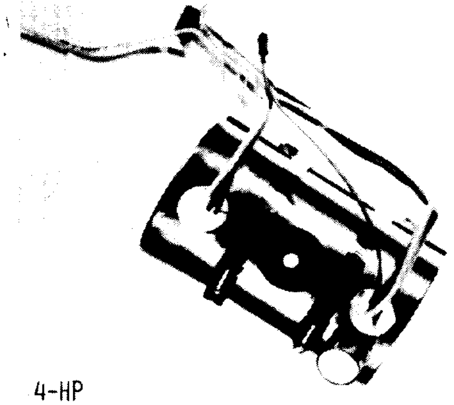

6-RHODE & SCHWARZ

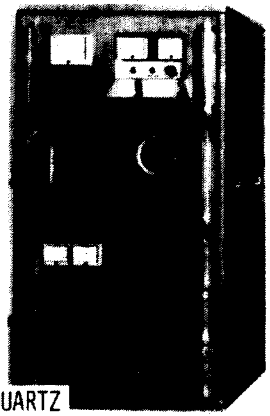
Fig. 13-1. Tracor, Inc., USA. Rb standard Mod. 304D.
2. Hewlett-Packard Co., USA. Rb standard Mod, 5065A.
3. Thomson-CSF, France. Rb standard Mod. HAM 111.
4. Nippon Electronics Co., Japan. Rb standard. Mod. Neatomic Rb-1003.
5. Efratom, Calif., Inc., USA. Rb standard Mod. FRK (width approx. 10cm).
6. Rhode & Schwarz, Germany. Rb standard Mod. XSPM (panel width approx. 10cm).


1-HP


2-HP


3-HP


4-HP


5-OSCILLOQUARTZ

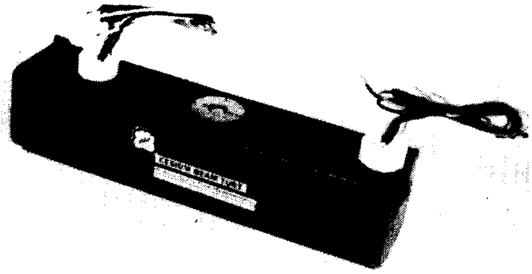

6-FTS

Fig. 14
1. Hewlett-Packard Co., USA. Cs standard Mod. 5061A with separate battery power supply.
2. Hewlett-Packard Co., USA. Cs beam tube, 40cm long, 14cm diameter, used in Mod. 5061A.
3. Hewlett-Packard Co., USA. Cs standard, Mod. 5062C.
4. Hewlett-Packard Co., USA. Cs beam tube, 16cm long, 11cm diameter, used in Mod. 5062C.
5. Oscilloquartz SA, Switzerland. Cs standard Oscillatom 1 with separate battery power supply.
6. Frequency and Time Systems, Inc., USA. Cs beam tube, 32cm long, 8cm x 8cm cross section.

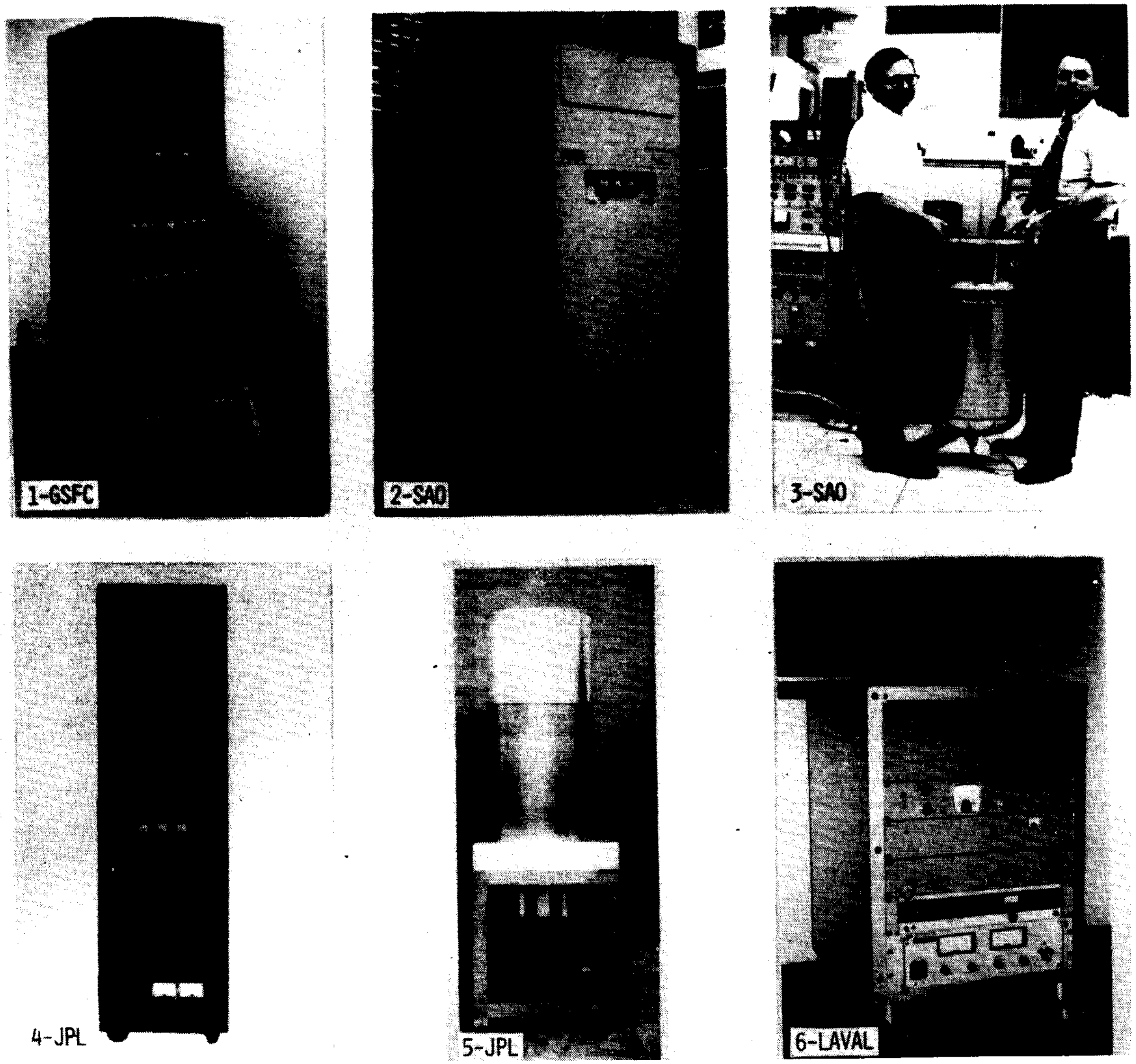


Fig.15 (1) NASA-GSFC, USA, H-maser standard of the NP-series. Several of this type have been built; (2) Smithsonian Astrophysical Observatory, USA, H-maser standard of the ground-station type; (3) Smithsonian Astrophysical Observatory, USA, H-maser for space flight application; (4) Jet Propulsion Laboratory, USA, H-maser standard; (5) Jet Propulsion Laboratory, USA, H-maser; (6) Laval University, Canada, Rb-maser standard.

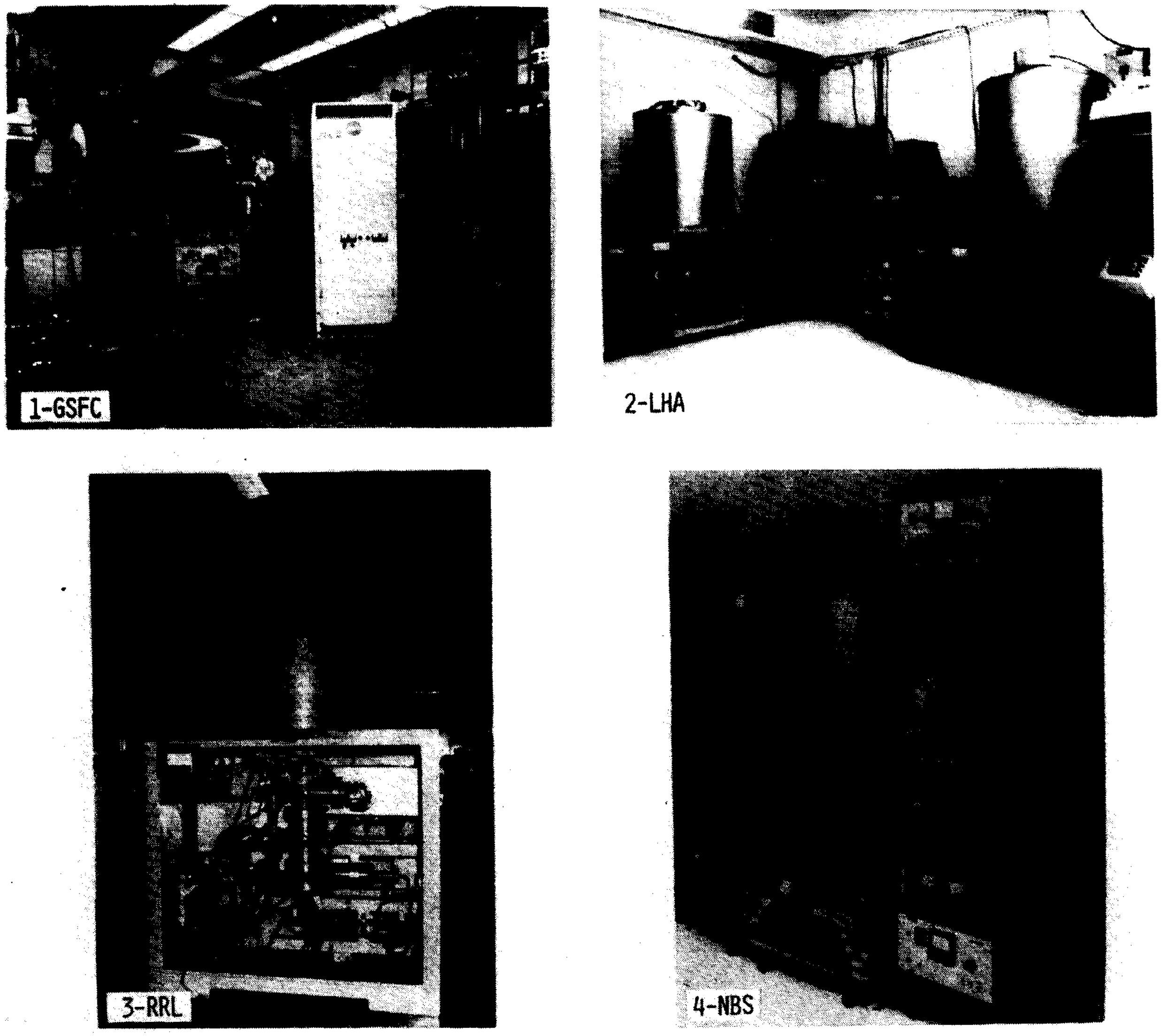
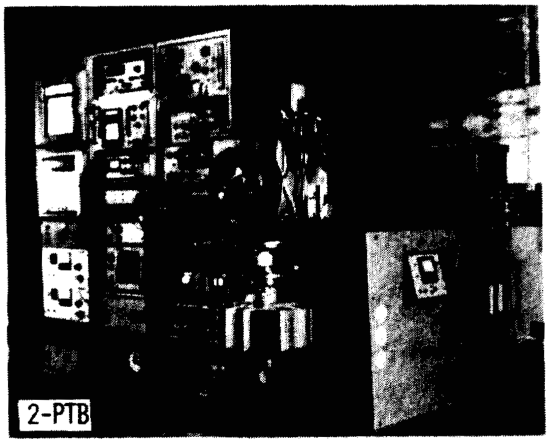
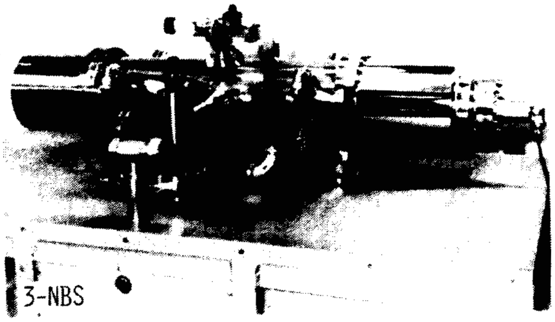
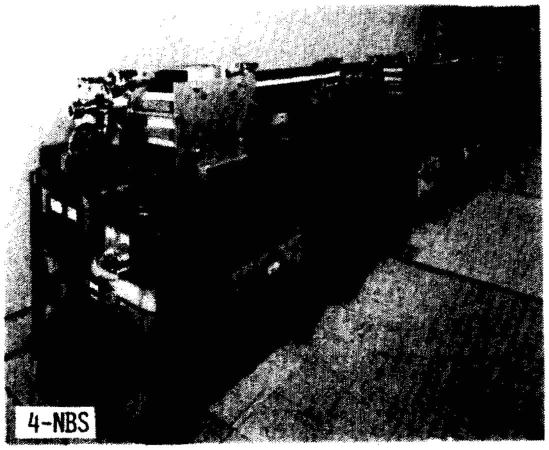


Fig. 16-1. NASA-GSFC, USA. Hydrogen program: left; free H-beam device; center; H-maser standard of the new NX-series; right; experimental H-maser.
2. Laboratoire d'Horloge Atomique, France. Two H-maser standards.
3. Radio Research Laboratory, Japan. H-maser standard.
4. National Bureau of Standards, USA. Passive H-storage device (right) and experimental H-beam (left).







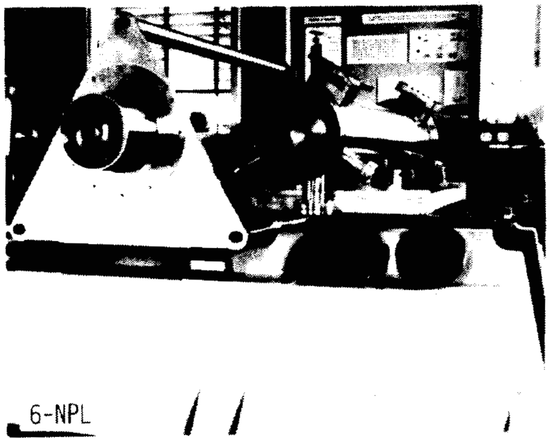


Fig. 17-1. National Research Council, Canada. Operational primary cesium standard Cs V.
2. Physikalisch Technische Bundesanstalt, Germany (BRD). Operational primary cesium standard Cs 1.
3. National Bureau of Standards, USA. Operational primary cesium standard NBS-4.
4. National Bureau of Standards, USA. Operational primary cesium standard NBS-5.
5. National Research Laboratory of Metrology, Japan. Primary cesium standard.
6. National Physical Laboratory, UK. Primary cesium standard NPL III (unassembled).

TABLE 1

STABILITY

	SHORT TERM	"FLOOR"	DRIFT (PER YEAR)
SMALL COMM Rb	$\sigma_y = K\tau^{-\frac{1}{2}}$ $K = 1\times10^{-11}$	5×10^{-13}	10^{-9}
COMM Rb	$\sigma_y = K\tau^{-\frac{1}{2}}$ $K = 5\times10^{-12}$	3×10^{-13}	10^{-10}
Rb MASER	$\sigma_y = K\tau^{-1}$ $K = 1\times10^{-13}$	1×10^{-13}	NO DATA AVAILABLE
SMALL H MASER	$\sigma_y = K\tau^{-1}$ $K = 5\times10^{-13}$	1×10^{-14}	NO DATA AVAILABLE
H MASER	$\sigma_y = K\tau^{-1}$ $K = 5\times10^{-13}$	2×10^{-15}	NONE DETECTED 10^{-13} LIMIT
SMALL COMM Cs	$\sigma_y = K\tau^{-\frac{1}{2}}$ $K = 5\times10^{-11}$	INSUFFICIENT DATA AVAILABLE	
COMM Cs	$\sigma_y = K\tau^{-\frac{1}{2}}$ $K = 5\times10^{-11}$	1×10^{-13}	SEVERAL 10^{-13} IN SOME CASES
HIGH PERF COMM Cs	$\sigma_y = K\tau^{-\frac{1}{2}}$ $K = 5\times10^{-12}$	3×10^{-14}	NO DATA AVAILABLE
EVALUABLE LAB Cs	$\sigma_y = K\tau^{-\frac{1}{2}}$ $K = 1\times10^{-12}$	1×10^{-14}	NONE DETECTED 10^{-13} LIMIT

TABLE 2

PHYSICAL CHARACTERISTICS

	VOLUME (LITER)	WEIGHT (Kg)	LIFETIME (YEARS)	POWER* DEMAND (WATTS)	EST PURCH PRICE FOR SINGLE UNITS(K$)
SMALL COMM Rb	A FEW 1	1-2	>3 LIMITED BY LAMP, FILTER, GAS CELL	10-15	5
COMM Rb	A FEW 10	10-20	>3	30-40	7-10
Rb MASER	~ 50	50	NO DATA	EST >30	EST >20
SMALL H MASER	~ 100	45	>0.3 LIMITED BY VAC PUMP CAPACITY	20	
H MASER	~ 1000	200	>5	30-100	100
SMALL COMM Cs	~ 20	20	>1 LIMITED BY Cs EXHAUSTION AND/OR Cs GETTER SATURATION	30	15
COMM Cs	A FEW 10	30	>3	30	17
HIGH PERF COMM Cs	A FEW 10	30	>1	30	19
EVALUABLE LAB Cs	A FEW 1000	1000	>0.3	~ 100	200

TABLE 3

RECENT DESIGN CONSIDERATIONS

Rb GAS CELL	OPTICAL/MW PACKAGE	- SEPARATED (LAMP-FILTER-CELL) - COMBINED (ISOTOPE MIXTURE -NO FILTER)
H MASER OSCILLATOR	VACUUM	- 2 CHAMBER - 1 CHAMBER
	CAVITY	- LOW TEMP COEFF CERAMIC - METAL
	CAVITY CONTROL	- TUNING SERVO - THERMOSTAT
Cs BEAM TUBE	CAVITY	- SINGLE (RABI) - SEPARATED (RAMSEY)
	MAGNETS	- DIPOLE - HEXAPOLE
	BEAM	- SINGLE - MULTIPLE
	MAG FIELD	- TRANSVERSE - AXIAL

TABLE 4

PRESENT ACCURACY LIMITATIONS

Rb GAS CELL	WORSE THAN 10^{-10}	BUFFER GAS MIXTURE SIMULTANEOUS OPT PUMPING/ MW RADIATION
H MASER OSCILLATOR	1×10^{-12}	WALL COLLISIONS 2nd ORDER DOPPLER EFFECT
Cs BEAM TUBE	1×10^{-13}	CAVITY (RAMSEY) PHASE DIFFERENCE 2nd ORDER DOPPLER EFFECT

TABLE 5

ACCURACY EVALUATION METHODS

Rb GAS CELL	NONE USED, NONE PLANNED	
H MASER OSCILLATOR	2ND ORDER DOPPLER EFFECT	- ACCURATE TEMP MEAS
	WALL COLLISIONS	- STORAGE BULBS OF DIFFERENT SIZE - FLEXIBLE STORAGE BULB - EXTERNAL (BIG BOX) STORAGE BULB - TEMPERATURE CHANGE
Cs BEAM TUBE	2ND ORDER DOPPLER EFFECT	- LINEWIDTH & NARROW VELOCITY DISTR - MW(RAMSEY) SPECTRUM - PULSED MW POWER
	CAVITY(RAMSEY) PHASE DIFFERENCE	- BEAM REVERSAL - BEAM OPTICS CHANGE - MW POWER SHIFT - PULSED MW OPERATION

TABLE 6

INTERNATIONAL AGREEMENT...Cs STANDARDS

REF: FALL 1973

	TAI - Cs	1 SIGMA UNCERTAINTY	TECHNIQUE
PTB	11×10^{-13}	1.5×10^{-13}	BEAM OPTICS CHANGE BEAM REVERSAL
NRC	10×10^{-13}	$1\text{-}2 \times 10^{-13}$	BEAM REVERSAL
NBS	10×10^{-13}	1.6×10^{-13}	BEAM REVERSAL MW POWER SHIFT PULSED MW OPERATION

TABLE 7

INTERNATIONAL AGREEMENT...H MASER OSC (SINCE 1970)
(MEAS IN TERMS OF Cs)

	DATE OF PUB	1420405751 HZ PLUS	1 SIGMA
NBS, U.S.	1970	0.769 Hz	1.7×10^{-12}
NBS/SAO/HARVARD, U.S.	1970	0.767 Hz	1.4×10^{-12}
NRC, CANADA	1971	0.770 Hz	2.1×10^{-12}
NASA-GSFC, U.S.*	1972	0.775 Hz	2.2×10^{-12}
NPL, U.K.	1973	0.766 Hz	2.1×10^{-12}
HARVARD, U.S. ("BIG BOX")	1974	0.768 Hz	1.4×10^{-12}
LHA, FRANCE*	1974	0.770 Hz	2.1×10^{-12}
RRL, JAPAN	1974	0.773 Hz	3.5×10^{-12}

* WALL SHIFT CORRECTION NOT INDEPENDENT

TABLE 10

RESEARCH AND DEVELOPMENT ACTIVITIES ON FREQUENCY STANDARDS (non-commercial, Status: 1974)

Bureau Internationale des Poids et Mesures Sevres, France	Saturated absorption, methane stabilized and iodine stabilized helium-neon lasers.
Centre National d'Etudes des Telecommunications Issy les Moulineaux, France	Hydrogen maser oscillator.
Harvard University Cambridge, MA	Fundamental research on hydrogen maser oscillators. External ("big box") storage bulb maser.
Istituto Elettrotecnico Nazionale Turin, Italy	Cesium gas cell, optically pumped.
Jet Propulsion Laboratory Pasadena, CA	Hydrogen maser oscillator (esp. as precision clocks for long life).
Laboratoire d'Electronique Fondamentale Orsay, France	Rubidium beam with optical pumping for state selection and detection.
Laboratoire de l'Horloge Atomique Orsay, France	Hydrogen maser oscillator. Ion storage devices (esp. heavy ions). Saturated absorption methane and iodine stabilized helium neon lasers.
Laboratoire Suisse de Recherche Horlogeres Neuchâtel, Switzerland	Hydrogen maser research (esp. wall coating equipment).
Laval University, EE Dept. Quebec, Canada	Hydrogen maser oscillator. Rubidium gas cell and rubidium maser.
MIT, Dept. of Aeron. & Astron. Cambridge, MA	Optical beams: I_2 beam stabilized argon-ion laser.
MIT, Lincoln Lab. Cambridge, MA	Stable and saturated absorption (esp. CO) stabilized CO_2 lasers.
MIT, Physics Dept. Cambridge, MA	Stabilized lasers (HCN, H_2O, CO_2, etc.) and saturated absorption devices.
NASA - Goddard Space Flight Center Greenbelt, MD	Hydrogen maser oscillator (esp. as precision clocks for long life). Passive free hydrogen beam.

National Bureau of Standards Boulder, CO	Cesium beam standard. Passive hydrogen storage beam. Saturated absorption methane stabilized helium neon laser. Saturated absorption stabilized CO_2 laser.
National Bureau of Standards Gaithersburg, MD	Saturated absorption iodine stabilized helium-neon laser.
National Physical Laboratory Teddington, UK	Cesium beam standard. Hydrogen maser oscillator. Saturated absorption stabilized lasers.
National Research Council Ottawa, Canada	Cesium beam standard. Hydrogen maser oscillator. Iodine stabilized helium-neon laser. Other saturated absorption devices.
National Research Lab. of Metrology Tokyo, Japan	Cesium beam standards.
National Standards Laboratory Sydney, Australia	Hydrogen maser oscillator.
Physikalisch-Technische Bundesanstalt Braunschweig, Germany	Cesium beam standard. Hydrogen maser oscillator. Saturated absorption stabilized lasers.
Radio Research Laboratories Tokyo, Japan	Hydrogen maser oscillator. Rubidium gas cell devices.
Smithsonian Astrophysics Obs. Cambridge, MA	Hydrogen maser oscillator (esp. small size. For space use and VLBI).
Texas A&M Univ., Physics Dept. College Station, TX	Ion storage research
University of Pisa, Physics Dept. Pisa, Italy	Magnesium atom submillimeter beam. Cesium gas cell maser.
University of Tokyo, Physics Dept. Tokyo, Japan	Saturated absorption stabilized lasers (esp. methane stabilized helium-neon laser).
University of Washington, Physics Dept. Seattle, WA	Fundamental research on ion storage
Williams College, Thompson Physics Lab. Williamstown, MA	Hydrogen maser oscillator (esp. storage bulb phenomena).

TABLE 8

COMMERCIALLY AVAILABLE

	TYPE	COMMENTS
EFRATOM, INC. COSTA MESA, CA	SMALL COMM Rb MODEL FRK-H	10 MHz OUTPUT
HEWLETT-PACKARD CO. PALO ALTO, CA	COMM Rb MODEL 5065A	
	SMALL COMM Cs MODEL 5062C	
	COMM Cs MODEL 5061A	
	HIGH PERF COMM Cs MODEL 5061A OPTION 004	
NIPPON ELECTRONICS CO., LTD. KAWASAKI, JAPAN	COMM Rb NEATOMIC RB-1003 & RB-2003	ANOTHER SPECIAL UNIT MADE FOR CARRIER SYSTEMS
OSCILLOQUARTZ NEUCHATEL, SWITZERLAND	COMM Cs OSCILLATOM I	CESIUM TUBE NOT MANUF BY OSCILLOQUARTZ,
RHODE & SCHWARZ MUNCHEN, GERMANY	SMALL COMM Rb MODEL XSRM	WEIGHT & SIZE LARGER THAN INDICATED IN TABLE 2
THOMSON - CSF PARIS, FRANCE	COMM Rb MODEL HAM111	
TRACOR, INC. AUSTIN, TX	COMM Rb MODEL 304D	LOWER COST BUT LOWER PERFORMING MODEL (308A) AVAILABLE; SIMILAR PHYSICAL CHARACTERISTICS

TABLE 9

OTHER COMMERCIAL EFFORTS

	TYPE	COMMENTS
COLLINS RADIC CO. CEDAR RAPIDS, IA	COMM Rb	SOME DEVICES BUILT & USED
FREQUENCY & TIME SYSTEMS, INC. DANVERS, MA	COMM Cs HIGH PERF Cs	CESIUM TUBES BUILT & TESTED FULL STANDARD LIKELY AVAILABLE IN 74
FREQUENCY ELECTRONICS, INC. NEW HYDE PARK, NY	COMM Cs	
GENERAL TIME STAMFORD, CT	Rb MASER	
QUANTA-TRON, INC SANTA ANA, CA	SMALL COMM Rb	UNITS LIKELY AVAILABLE IN 74

TABLE 11

INTERNATIONAL EFFORT

	LABS WITH ACTIVE EFFORTS	
	NON-COMM	COMM
Cs BEAM	5	4
H MASER OSC	14	0
Rb GAS CELL (INCL MASER)	2	9
SATUR ABS STABILIZED LASER	10	0
OTHER	8	0

TABLE 12

SCIENCE IMPACT

DEFINITION OF THE SECOND	TAI RUNS 1×10^{-12} TOO HIGH
DEFINITION OF THE METER	PROPOSAL TO DEFINE LENGTH BY TIME STD VIA DEFINITION OF C
VERY LONG BASE LINE INTERFEROMETRY	ASTRONOMICAL DATA & CONSTANTS
	GEOPHYSICAL DATA (POSITION ON EARTH, CONTINENTAL DRIFT, EARTHQUAKES)
RELATIVITY	ALTITUDE EFFECTS ON EARTH
	ROTATING EARTH
	SPACE PROBES
SPECTROSCOPY	MW, SUB-mm, & IR DATA

TABLE 13

TECHNOLOGY IMPACT

1ns/DAY $\xleftrightarrow{\text{APPROX}}$ 1×10^{-14}

NAVIGATION (1m $\xleftrightarrow{\text{APPROX}}$ 3ns)

STANDARDS (CLOCKS) FOR: VEHICLES, SHIPS, AIRCRAFT, SPACECRAFT

EXISTING NETWORKS: STANDARD FREQ & TIME BROADCASTS
OMEGA
LORAN C
NASA TRACKING STATIONS

PROPOSED NETWORKS: AIRCRAFT COLLISION AVOIDANCE SYSTEMS
SATELLITE SYSTEMS (e.g. GPS)

COMMUNICATION (100 Mbit/s $\xleftrightarrow{\text{APPROX}}$ 10ns)

EXISTING NETWORKS: NATIONAL & SUPRANATIONAL TV NETWORKS

PROPOSED NETWORKS: HIGH BIT RATE COMMUNICATIONS