CHAPTER 4—PART B

RECENT PROGRESS ON ATOMIC FREQUENCY STANDARDS*

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Contents

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"Progress is the activity of to-day and the assurance of to-morrow."
Ralph Waldo Emerson

Recent progress on laboratory and commercial atomic frequency standards is summarized for the 1967–1973 period. The discussion is restricted to those devices which are judged to be leading contenders in the primary laboratory standards field or which have present or short-term future commercial potential. In the laboratory standards classification a number of cesium beam devices are now in operation with reported accuracies of 1×10^{-12} or better and measured stabilities of a few parts in 10^{12} for 1-second averaging times. Hydrogen standards, in the maser form, have demonstrated the best reported stability yet for moderate averaging times (≈ 1000 seconds) of better than 1×10^{-14}, although the accuracy potential has not yet proved as good as for the cesium beam devices. Other forms of hydrogen standards, operating as passive beam devices, are also under investigation and show considerable promise in both their accuracy and stability characteristics.

Commerical activity remains concentrated on cesium beam and rubidium gas cell standards with hundreds of both types having been sold. Commercial cesium standards are achieving both improved performance—in fact, approaching that of some recent laboratory devices—and a greatly reduced sensitivity to environmental influences. The major rubidium standards improvements have consisted of achieving very respectable stabilities under much more severe environmental conditions and in much smaller package sizes.

Key words: Atomic frequency standards; cesium beam standards; hydrogen beam standards; hydrogen masers; rubidium frequency standards.

4B.1. INTRODUCTION

Chapter 4A of this volume describes the historical development of various types of laboratory and commercial atomic frequency standards during the period ending in 1967. This chapter is intended to summarize further developments in this field which have occurred in the 1967–1973 period.

Before discussing specific details of some of this more recent progress, it may be of interest to consider briefly the related question of "Why do organizations continue to invest so much time, money, and energy in pursuing work on atomic frequency standards that already possess almost unbelievable accuracy and stability?" The answer—at least in recent years—seems to lie not so much in some rather nebulous desire to "build a better mousetrap" for the challenge and prestige, but rather in the fact that the atomic standard has proved to a great many people that it is a most useful device in a wide variety of applications. As important practical benefits have been realized by the scientific and technological segments of our society from using atomic standards, several trends began to develop more or less simultaneously.

First, based on some of the earlier successful applications of atomic standards in such areas as metrology, navigation, and satellite tracking, systems designers in many other technological areas began thinking in terms of solving their own problems by using time and frequency technology. An example here would be the conceptual design of an aircraft collision avoidance system (ACAS) that is based on time and frequency techniques using state-of-the-art atomic standards for frequency and time reference functions both on board the aircraft and on the ground.

Second, as these new applications appeared, the commercial potential of such devices increased greatly, leading to an intensive development effort to produce better atomic standards in terms of performance, cost, reliability, and suitability for field applications in relatively hostile environments.

Third, in response to the increasing availability of atomic standards with continually improving performance, reduced sensitivity to environmental conditions, and especially at an acquisition cost reduced from the original price in excess of $50,000 per unit down to under $10,000, the systems designers were able to consider even more sophisticated systems and techniques, based on the new atomic standards and the related time and frequency technology. We are now seeing some of the practical results in the form of advanced navigation systems, such as Loran-C, Omega, and various military satellite navigation systems; advanced communications systems employing synchronized digital transmissions; and better satellite tracking systems which make use of cesium or hydrogen maser atomic frequency standards. Also, improved methods and equipment have been devised for disseminating highly accurate time and frequency information over large geographical areas using existing or proposed satellites, television network facilities, and radio navigation systems. The increasing use of atomic standards in scientific applications has already made possible the design and, in some cases, the performance of new relativity experiments [1],[1] significant advances in metrology which may eventually lead to a unified standard for at least time, frequency, and length [2]; and greatly improved knowledge of the earth and other components of our solar system through long-baseline interferometry [3] and satellite-based measurements. For example, the Goldstone LBI system, using hydrogen maser frequency and time references, can already detect relative earth movements with a resolution of about 10 cm. Jet Propulsion Laboratory (JPL) personnel would like even *better* resolutions in order to study possibilities of predicting earthquakes, but are limited at present to 10 cm because the maser references "flicker out" at about 7 × 10^{-15} [4]. This particular application, and the collision avoidance system mentioned before, are rather interesting because they offer two examples where important public benefits—that is, safety from air collisions and earthquakes—may eventually be rather directly dependent on the existence of atomic standards with state-of-the-art performance.

These interrelated processes that have been described—namely, the increasing availability of useful atomic frequency standards making possible new applications and systems with important benefits to many segments of the population which in turn generate further demands for still better atomic standards—seem likely to continue in the foreseeable future, generating in the process the motivation needed to insure continued development of atomic standards.

4B.2. LABORATORY CESIUM STANDARDS

In discussing now more specifically some of the recent progress in this field, it should be noted that recent improvements already achieved in atomic standards and those that will be needed in the future are not confined to better performance, in the sense only of accuracy and stability. In many applications the accuracy and stability already available is adequate for the purpose. But, field use may require greater reliability, less sensitivity to the environmental conditions, smaller size and weight, and simpler operation. In other applications, particularly when several standards are needed, reduced acquisition cost may be the most important consideration.

During the past few years we have already seen substantial improvements with regard to many of

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[1] Figures in brackets indicate literature references at the end of this chapter.

these aspects. If we first consider progress from the laboratory standards point of view, cesium beam devices continue to serve as the national reference standards in many nations, based on the 1967 definition of the second in terms of the cesium resonance frequency. Work is still active on hydrogen masers, however, and new techniques using hydrogen beams, for example, may eventually lead to a better absolute standard than cesium.

The state of the art for laboratory cesium beam standards has now advanced to the point where documented accuracies for at least three national laboratory reference standards—those at the National Research Council (NRC) in Canada, the Physikalisch-Technische Bundesanstalt (PTB) in Germany, and the National Bureau of Standards (NBS) in the United States—have been published at $\pm 1 \times 10^{-12}$ or better [5, 6, 7]. Perhaps the extent of these accomplishments can best be seen by considering the plot in figure 4B.1 showing how published accuracy figures for various laboratory cesium standards have improved over the past 16-year period. The plotted points are generally equivalent to 1-sigma type estimates. While the exact placement of some of the values may be a little uncertain due to some necessary guessing about confidence levels of a few of the published estimates, three conclusions seem fairly clear. First, substantial steady progress has occurred over a long period in designing, building, and evaluating more accurate laboratory cesium standards. Second, several of the present devices have broken the 1×10^{-12} barrier. And, third, further improvement to near the 1×10^{-13} level is already taking place.

The better-than-1×10^{-12} accuracies already achieved have been made possible largely by careful attention to the three principal sources of errors identified in several different laboratories throughout the world as experience was gained with earlier versions of cesium beam standards. These primary sources of inaccuracy are associated with phase shifts in the microwave cavity, uncertainties in the magnetic C-field, and various problems in the excitation electronics.

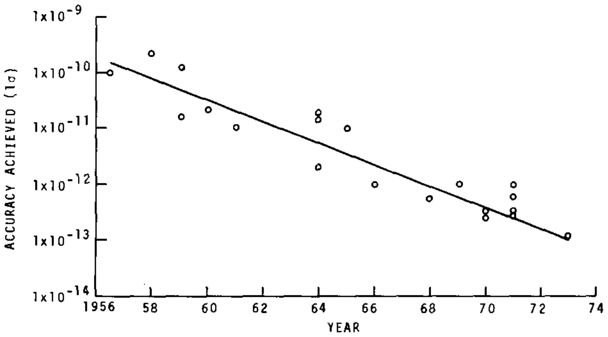

Fig. 4B.1. Accuracy trends in laboratory cesium standards: 1956–1973.

The phase shift problem has been attacked in the recent laboratory standards by providing greatly improved capabilities for detecting the presence and the magnitude of any residual phase shift error using techniques that are convenient enough to permit relatively rapid determinations as often as desired and precise enough so that the *uncertainties* in the phase shift error determination can be much less than 1×10^{-12}. NRC, PTB, NBS, National Physical Laboratory (NPL) in England, and the National Research Laboratory of Metrology (NRLM) in Japan have accomplished this by designing standards which allow the direction of the atomic beam traversal through the microwave cavity to be reversed, thus reversing the sign of any phase shift error in the process. In earlier versions, reversal was accomplished by physically rotating the cavity structure itself or by physically interchanging the cesium oven and detector leaving the cavity undisturbed. Both techniques suffered somewhat from lack of reproducibility, yielding measurement uncertainties of near 1×10^{-12}. The newer standards now in operation at NRC, NRLM, NPL, and NBS include ovens and detectors at each end of the machines so that frequency measurements can be made for each beam direction sequentially in a short time and without disturbing the microwave cavity or interrupting the vacuum inside the beam tube. This technique, using repeated measurements, should reduce uncertainties in the phase shift error correction in these new standards significantly, provided that sufficient knowledge is available concerning the beam velocity distributions and trajectories for each direction of traverse.

A different method for measuring phase shift errors at the 1×10^{-13} level is used in the present PTB standard, consisting of making a frequency measurement at two widely differing mean beam velocities, which can be selected at will by interchanging two different sets of focusing magnets, designed to focus different velocities [8]. Because any phase shift error is velocity dependent, this technique provides a convenient estimate of the error.

Two other techniques are in use at NBS to evaluate possible frequency errors due to cavity phase shift [9]. Both also make use of the fact that any cavity phase shift error present will vary with the mean velocity of the atoms contributing to the resonance signal. With the first method frequencies corresponding to different beam velocities can be measured by varying the input microwave power, since the effective mean beam velocity depends on the power level in the cavity. If the appropriate velocity distributions are known from other measurements (see below) or calculations, the cavity phase shift, and the resultant frequency bias, can be computed.

The second, more novel, technique makes use of pulsed microwave excitation to preferentially select only a certain narrow range of atomic velocities, according to their time of flight between the two ends of the microwave cavity and the pusle repetition rate [10]. The velocity distribution can be inferred rather directly, and the measurement of the standard's frequency at different velocity settings yields the phase shift bias.

C-field errors, due to magnetic field non-uniformities and instabilities, have also been successfully reduced in most recent standards to below the 1×10^{-13} level. The credit belongs primarily to use of better shielding materials and designs. Several of the newer lab standards are making use of longitudinal C-fields, which can be produced with great uniformity by means of solenoid coils.

Electronic problems continue to provide major difficulties at times in the laboratory cesium beam standards, but some significant progress has been made. Frequency multipliers, beam signal processing components, and even crystal oscillators are now becoming available, which have greatly improved phase-noise characteristics. These inherently more stable circuits, combined with new modulation schemes, such as the square-wave modulation systems in use at NRC and PTB, have resulted in some estimates for inaccuracies contributed by major electronics systems associated with the standard of only about 1×10^{-13} [9, 11].

A final area of increasing concern as accuracy levels below 5×10^{-13} are sought is the uncertainty associated with the correction applied for 2d-order Doppler shift. Better knowledge of the actual beam velocity distribution will be needed for each individual standard in order to attain accuracies near 1×10^{-13}. Studies at NBS and NRC indicate some success in deducing the necessary velocity information from a computer analysis of the experimental Ramsey resonance curves [9, 12]. The pulsed-excitation method mentioned above in connection with the phase shift error evaluation also provides rather directly the velocity information needed for the 2d-order Doppler shift correction.

The stability performance of present laboratory cesium standards, along with some projections for the near future, is summarized in figure 4B.2 by means of a stability versus averaging time plot. Recent state of the art is indicated by the upper band which shows measured 1-second stabilities ranging from 3×10^{-12} for the PTB standard [13] up to about 1×10^{-11} for some of the recent NRC and NBS devices [7, 11]. The upper dashed line shows the performance expected within the next few months from the NBS–X4 beam tube, developed jointly by NBS and the Hewlett-Packard Company. The 1-second stability goal for NBS–X4 is about 1×10^{-12} and results from a relatively large beam flux and an efficient dipole beam optics system. The lower dashed line shows the anticipated stability for NBS–5, a new long-beam standard that is now in the evaluation phase at NBS [9], as inferred from beam noise measurements. This performance results principally from use of a very large beam and an efficient beam optics system designed with the aid of a large digital computer. One motivation for seeking such high stability is that the large number of necessary measurements involved in the accuracy evaluation of such a standard at the 1×10^{-13} level can be performed and repeated in reasonably short time periods.

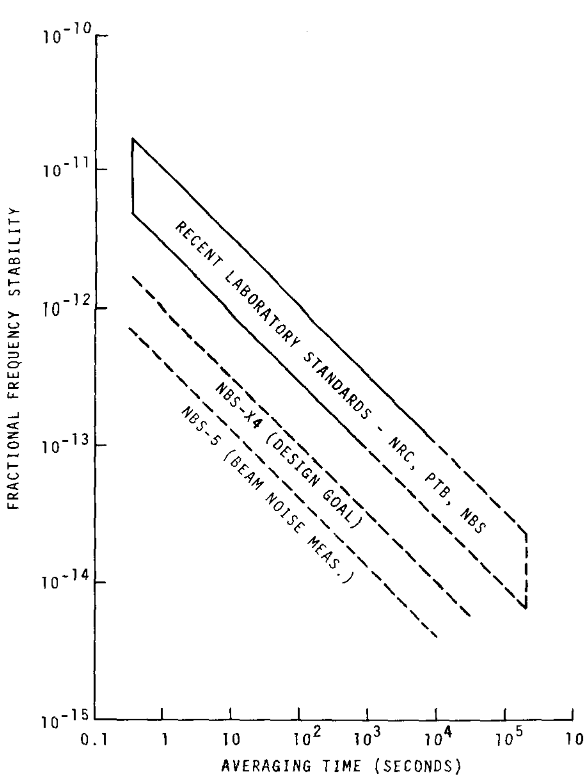

Fig. 4B.2. Stability performance data for laboratory cesium standards.

4B.3. HYDROGEN STANDARDS

Although cesium standards have demonstrated very impressive accuracy and stability performance and still seem to have a bright future in the primary standards area, some old and new competitors are also attracting considerable interest. The hydrogen maser, while not yet achieving an accuracy performance that *exceeds* the laboratory cesium devices, nevertheless has come close, and its stability performance for moderate averaging times has not been matched by any other type of device. The main impediment to accuracies better than about 1×10^{-12} [14, 15, 16] is still the uncertainty in determining the wall shift caused by the hydrogen atoms bouncing off the walls of the storage bulb. Several interesting attempts are being tried to reduce this error source, including the Harvard large-bulb maser, featuring a 150-cm storage bulb intended to reduce the number of wall collisions per second and thus the magnitude of the wall shift by perhaps a factor of 10. The desired accuracy goal has not yet been reached, but some modifications being added to this maser in the form of a deformable storage bulb may permit the wall shift error source to be reduced to about $\pm 1 \times 10^{-14}$ [17]. This technique involves the use of a deformable storage bulb built in such a way that the volume of the bulb can be changed by a large factor without changing the bulb's surface area [18]. It allows evaluation of the wall shift without introducing the uncertainties caused by using a series of different size bulbs with similar, but not identical, surfaces. A third method being tried is operation of a maser at a bulb temperature of about 100 °C., where some experiments have shown the wall shift goes through zero [19]. Somewhat on the other side of the coin, however, is the recent suggestion by Crampton that two previously unexpected effects involving hydrogen spin exchange shifts and magnetic field gradients may produce H-maser inaccuracies amounting to several parts in 10^{12} [20].

The stability performance of some hydrogen masers at NRC Canada, Jet Propulsion Laboratory (JPL), NASA Goddard Space Flight Center, and also at Smithsonian Astrophysical Observatory (SAO), is summarized in figure 4B.3. Stabilities as good as 6×10^{-15} have been observed for averaging times in the 100–1000 second range [21, 22].

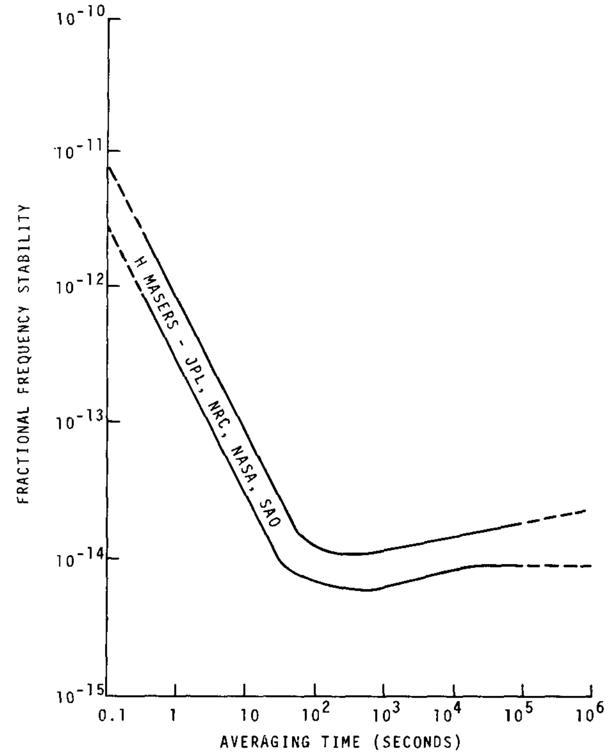

Fig. 4B.3. Stability performance data for hydrogen maser standards.

The NRC maser is a laboratory device; the JPL and NASA versions have been developed for long term, trouble-free operation at NASA tracking sites; and the SAO maser has been developed specifically for relativity tests aboard a spacecraft or rocket vehicle.

Largely because of the wall-shift limitations on the accuracy potential of the hydrogen maser, two groups at NBS and NASA-Goddard have been recently working on other ways for using the simple hydrogen resonance as a frequency standard which do not involve the disadvantages associated with maser action. In both cases the intent is to combine the advantages of the cesium beam and hydrogen maser technologies, while eliminating or reducing some of their disadvantages.

NBS has demonstrated the technical feasibility of a hydrogen storage beam standard which uses a hydrogen beam with atom detection as in a cesium standard, but with the added feature of a storage or bounce box in the beam path [23]. This increases the atom's interaction time with the *rf* field, resulting in a narrower resonance. The technique appears to offer reduced cavity-pulling effects and a better way to evaluate the wall shift in the storage bulb relative to the maser method. Development into a full atomic frequency standard with potentially superior performance will, however, require considerable work on a more efficient detector for atomic hydrogen.

A more basic hydrogen beam standard, without the storage feature, has been built and successfully operated at NASA-Goddard [24]. The operation is similar to that of a cesium atomic beam machine, but some significant advantages are realized with hydrogen due to its much simpler atomic spectrum. Figure 4B.4 shows some of the Ramsey resonance curves obtained at three different C-fields. Because of the simpler spectrum, no overlap occurs between the standard frequency transition and others, even

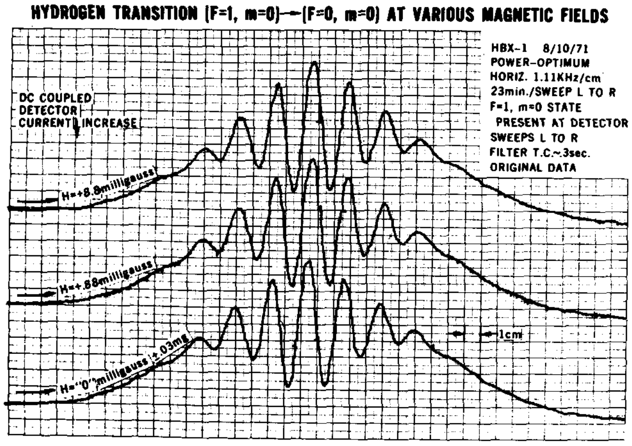

Fig. 4B.4. Hydrogen transition curves from NASA–GSFC hydrogen beam standard (courtesy H. Peters, Goddard Space Flight Center).

at very low C-field values. The Ramsey resonance width shown here of 1.2 kHz was obtained with room temperature atoms and some preferential selection of low-velocity atoms. Although this line Q of about 1.2×10^6 is much lower than for present cesium standards, a planned cryogenic beam source may later produce narrower resonances with a resulting increase in line Q. Dr. Peters of NASA-Goddard believes the hydrogen beam standard should prove as stable as the hydrogen maser and is potentially much more accurate—perhaps at the 1×10^{-13} level [24].

NBS has also made some preliminary frequency stability measurements with another variation of a hydrogen storage beam device in which one detects changes in the microwave signal caused by the hydrogen resonance rather than detecting the atoms themselves [23]. An oscillator was locked to the hydrogen transition frequency using the dispersion of the resonance. Stabilities of 4×10^{-13} were observed for averaging times of 30 seconds and 3 hours, using quartz oscillator and commercial cesium references, respectively.

Other potential techniques for laboratory frequency standards, such as ion storage and saturated absorption in methane or other gases are being investigated at several labs [25, 26, 27](see chap. 6).

4B.4. COMMERCIAL CESIUM STANDARDS

The remainder of this paper will attempt to summarize what has been happening recently in the commercial frequency standard field. As has been the case for some time now, recent commercial efforts have been concentrated on cesium and rubidium devices. Hundreds of both types have been sold and new improved versions are appearing on the market in response to the development of new and expanding application areas.

Commercial cesium standards are designed primarily for high stability; reasonable accuracy; small size and weight; moderate electrical power requirements; high reliability; and insensitivity to environmental effects. Presently existing models, and expecially some newer versions under active development, show significant advances in each of these areas.

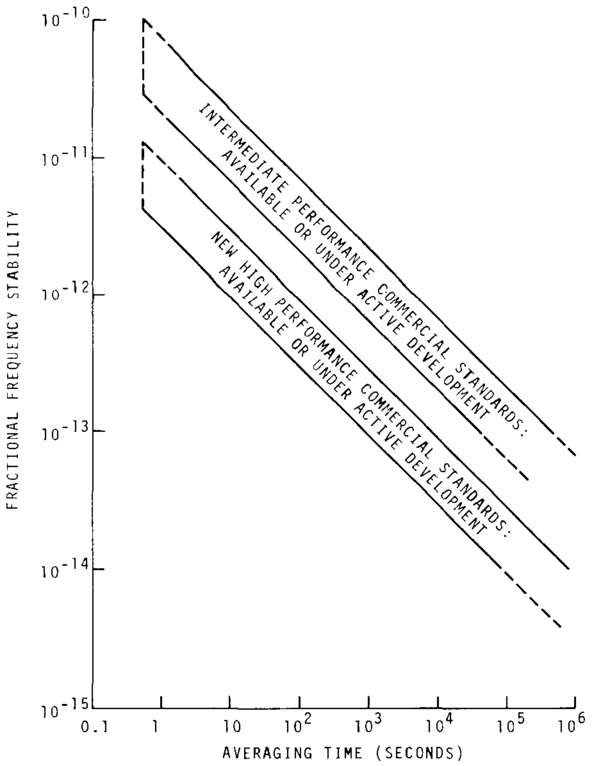

Fig. 4B.5. Stability performance data for commercial cesium standards.

Figure 4B.5 summarizes stability performance for various commercial cesium standards which are either presently available or which are in an advanced stage of development. The upper band, labeled intermediate-performance standards, includes the great majority of commercial cesium standards now in use and some new versions being developed for field applications where small size and weight and intermediate stability performance over a wide range of environmental conditions are the most important design considerations. For example, one manufacturer has succeeded in maintaining this intermediate-level stability performance in a package one-third the size and one-half the weight of earlier versions [28]. This achievement is made possible largely through use of a recently developed 15-cm long beam tube, employing six separate pairs of stacked beams to provide a relatively high beam flux. In addition to the high signal-to-noise ratio resulting from this design, its use of back-to-back beam pairs provides a greatly reduced sensitivity of the output frequency to acceleration. Corresponding improvements have been made in the associated electronics and in its performance under severe environmental conditions, such as those encountered in many field applications.

Another manufacturer has independently developed a smaller beam tube with a volume of about 115 cm^3 and an accompanying improved electronics package, which is designed to reduce the user cost relative to previous versions available. The stability of this standard is also expected to fall within the upper band plotted in figure 4B.5 [29].

The lower band in figure 4B.5 indicates some documented and projected results for several versions of high-performance cesium beam tubes developed by private industry. One particular model, already commercially available, is about 40 cm (16 in) long and employs multiple beams for high beam flux [28]. This tube has a specified stability performance equivalent to σ_y (100 seconds) $= 9 \times 10^{-13}$ or better [30] and has demonstrated a long-term stability of σ_y(10 days) $= 1 \times 10^{-14}$ [31].

A different design, high-performance cesium beam tube has been developed by another manufacturer which may eventually offer even better performance. Though not yet in commercial production, a prototype version has achieved measured stabilities corresponding to σ_y(100 seconds) $= 3 \times 10^{-13}$ [29]. This tube is about 53 cm (21 in) long and uses a novel form of hybrid beam optics featuring one dipole and one hexapole deflecting magnet. It is interesting to note that the stabilities produced by these commercial high-performance beam tubes are equal to or better than those characteristic of the most advanced laboratory standards until very recently.

Some of the newer commercial cesium standards also reflect significant improvements in their ability to operate within their stated performance limits under rather severe environmental conditions. One model is designed to operate within $\pm 1 \times 10^{-11}$ over a temperature range from −55 °C. to +74 °C. [28]. The same version also provides a greatly reduced sensitivity to external magnetic fields and a much improved stability of its internally-generated C-field by virtue of better magnetic shielding, more efficient degaussing techniques, and an improved C-field structure. More attention has been paid in recent years to the mechanical design of cesium beam standards and the newer units are now less sensitive to shock and vibration effects. In some cases faster warmup of the instrument has been made possible. These advances, when combined with the trend towards smaller size, weight, and electrical power consumption, are likely to stimulate wider use of atomic frequency standards for field applications in the future.

4B.5. COMMERCIAL RUBIDIUM STANDARDS

Recent developments in the rubidium standard marketplace have perhaps been a little less dramatic than for cesium, but nevertheless very significant. Figure 4B.6 presents the current state of the art with respect to the stability performance of commercial instruments. Models manufactured by a number of different companies in the United States, Germany, and Japan provide frequency stability reasonably consistent with the plotted curve. Development efforts in the rubidium case have concentrated primarily on units which maintain the level of performance indicated in figure 4B.6 over wider ranges of environmental conditions; require smaller size, weight, and electrical power; and cost less.

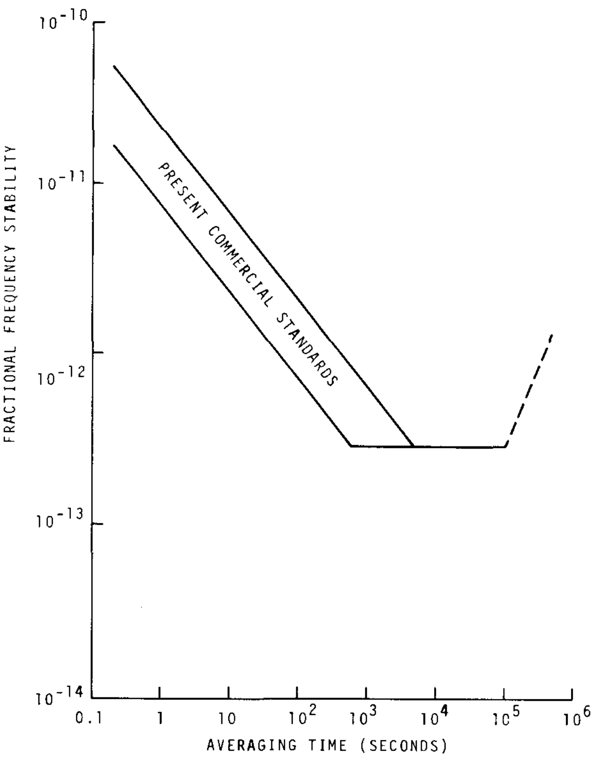

Fig. 4B.6. Stability performance data for commercial rubidium standards.

One version has been developed under military contract which has demonstrated state-of-the-art stability performance in military and airborne environments [32]. This rubidium standard has successfully passed all required military specifications for temperature extremes, shock, vibration, and so forth, staying generally within a few parts in 10^{11} even under the most severe conditions.

Another interesting development in the rubidium standard field has appeared recently in the form of a very compact standard manufactured in Europe, but also commercially available within the U.S. [29]. Although its stability specifications of better than 5×10^{-11} over 1 second and better than 1×10^{-10} from month to month are somewhat inferior to those achieved in larger, commercial units, the device represents a significant technological advance in several other respects. Its packaged size in one form is only about 10 cm × 10 cm × 11 cm and it weighs only 1.3 kg. It requires only 10 minutes for warmup, 13 W of electrical power at 25 °C. ambient, and will operate within 1×10^{-9} over a temperature range from −25 °C. to +65 °C.

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