FREQUENCY STANDARDS FROM INDUSTRY OVER THE NEXT TWENTY FIVE YEARS

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Abstract

Present and possible future performance for many of the existing and new commercial frequency standards is presented here. Recent progress in the gas cell atomic standards with regards to size and cost is significant and considerable improvement is expected. Cesium beam standards will benefit in stability and accuracy from optical pumping. Cooled hydrogen masers will offer extremely good stability. Advances in trapped ion and cesium fountain technologies make them good high performance candidates for the future. The quartz oscillator field is more mature and consequently performance improvements for the future are going to be less spectacular. Oscillators stabilized to GPS will have many applications. Recent performance of cooled microwave dielectric resonator oscillators is very good and they offer the promise of serving as flywheel oscillators for advanced performance atomic standards.

INTRODUCTION

Present and future performance for the well known atomic frequency standards is presented here. In addition, some of the newer standards that may well become commercial will be discussed. These include trapped ion and cesium fountain standards. Gas cell standards are decreasing in size and cost and will find many applications as a result. Quartz oscillators are also covered. They are fairly mature and have many direct applications as well as filling many of the needs for flywheel oscillators. Oscillators stabilized to GPS will have wide use and potentially could replace moderate-to-high-performance atomic standards in some applications. Cooled dielectric resonator oscillators, also discussed here, are promising candidates for flywheel oscillators for advanced atomic standards and may well have application in optical frequency standards.

GENERAL OVERVIEW

There has been a lot of progress recently in many areas of the frequency standard arena and the future prospects are quite promising. Telecom and datacom are becoming very important and are driving many aspects of the commercial frequency standard business. Crystal oscillators and gas cell standards stabilized to GPS will be widely used in moderately demanding applications.

The main driving forces for the future include lower cost, smaller size, higher performance, and improved reliability. In particular, lower cost and smaller size are extremely important particularly in high usage applications and therefore continued progress in micro–miniaturization and increased integration of electronics is crucial. Better performance in both stability and accuracy will always be needed and considerable progress is being made here.

QUARTZ OSCILLATORS

Performance of present high quality quartz oscillators is limited by the resonator and environmental control of the resonator and associated critical circuitry. BVA crystals, made from an all quartz structure with electrodes spaced from the crystal surface, are the best resonators available today from the standpoint of frequency stability and drift. They are more expensive than conventional resonators with electrodes formed directly on the crystal. But, conventional resonators may have less sensitivity to vibration and shock.

Performances of several oscillators are show in Table 1. The ultra–precision 5 MHz BVA oscillator has the best overall performance. The 10 MHz BVA is next. The third oscillator uses a 10 MHz conventional SC cut resonator. The aging rate of the best oscillators is occasionally as low as $2x10^{-12}$ per day but more typical values are 1 to $5x10^{-12}$ per day. Occasionally flicker floor levels as low as $4x10^{-14}$ are seen. These results are mainly determined by the resonator as long as the circuitry is reasonably well designed.

Temperature sensitivities range from 0.2 to $40x10^{-12}$ per deg. C. Clearly the temperature results are quite variable depending on the design and construction of the oscillators.

The fact that very good aging and flicker performance can be obtained occasionally indicates that considerable improvement in resonators is possible but the processing and/or material is presently not well enough controlled.

Advances needed in quartz oscillators include: better material for the resonators perhaps accompanied by higher intrinsic Q; improved understanding and technology of the quartz–electrode interface; better oven designs and perhaps hermetic sealing to reduce environmental effects. Ultimately, the electronics will need improving. The multiple series resonator approach patented by Westinghouse can give better overall performance and may be used in the most critical applications.

Table 2. shows what might be expected in future ultra–precision oscillators.

GAS CELL DEVICES

Gas cell frequency standards work by passing a beam of pumping light through a gas cell containing vapor of the atoms being used (typically rubidium or cesium) with usually a buffer gas in an excited microwave cavity. The system is designed so that the intensity of the pumping light transmitted through the cell is a minimum when the microwave excitation frequency is at the atomic resonance.

The quantity of present rubidium standards sold is considerably larger than any of the other atomic frequency standards primarily due to cost and size. They are becoming an important element in telecom. Their performance is typically between quartz and cesium beam standards. Properly designed units can have considerably better shock and vibration performance than quartz. The same is true with regards to shifts due to change in orientation in the earth's g–field. Cost and size of these units is of prime importance and these are continually being reduced.

Most of the present units are optically pumped with an RF excited lamp. Typical performance is shown in Table 3. Using laser pumping can lead to smaller size and perhaps the performance shown in Table 4.

Using a laser for pumping the rubidium cell and designing the system for optimum performance rather than small size can give short term stability perhaps as good as $2\text{x}10^{-14}/\tau^{1/2}$ where τ is the averaging time. Very Low flicker floor may also be achieved. This type of device is a good candidate for a flywheel source for advanced very–high–stability atomic standards.

Work is presently being done on a laser pumped cesium gas cell device. This can be significantly smaller than rf lamp pumped rubidium devices because of the shorter wavelength of the cesium line (3.26 cm versus 4.39 cm for rubidium) and the small size of the laser compared to the rf excited lamp. The performance should be comparable to rubidium but the aging may be poorer due to the relatively high surface–area–to–volume– ratio in a small, elongated cell. A highly integrated set of electronics along with the small physics package could reduce the volume to 10 cm^3 or less and perhaps lead to lower cost if the manufacturing volume is large.

The already large market for gas cell devices has the potential to grow even larger if cost and size can be brought down. Laser pumping is important for size reduction and performance improvement and could reduce the cost compared to RF excited pumping lamps. Laser availability and price are crucial and depend on having large unit volume.

CESIUM BEAM STANDARDS

Cesium beam standards work by passing a beam of state selected cesium atoms through an excited microwave cavity. On exiting the cavity further state selection is used to select atoms that have made a microwave transition and eventually obtain a signal that is maximum when the microwave excitation frequency equals the resonance frequency of the atoms.

Cesium beam frequency standards are important where high accuracy and reproducibility, and negligible drift are needed. The present highest performance commercial unit has accuracy better than $1\text{x}10^{-12}$, drift much less than $1\text{x}10^{-15}$ per day, flicker floor less than $1\text{x}10^{-14}$, and short term stability better than $8\text{x}10^{-12}/\tau^{1/2}$. The high performance variety of cesium beam standards is moderately expensive.

Optical pumping of cesium beam devices using lasers to achieve state selection and atom detection is going on in a number of laboratories at the present time. The new laser pumped standard at NIST is now operational and is giving outstanding performance. Application to commercial standards will improve their accuracy by perhaps 3 to 5 and short term stability by more than 10. The latter comes about because of the much better utilization of the cesium in the beam. Improved short term stability is particularly important since that is the weakest performance area in present commercial cesium beam standards. Improving the short term stability by 10 reduces the time to make a measurement to a given precision by 100 – it would take 100 unimproved standards to get to the same precision in the same time! Accuracy improvement is due to several things. Rabi and Ramsey pulling are reduced and the C field homogeneity is better. These are due to the lack of deflection magnets in the optically pumped tube and the better symmetry achievable of the microwave transitions close to the main transition. In addition, better correction can be made for the frequency shifts due to cavity phase shift and relativity (the second order Doppler shift). Again, laser availability is crucial.

The market for lower cost, and consequently lower performance, cesium beam standards may grow due to continual increases in timing and synchronization requirements as communication rates go up.

HYDROGEN MASERS

Active hydrogen masers utilize the stimulated emission of hydrogen atoms in a cavity to produce an actual oscillation at the hydrogen hyperfine frequency in contrast to the passive standards we have discussed so far. They provide the best short term stability presently available from an atomic standard in the microwave range. Typical performance is about $1\text{x}10^{-13}/\tau$ for times shorter than about 20 seconds and $2.2\text{x}10^{-14}/\tau^{1/2}$ till the flicker floor or drift is reached. The best stability reached is typically somewhat better than $1\text{x}10^{-15}$. Active hydrogen masers are the standards of choice when extremely good short term stability is required such as in Very Long Baseline Interferometry, a form of radio astronomy. Drift rates of units without auto-tuning of the cavity are about $2\text{x}10^{-15}$ per day. Due to lack of precise knowledge of the wall shift, the accuracy is presently limited to about $1\text{x}10^{-12}$. Active hydrogen masers are relatively expensive and the market for them is not large at this time.

Passive hydrogen masers are similar to the gas cell devices and the cesium beam standards already discussed. Their short term stability is considerably poorer than an active maser but somewhat better than a high performance cesium. They have the same wall shift uncertainty as the active maser. Work has been done in the U.S. for some time on passive masers but no U.S. commercial units are on the market. However, commercial units are presently for sale by a Russian firm. The market is not large for these standards either.

Work has been going on in several places on cold (cryogenic) active hydrogen masers. They are expected to have extremely good short term stability, around $1\text{x}10-15/\tau$, and very good stability with ambient temperature. The required refrigeration is fairly complex and therefore these masers would be fairly expensive. They could be an excellent flywheel oscillator for some of the advanced standards.

There are concerns that the limited market for hydrogen masers and the shortage of government funding may hurt future maser R&D in the U.S.

TRAPPED ION STANDARD

Trapped ion standards use an RF quadrupole to trap quantities of one to many ions so that they can be interrogated for long periods of time leading to very narrow resonance lines. In the mercury 199 version, optical pumping using an rf excited lamp or a laser source is used for state preparation and observation of the resonance. Line widths well below 0.1 Hz at 40 GHz have been achieved. The biggest systematic frequency offset is due to the relativistic velocity effect (second order Doppler shift) caused by the induced motion of the ions in the RF field. This is minimized by using elongated clouds or virtually eliminated by using a line of single ions or a single ion.

Several trapped ion standards have been built using mercury 199 ions with an rf excited lamp for optical pumping. At least two groups are actively working in the field at present. Excellent short term stability, about $1\text{x}10^{-13}/\tau^{1/2}$, has been demonstrated with an rf lamp pumped, elongated mercury ion cloud trapped in a two–dimensional quadrupole trap.

Background gas can cause fairly large frequency shifts so cryogenic operation may be required for the ultimate in stability. Calculations indicate that a single trapped ion using laser cooling and cryogenic pumping to get rid of background gas could have offsets from the free ion resonance frequency as low as $1\text{x}10^{-17}$.

Trapped ion standards without either cryogenic cooling or laser optical pumping could be only somewhat more expensive than a high quality cesium standard. Adding laser pumping for mercury ions is very expensive at the present state of the art.

No units are available commercially at this time. A version using an rf lamp pumped elongated mercury 199 cloud and low pressure helium gas cooling could be made commercially and would have performance superior to high quality cesium beam standards at not too great a cost.

CESIUM FOUNTAIN

The cesium fountain is a passive standard that uses laser cooling and manipulation to toss a ball of extremely cold (microkelvin level), state selected cesium atoms upwards through an excited microwave cavity. They then fall back through the cavity under the influence of gravity and their state is determined to see if a transition has occurred. Transit times as long as a second are achieved leading to quite narrow lines with good signal–to–noise ratio. Several groups are presently working on these devices and progress is rapid.

Accuracy is expected to be $1\text{x}10^{-15}$ or better. The main limitation is a density dependent frequency shift due to spin exchange collisions. This shift can be quite large at the low temperatures and moderate densities used. Extrapolation to zero density can be done by a series of measurements and the accuracy value given above assumes this procedure has been carried out.

Frequency stability of $3\text{x}10^{-14}/\tau^{1/2}$ may be obtained with the signal–to–noise ratio already obtained.

Acceleration and orientation effects will be large with such slow atoms. This will make the fountain standard unsuitable for some applications.

No commercial units are presently available.

OSCILLATOR STABILIZED TO GPS

If an oscillator is stable enough it can be used with a GPS receiver and can average out the frequency variations (called Selective Availability) intentionally put on the GPS signals. If the oscillator is then locked to the average GPS frequency with a long time constant, excellent long term stability with respect to GPS can be achieved. Any high quality oscillator or standard can be used: quartz, rb cell, cs beam, hydrogen, etc.

Time uncertainty, rms, with respect to GPS of about 2 nsec can be achieved with high quality cesium and a good receiver. The uncertainty expected with a high quality quartz oscillator is perhaps 20 nsec.

This technique is relatively low–cost. It is not currently available commercially but could displace atomic standards in a number of applications when it does become available.

OSCILLATOR STABILIZED WITH COOLED SAPPHIRE RESONATOR

Cooled sapphire has extremely low dielectric losses at microwave frequencies and consequently a sapphire microwave dielectric resonator can have very high Q (in excess of 10^7 at X–band has been measured). Several groups are working on oscillators stabilized by such resonators and are achieving excellent results in the X–band region with temperatures 77 Kelvin and below.

The spectral purity achieved at X–band is about –50 dBc in a 1 Hz bw at 1 Hz. The noise floor is about 162 dBc and is reached at about 3 kHz. These, particularly the noise floor, are better than can be achieved with a high quality 10 MHz quartz oscillator multiplied in frequency to X-band. This stability at X–band has only been exceeded by an oscillator stabilized by a superconducting niobium cavity. A source with this kind of spectral purity is needed for high performance Doppler radars. It would also be useful as a high performance flywheel for advanced microwave and optical atomic standards.

Careful design and construction is necessary to avoid modulation by acoustic noise and vibration.

No units are available commercially at this time.

OPTICAL FREQUENCY STANDARDS

Optical atomic frequency standards have the potential for very high accuracy and stability. Stabilized helium–neon lasers at 633 nm using the Lamb dip and other techniques have been sold for more than 25 years. Their reproducibility and accuracy is around 1×10^{-7}. Much better performance was obtained with lasers stabilized to iodine absorption lines. Methane stabilized lasers in the near infrared appeared with reproducibility of a few parts in 10^{12}. A great deal of work on methane was done in the U.S. at what was then NBS (now NIST) and also in the USSR. A number of portable methane standards were built and used in the USSR.

Very good candidates exist among atoms and ions with very narrow optical spectral lines. The mercury ion is a good example. Accuracy of standards built using these lines is predicted to be considerably better than $1\text{x}10^{-15}$.

While these standards are excellent in the optical range, it is still very difficult, complicated, and expensive to connect their frequency with the rf/microwave region. Work is being done in this interesting and challenging area in several locations and there are some promising ideas that may ultimately lead to a practical solution to the connection problem.

SUMMARY

Continued improvement will be made in performance, size, cost, and reliability in many of the existing standards. Inexpensive, small gas cell devices will have a large market. Telecom and datacom are rapidly growing fields and their synchronization requirements are getting tighter. These are strong driving forces for the frequency standard market. GPS stabilized oscillators will be widely used.

In the higher performance area a number of things are happening. Optically pumped commercial cesium beam standards will offer considerable improvement in stability and accuracy. Trapped mercury ion devices have very good potential. Good flywheel oscillators will always be needed and their performance requirements are severe for the advanced atomic standards coming along. Very high performance standards such as the cesium fountain and single ion devices are in active development and may be commercialized in the future. Optical standards have great promise but the problem of connection to the rf/microwave range needs to be solved. Very high performance standards will always be needed but their market is not large.

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Parameter	5 MHz ultra-prec.	10 MHz ultra-prec.	10 Mhz prec.	UNITS
aging	2 to 50	5 to 50	<100	10^{-12}/day
g sensitivity	1	0.5	<10	10^{-10}/g
flicker floor	0.4 to 2	1 to 3	10	10^{-13}
temperature sens.	2 to 5	<50	<400	10^{-13}/°C
spec. purity: 1 Hz 100 KHz	-130 -160	-120 -155	-105 -162	dBc in 1 Hz bw dBc in 1 Hz bw

Table 1

Performance of several present high quality quartz oscillators

Parameter	ultra-precision.	UNITS
aging	1 to 5	10^{-12}/day
g sensitivity	<1	10^{-10}/g
flicker floor	0.1 to 0.5	10^{-13}
temperature sens.	<1	10^{-13}/°C
spec. purity: 1 Hz 100 KHz	-145 -165	dBc in 1 Hz bw dBc in 1 Hz bw

Table 2

Possible performance of future ultra-precision quartz oscillators

Parameter	compact rb. (lamp)	UNITS
aging	1 to 2	10^{-11}/mo.
g sensitivity	<1	10^{-10}/g
flicker floor	3 to 5	10^{-13}
temperature sens.	<6 (but non-linear)	10^{-12}/°C
spec. purity: 1 Hz	-80	dBc in 1 Hz bw
10 KHz	-145	dBc in 1 Hz bw
short term stability	3	10^{-12} (1 sec.)
	3	10^{-13} (100 sec)
volume	16	in^3
	260	cm^3

Table 3

Performance of present compact lamp pumped rb gas cell standards

Parameter	compact rb. (laser)	UNITS
aging	1 to 2	10^{-11}/mo.
g sensitivity	<2	10^{-11}/g
flicker floor	1	10^{-13}
short term stability	1	10^{-12} (1 sec.)
	1	10^{-13} (100 sec)
volume	6	in^3
	100	cm^3

Table 4

Possible performance of future compact laser pumped rb gas cell standards

QUESTIONS AND ANSWERS

Dr. Klepcynski, USNO: One of the areas where I feel that there really needs to be development or something to be done now and in the immediate near future is with the development of basic laboratory cesiums. Because right now, we only have effectively two in operation. NIST's seven will come on line shortly. And everybody a few days ago and this morning was talking about having UTC as good as possible. But UTC is steered to these devices. And is anything being done in the way of trying to get more of these devices on line to help with the recommendations, the paths to steer UTC to the primary cesium laboratories?

Dr. Cutler: Well as far as additional work in laboratories is concerned, certainly the French are working on an optically-pumped standard. And they are also doing some work on cesium fountains. So I think you are going to see considerable improvement on the laboratory cesium standards that will be contributing to the time scale in the near future.

The other thing, as Claudine Thomas has mentioned, is that the active hydrogen masers with the cavity auto–tuning systems are very good contributors to the time scale at the present time.

Dr. Winkler, USNO: I found this paper extremely interesting and stimulating. And I am sure that there is a great deal of reality which will develop in what you have said. But I am reminded that if one really wants to look into the future, one must not believe the experts too much because we remember what Edison had to say about the future of AC as a power, or others – Ramsey has been mentioned. There is really a problem. And the reason why that is so is because the experts see the problems and difficulties. And they may suddenly disappear because of some opening of technology. There are breaks. Because with the established technology, there is inevitably a point of diminishing returns. I think we are seeing that or have been seeing that with cesium. That is the answer to your observation that the absolute laboratory standards have not reached a part in ten to sixteenth or seventeenth, as could have been predicted by the first slide.

So there is a point of diminishing returns. And therefore, opening must come from entirely different technologies. And that means also entirely different technologies concerning the radio frequency or high frequency circuits which they are using. I think the good old RG–58 and the BNC connector and all that will be out of the window. In fact, they are going out now already. You can see that.

There is also going to be a fantastic degree of simplication. Any maturing of a technology is marked by a drastic simplication of everything. If we compared the devices, for instance, computers, today with their ancestors of comparable capability, it is drastic. The volume is a fraction and the cost is a fraction.

But in everything, I was surprised by one omission. I have not heard anyone predicting that the Mössbauer effect will be used. I am surprised by that.

Dr. Cutler: Well I would like to make a comment there. The ability to use stimulated emission there is extremely low because of the large energy separation. It is pretty much going to be spontaneous emission. So it really is very narrow band noise. However you are right, it is very narrow bend.

Dr. Maleki, JPL: Actually in a roundabout way, the idea of the Mössbauer effect was mentioned in a sense that one can go ahead and have a single ion in the matrix, similar to the notion of the Mössbauer effect, the difference, of course, being the transition – in one case being a nuclear transition, and therefore a very, very high frequency. The reason it wasn't mentioned is that for the past ten or 15 years, if one extrapolates again and sees how well have we done in just tying the terahertzes to GHzes. And we have done very poorly. In fact, I claim that we haven't done it except in very cumbersome laboratory chains. So one extrapolates from this on how are we going to do terrahertzes to I don't know what six orders magnitude higher would be, and that is the difficulty. But you are absolutely right. I didn't mention them because I don't see how to overcome that difficulty.

Dr. Cutler: I would like to make one response to Dr. Winkler's comment on simplification. Indeed things, as time goes on, get smaller, more reliable and so forth. But I don't believe they really get simpler. In fact, if you look at the computers of today and the frequency standards of today as compared to what we had 20 years ago, they are much more complex in their circuitry and so forth. But they appear on the surface to be simpler because the level of integration of the electronics is much greater and you can do so much more. And as a result, you get the ability to have higher performance, higher reliability and smaller size, even though they are more complex.