FREQUENCY STANDARDS FROM GOVERNMENT LABORATORIES OVER THE NEXT 25 YEARS

L. Maleki
Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, California 91109

Abstract

Based on a number of considerations including projected needs, current status, future trends, and status of key technologies, an attempt is made to project the future of government supported frequency standards development in the next 25 years.

INTRODUCTION

Any casual observer of prophesies made in the past regarding events to occur twenty–five years in the future is readily aware of the inevitable inaccuracies. This is so much more true about predictions of scientific and technical advances, since the outcome and the course of the future research is dependent upon future advances in a number of associated technologies which in turn are unknown. Nevertheless predicting the future of the course of science and technology, even as far as twenty–five years hence, serves to focus the present efforts and thus, in the most successful cases, may accelerate the rate of progress for at least the near term future. It is with this perspective that the present paper attempts to sketch the state of the frequency standards for the next twenty–five years.

The scope of the predictions, as suggested in the title, will be limited to the government supported laboratories. This implies that only the results of research perceived to be suitable for government support will be considered. This perception is that of the author and admittedly is subjective. It is founded on the notion that government support is to be directed for the development of technologies which do not readily point to near term commercial payoffs, and thus will be out of the scope of interest of the for–profit entities. Included in this class of technological endeavors are those that are clearly needed in support of other government sponsored projects, and thus may not be left to a chance development by the private sector. Based on this notion, the discussions in the paper will be limited to the ultra–stable frequency standards setting the limit of achievable stability. While this choice does not imply that other characteristics of frequency standards, for example reliability or cost, are not of concern, or will not be expected to be a part of government laboratories' work in the future, it is made on the basis that almost all future advances in the development of ultra–stable frequency standards are expected to be government funded. This is because of the cost associated with the fundamental research, and the uncertainty in short term commercial payoff, for the development of improved stability performance. The limited need for the number of such standards manufactured also places the burden of the development of the ultra-stable frequency standards on government sponsored research.

Within the boundary conditions outlined above, this paper will first present a brief review of the state of the frequency standards of twenty-five years ago, followed by a discussion of the present day and near term future capabilities. This information will then be used to extrapolate to the next twenty-five years. The extrapolation will be guided by the identification of the areas of need already known to exist. Since the pace of the future development will be strongly influenced by advances in technologies which directly affect the performance of frequency standards, several key technologies will be identified.

MOTIVATION

Before a prediction of the performance of the future frequency standards can be made the assumption that in fact they will still be needed twenty-five years from now merits some discussion. In the case of the frequency standards, the assumption of their need a quarter of a century from now is an easy one to justify. As an enabling technology for communications, the role of reference frequency signals will not be diminished in the future, and may well be expanded. This is because every received or transmitted signal in a communication system is synthesized from, or referenced to, a stable frequency derived from a frequency standard. Since the domain of communication is ever expanding, with no technological, economical, or sociological imperative to head off the expansion, it is clear that the need for frequency standards will also expand.

The second reason for expecting a persisting demand for frequency standards during the next twenty-five years is the position of frequency and time as the most precisely measurable of all physical parameters. Thus measurements requiring the most achievable precision by necessity depend on frequency and time standards. This ensures that the demand for ultra-stable frequency standards will continue in the future.

The third reason for needing frequency standards in the future is related to the above, and pertains to the fact that every theory in physics fails at some limit. That is to say, every theory in physics, including those that have been proven to everyone's satisfaction to hold true, have a finite domain of applicability. It thus becomes an important endeavor in physics to identify the boundaries of each theory, particularly those that hold so well! This exercise requires the most precise measurements possible for the highest resolution. Here again, the most precise tool of the physical metrology is the frequency standard.

I believe the above reasoning place the assumption of a need for frequency standards on sure enough a footing to justify the exercise of the prediction of their future status.

A BRIEF LOOK AT HISTORY

It is instructive to look at the state of the technology of frequency standards twenty-five years ago, and search for guidelines for making future prediction. The proceedings of the first PTTI, as well as proceedings of the Frequency Control Symposium (FCS) some twenty-five years ago, contain numerous interesting and instructive examples. Papers pertinent to our discussions may be best summarized in one of the following three categories: Those that promise of new, and sometimes bold, innovations which have since been found unfulfilled; those that predict a performance that we now find to be grossly underestimated; and those whose predictions were overestimates.

Virtually all papers making predictions fall within one of the above categories. As typical examples consider a survey paper on cesium beam frequency standards in the Proceedings of the FCS in 1971[1]. Here the performances of various Cs standards are used to develop an accuracy trend versus time, a plot that is reproduced in Fig. 1. Based on these results evidently the accuracy of the cesium standard had improved by about two orders of magnitudes every ten years (two decades per decade). Thus based on this information it wouldn't have been too unreasonable to have predicted a performance accuracy of a part in 10^{17} for a 1993 version of the cesium standard, since the accuracy in 1971 was about a part in 10^{13}. With hindsight one can easily point to reasons why this extrapolation is not justified, but such reasons were not present in 1973.

As a second example consider the paper by H. E. Peters in the Proceedings of the 3rd PTTI in 1971[2]. Here results for the performance of the NASA prototype atomic hydrogen standard NP-1 is given. Based on this example, the author argues that the maser has the potential for stability of a few parts in 10^{15}. Hydrogen masers exceeding this stability performance have since been developed by Peters and his co-workers at Sigma Tau company, and by Vessot and co-workers at the Smithsonian Astrophysical Observatory, where some have operated at about 8×10^{-16} stability. Again, it is easy to justify with hindsight why in 1971 the ultimate performance of the H-maser was underestimated.

Finally as our last example we can point to the work at Harvard in N. Ramsey's group on the large storage box maser. In a paper by Uzgiris and Ramsey in the 22nd FCS in 1968[3] the problem of wall collisions is considered and a solution is described in the form of a large diameter storage box to increase the time spent by atoms in the storage volume, thus reducing the fraction of the time atoms spend on the wall. A picture of this maser is given in Figure 2 of the paper showing the storage box, which has a linear dimension of approximately five feet long and five feet in diameter. The improvement obtained by this instrument evidently did not warrant its cumbersome size, and large storage masers did not receive any more serious attention. Thus the promise held by this innovation remained unfulfilled, despite its initial success.

In reviewing the three examples given above it is clear that advances in our understanding of the underlying physics of frequency standards coupled with innovations in the associated technologies makes the subject of future predictions a rather risky enterprise.

A Look at the Current Status and Near Term Future Developments

Recent progress in a number of scientific and technological fields has led to significant advances in the performance of ultra-stable frequency standards. In particular the advent of semiconductor and solid state lasers with narrow linewidth and suitable wavelength have resulted in significant improvements in the performance of cesium and rubidium standards. The development of novel approaches such as the linear ion trap has allowed increased signal to noise ratio for high performance lamp based ion standards. Advances in the understanding of the physical mechanism for laser trapping and cooling have led to the development of a new class of standards based on an old proposal, the cesium fountain clock first considered by Zacharias[4] Laser cooling of small clouds of ions has pointed to the possibility of developing a primary standard based on a bead of a small number of trapped and cooled mercury ions.

Laser optical pumping has virtually replaced magnetic selection in most primary frequency standards. An example of this is the recent progress obtained with NIST–7, an optically pumped cesium standard, which has yielded a short term stability of $8 \times 10^{-13}\tau^{-1/2}$[5].

Similarly progress in ion standards has led to stability performance reported at $7 \times 10^{-14}\tau^{-1/2}$, for intervals measured to about 10^4 seconds[6]. This performance is expected to persist for averaging intervals longer than 10^6 seconds.

Preliminary results have been obtained with cesium fountain clocks, using laser cooling and manipulation of atoms trapped in a Zeeman optical trap (ZOT)[7]. Stability performance of $3 \times 10^{-12}\tau-1/2$ has been demonstrated, which has led the researchers to predict a potential for short term stability of $2 \times 10^{-14}\tau-1/2$ for cesium fountain clocks.

Laser cooled trapped ions have been known to hold the potential for much improved stability. Recent advances in laser cooling of mercury ions in a miniature linear trap at NIST are expected to realize the potential for a high performance microwave standard. Stability of about $5.5 \times 10^{-14}\tau-1/2$ has been projected for 50 cooled mercury ions undergoing the clock transition at 40.5 GHz[8].

In the past few years room temperature hydrogen masers have demonstrated stability of about 8×10^{-16}. Several units operate at this level for relatively long time before degradation due to environmental influences set in. Recent advances in cryogenic hydrogen masers have led to projections of two to three orders of magnitude improvements compared to the performance of room temperature masers[9].

The only other ultra–stable frequency standard which is not based on an atomic transition is the cryogenic cavity stabilized oscillator. Performance of these instruments extends only to a few hundred seconds, but future improvements are expected. Stability of the Superconducting Cavity Stabilized Maser Oscillator (SCMO) has been demonstrated at about 2×10^{-15} for averaging intervals to about 800 s[10]. Higher performance is anticipated with improvements in cavity Q and stabilization of the power pumping the ruby maser.

In Figure 2 the performance of ultra–stable frequency standards of today are summarized, together with near term predictions within the next five years. These predictions are based on the author's subjective judgment as to the state of readiness of these standards, and do not necessarily agree with predictions of other researchers in the field. They are extrapolated from the current performance, and anticipated progress.

FUTURE NEEDS FOR ULTRA-STABLE STANDARDS

Clearly the progress in the development of future standards will be driven by outstanding needs for various applications. Some of the reasons why frequency standards will be needed in the next 25 years were mentioned above. In this section areas where lack of capability exists, and yet numerous applications have laid out requirements will be mentioned.

Applications of ultra-stable frequency standards in scientific investigations imply yet another class of instruments. Since environmental perturbations on earth can limit the ultimate sensitivity required for many science experiments, it is natural to design experiments that can take advantage of the relatively benign environment of space. Space experiments however must be performed within the constraints of low mass and low power available to practical spacecraft. Thus far the development of a low mass, and low power frequency standard (mass less than 4 kg, power less than 5 W) with stability exceeding a part in 10^{15} has not been demonstrated. One of the outstanding needs in the areas of ultra-stable standards is such an instrument. Future work will also be driven by ever more stringent requirements of spacecraft navigation and position location.

Small and miniature ultra-stable standards represent yet another class of needs. The concept of miniaturization is related to the needs of spacecraft standards, but yet relates to terrestrial applications as well. There are at least two reasons for pursuing work in this area. First a small frequency standard will require allow a more effective shielding of the environmental perturbations. This is because it is practically more simple to stabilize the environment in a small region of space than a large one. Thus all other things being equal, miniaturization may lead to improved stability, especially for longer averaging intervals. Furthermore, reduced shielding requirements may also lead to reduced costs for such standards.

The second reason for miniaturization of frequency standards is to extend their range of applications. Already small receivers for GPS, for example, have led to an explosion in areas of applications. An ultra-high stability standard in a "small" package will similarly find an extended range of applications, including those that resulting from simply the ease of use.

Perhaps the most conspicuous lack in ultra-high frequency standards is in the area of optical standards. The reader may have noticed the absence of a performance curve in Fig. 2 for an optical standard. This is because ultra-high stability optical frequency standards have not as yet been demonstrated. Yet advances in optical communications and scientific experiments quietly await practical optical standards. Furthermore the direct dependence of the stability of atomic standards on the line Q (the ratio of the frequency of the clock transition to the observed width of the transition) points to the optical standard as the ultimate ultra-high stability frequency standard, where the frequency of the "clock" transition is in the range of 10^{14} Hz.

Perhaps the major obstacle for the development of an ultra-stable optical frequency standard is the lack of a practical scheme for phase coherent frequency division. Optical frequency division to RF (or alternatively, multiplication of RF frequency to optical) has only been demonstrated with cumbersome chains in national standards laboratories. Development of practical schemes to synthesize optical frequency in a continuous basis is also a requirement for optical frequency standards applications. Several proposals have been made, and preliminary work in the development of optical frequency synthesis has been encouraging[11].

The areas mentioned in this section are not exhaustive, but represent the most urgent needs that developers must address in the future. Already considerable activity in these areas is underway, and progress towards meeting these needs is being made.

Emerging Technologies Influencing Development of Future Standards

Another parameter which shapes the scope and speed of the future development of frequency standards is emergence of new supporting technologies, or progress in existing ones. An outstanding example of this is the progress made in the last decade in semiconductor, and solid state lasers. This progress has been the major enabling influence for the development of optically pumped standards. Further progress in this area will also play a crucial role in the development of laser based ion and atom standards. In particular, the realization of the major potential held in trapped ion standards will clearly depend on how soon practicable semiconductor lasers and semiconductor laser based devices will yield radiation in the UV portion of the spectrum. Progress in this area will also influence efforts to reduce the size and miniaturize ultra–stable atomic and optical frequency standards.

A second technology which has direct impact on the future frequency standards is material science. New materials for high Q resonators will help the development of cavity standards with more stability. Materials with lower mass density and smaller coefficient of thermal expansion will enable progress for spacecraft ultra–stable frequency standards. Finally new materials may allow development of lower cost and higher performance standards through, for example, providing more effective shielding of environmental perturbations.

The requirement for low noise and stable electronic components is already quite stringent for present day ultra–stable standards. Progress in superconducting electronics and photonic devices will be required to extend the stability range, and the range of reference frequencies produced by standards. Advances in high temperature superconductors and photonics will undoubtedly have the greatest impact on the pace of future developments in frequency standards technology.

Two other areas already a part of the frequency standards technology hold the key to future advances. One area is progress towards the development of low noise local oscillators to support ultra–high stability of atomic standards. This is particularly true since trapped atom standards realize higher stability with larger line Q's, which in turn is obtained by extending the interrogation time of the clock transition. Thus stable local oscillators will be required to maintain stability during these relatively long interrogation times. Associated with this need is the development of effective and practical techniques to lock to the stable clock transitions, especially in the optical domain. Further progress in this area will greatly improve the speed of the development practical standards of the future.

It is perhaps unnecessary to mention that progress in science and associated technologies will certainly point to other crucial areas in frequency standards development that have not been considered here.

PREDICTIONS FOR FUTURE DEVELOPMENTS

Based on the considerations discussed in preceding sections, an attempt will now be made to predict future trends in the next 25 years in government supported frequency standards work. Within the next quarter of century ultra–stable optical frequency standards based on atomic transitions will be developed. These standards based on laser cooled ions and atoms will exhibit line Q's of 10^{15} or higher. Standards based on three dimensional arrays of laser cooled and trapped atoms, such as Xe, will be possible. Use of squeezed light will allow sub–natural linewidths and sub shot noise limited signals to improve stability. Standards based on the emerging technology of Optical Parametric Oscillators (OPO)[12] will become available, and will make available stable references ranging in frequency from visible to RF.

Small and highly stable solid state standards based on new materials, high temperature superconductors, and optoelectronic circuits will become available. Some of these standards will be directly used in space, while others will be used in conjunction with other atomic standards to obtain ultra–high stability on board spacecraft.

Other stable frequency standards based on whispering gallery mode dielectric resonators and superconducting cavities will emerge in the future to extend the range of stability. Novel oscillators based on photonics will meet the needs of standards requiring improved local oscillators for their ultra–stable operation.

Based on these, predications for ultra–stable standards of the future are summarized in Figure 3. The figure depicts improved performance for standards that are based on existing technologies, and by necessity lacks information on other new technologies that will surely emerge within the next twenty–five years.

SUMMARY AND CONCLUSION

In this paper an attempt has been made to predict the future performance of government supported frequency standards for the next twenty–five years. These predictions were based on a number of considerations ranging from the needs of the future to the progress in certain key technologies which drive the frequency standards developments.

Despite these considered bases for the predictions made, it is important to also point to reasons why such predictions will prove to be highly inaccurate. To start with, there will undoubtedly be some new, and as yet unidentified, applications which will possibly guide the course of future development away from that considered here. New physics will certainly emerge and influence our present day knowledge of the fundamentals of ultra–stable frequency standards. Associated with the emergence of new physics is the birth of new technologies which will further influence advances. Advances in existing key technologies, such electronics, optics, and material sciences will also occur, and in an as yet undetermined manner influence the scope and the pace of future progress in the frequency standards technology.

Finally, all technologies, especially those such as frequency standards that enable so many other technical works depend greatly on societal priorities. Such priorities in turn determine the extent of their needs, and the size of the support that will become available to achieve technological progress. This single unknown of societal priorities in the next twenty-five years can by itself prove the predictions made here far off the actual mark.

ACKNOWLEDGMENTS

This work represents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract sponsored by the National Aeronautics and Space Administration.

REFERENCES

1. R. E. Beehler, *"Cesium atomic beam frequency standards: A survey of laboratory standards developed from 1949–1971,"* in Proc. 25th Freq. Cont. Symp., 1971, pp. 297–303.
2. H. E. Peters, *"Hydrogen masers and other standards,"* in Proc. Prec. Time and Time Interv. Appl. Plan. Mtg. PTTI, 1971, pp. 367–385.
3. Edijius E. Uzgiris and Norman F. Ramsey, *"Large storage box hydrogen maser,"* in Proc. 22nd Freq. Cont. Symp., 1968, pp. 452–464.
4. N. Ramsey, Molecular Beams. Oxford:Oxford University Press, 1985, p. 138.
5. R. E. Drullinger, J. P. Lowe, D. J. Glaze and Jon Shirley, *"NIST-7, The new US primary frequency standard,"* in Proc. 1993 IEEE Int. Freq. Cont. Symp., 1993, pp. 71–73
6. R. L. Tjoelker, J. D. Prestage, G. J. Dick and L. Maleki, *"Long term stability of* Hg^+ *trapped ion frequency standards,"* in Proc. 1993 IEEE Int. Freq. Cont. Symp., 1993, pp. 132–138.
7. A. Clarion, S. Salomon, S. Guelati, W. D. Phillips, *"A laser cooled caesium atomic fountain: Towards a high performance clock,"* in Proc. 5th Europ. Freq. Time Forum, 1991.
8. J. C. Berquist, Wayne M. Itano, D. J. Wineland, F. Diedrich, F. Elsner, and M. G. Raizen, *"Single ion optical frequency standard,"* in Proc. 45th Ann. Freq. Cont. Symp., 1991, pp. 534–538.
9. R. L. Wasworth, E. M. Mattison, and R. F. C. Vessot, *"Recent investigations with Harvard–Smithsonian cryogenic hydrogen maser,"* in Proc.1993 IEEE Int. Freq. Cont. Symp., 1993, pp. 129–131.
10. R. T. Wang and G. J. Dick, *"Improved performance of the superconducting cavity maser at short measuring time,"* in Proc. 44th Ann. Freq. Cont. Symp., 1990, pp. 89–93.
11. H. R. Telle, D. Meschede, T. W. Hanch, *"Realization of a new concept for visible frequency division: Phase locking of harmonic and sum frequencies,"* Opt. Lett. 15, pp. 532–534, 1990.

12. See for example R. C. Eckardt, C. D. Nabors, W. J. Kozlovsky, and R. L. Byer, *"Optical parametric oscillator frequency tuning and control,"* J. Opt. Soc. Am. B 8, p. 646–667, 1991; C. N. Wong and D. Lee, *"Optical Parametric Division,"* in Proc. 1992 IEEE Int. Freq. Cont. Symp., 1992, pp. 32–38, and references therein.

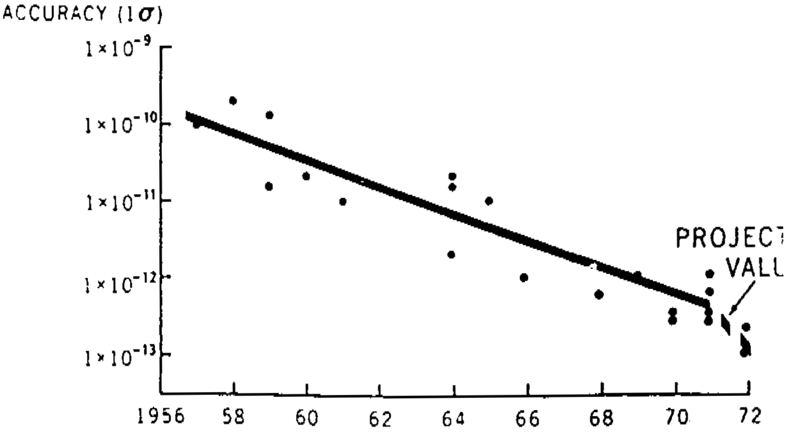

Figure 1. Accuracy Trends in Laboratory Cesium Standards, 1949-1971

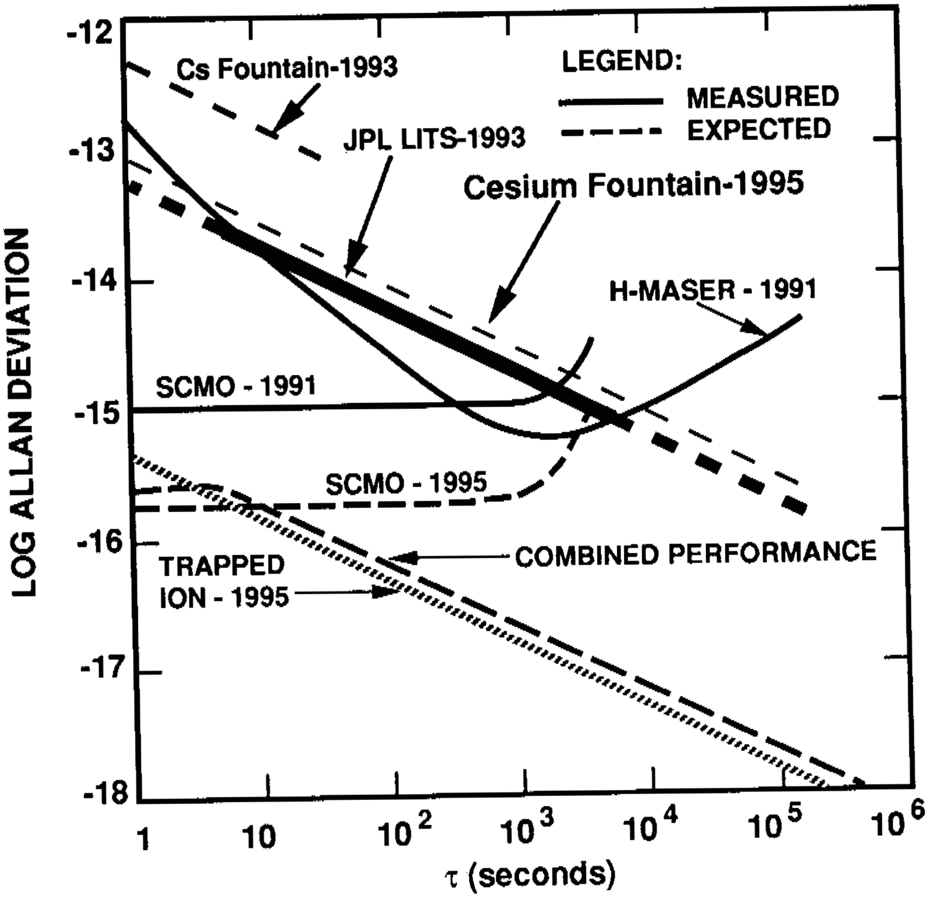

Figure 2. Performance of present day ultra-stable standards, and projected performance for the near term future.

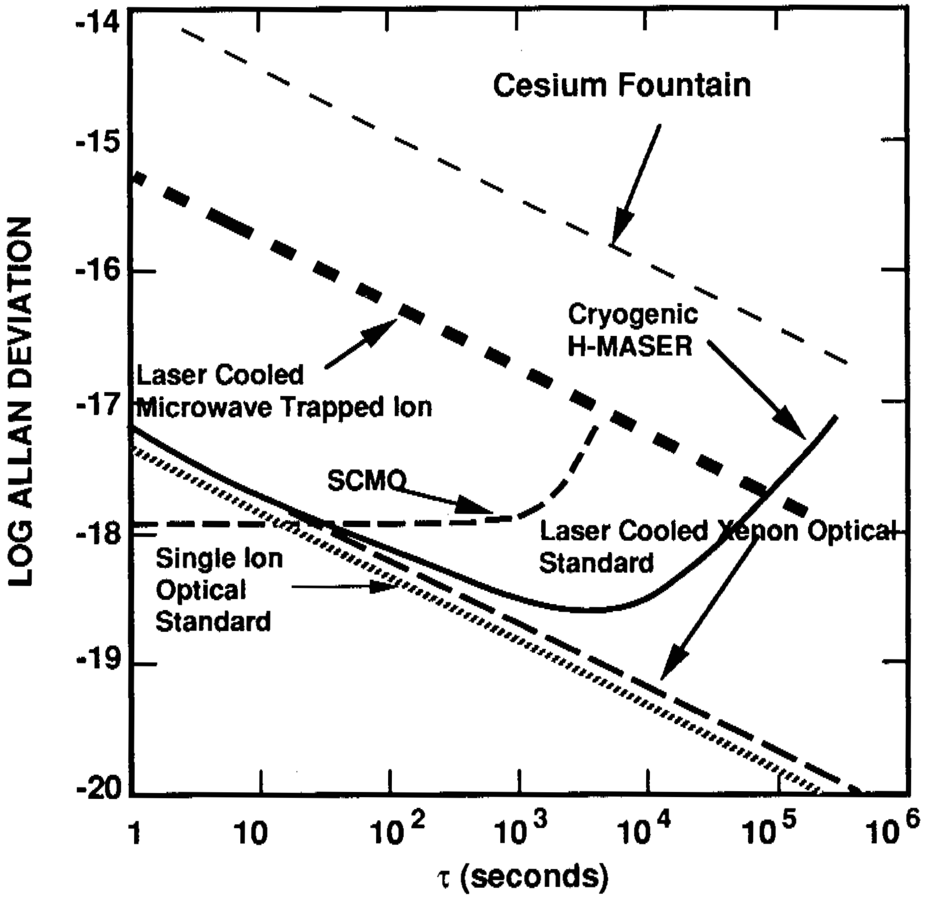

Figure 3. Projected stability of frequency standards in the next twenty-five years.