A REVIEW OF PRECISION OSCILLATORS

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ABSTRACT

Precision oscillators used in PTTI applications include quartz crystal, rubidium gas cell, cesium beam, and hydrogen maser oscillators. A general characterization and comparison of these devices is given including accuracy, stability, environmental sensitivity, size, weight, power consumption, availability and cost. Areas of special concern in practical applications are identified and a projection of future performance specifications is given. An attempt is made to predict physical and performance characteristics of new designs potentially available in the near future.

INTRODUCTION

Very recently, the author published a survey of atomic frequency standards [1,2]. This survey covered in an exhaustive way the presently available atomic standards, the manufacturers of these standards, as well as laboratories which are active in this field. The survey also included all known and published principles which are leading or may lead to new or improved frequency standards in the future. The reader is encouraged to study this and other recent surveys [3-8]. This paper does not duplicate these published results but rather expands them to include precision oscillators other than atomic oscillators and quantitative data on operational parameters such as warmup, retrace and several environmental effects. Also, this paper attempts to predict the performance of some new concepts which have been developed and which appear to pose no technical difficulties in their realization as frequency standards available in the near future. For these concepts stability, operational, and environmental parameters are predicted.

In this paper we will refrain from any discussion of new concepts or principles which, though promising, cannot yet be envisioned as being available in the near future. The following illustrates this important constraint: Saturated absorption stabilized lasers are omitted because their use as frequency standards or clocks is not possible at the present time because of the unavailability of a practical frequency synthesis chain in the infrared* which would allow the generation of precise standard frequencies and time signals from these standards which otherwise have documented competitive stability, and an interesting accuracy potential [10-13].

AVAILABLE STANDARDS

Figure 1 is adapted from Ref. 1 and 2. It includes crystal and superconducting cavity oscillators and various types of laboratory and commercial atomic frequency standards. Figure 1 shows that for short sampling times quartz crystal oscillators and superconducting cavity oscillators or rubidium masers are the oscillators of choice. For medium-term stability, the hydrogen maser and superconducting cavity oscillator are superior to any other standard which is available today. For very long-term stability or clock performance, cesium standards are presently the devices of choice. Rubidium standards are not superior in any region of averaging times, however, as shown in Table 1, they excel in the combination of good performance, cost and size.

It should be noted that in Fig. 1 the best available stabilities are listed for each class of standards regardless of other characterization of the devices. In contrast, Table 1 (and the following tables) combine stability data with operational data and other device characteristics. For each listed device in Table 1 the data may be viewed as being compatible, i.e., realizable in the very same device. Frequently, one finds in publications or other reference material that best performances are combined to create a super-device which is not actually available.

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* The present realization is still too complex and lacks precision [9]; however, this important problem is being studied at various laboratories, and significant technical breakthroughs may be expected in the future.

Table 1 and Fig. 1 illustrate that the choice of atomic frequency standards should be a matter of very careful consideration and weighing of the trade-offs and actual requirements. For any system application of precision oscillators, it is important to first determine the actually needed stability performance of the devices; secondly, to consider the environmental conditions under which the standard has to perform; and thirdly, the size, weight, cost and turn-on characteristics of the standard. Occasionally a system designer will find that a standard with all the characteristics needed does not exist yet on the market. In this case, the designer has two alternatives: either to adjust his system parameters to accommodate one of the available standards or to choose a combination of these standards to fulfill his need. The latter is an important aspect; for example, we assume that a system requires very good long-term stability and clock performance but at the same time high spectral purity, i.e., very good short-term stability. In addition, no cost, weight or size constraints are imposed. An optimum combination for this case could be a crystal oscillator paired with a cesium beam frequency standard. The systems concept as a solution to a design problem is a very powerful tool, and it can be realized technically at no sacrifice to the performance of the individual components of the system. The only actual restrictions may be physical size and cost. It should be noted here that many time scale generating systems are based on clock ensembles which feature not only several clocks of the same type but a combination of clocks of different design. For example, at the National Bureau of Standards we routinely use a combination of crystal oscillators and cesium standards when testing precision oscillators.

POTENTIALLY AVAILABLE STANDARDS

As was outlined in the Introduction, we list here only those devices and concepts which appear to be easily realizable within today's technology. A great many of highly promising and interesting concepts have been omitted at this time because they are too far removed from practical realizations or even practicality.

First, we assess existing standards (Table 1) and their future development capability (Table 2). In particular, we note that we expect stability improvements of about 1 order of magnitude in all four devices: crystal oscillators, hydrogen masers, cesium beam tubes, and rubidium standards.

In the case of crystals, this is due to better understanding and control of the noise behavior [14,15]. In the case of hydrogen, we expect an even better control of the cavity pulling effects which transduce temperature, pressure and vibrational effects into frequency fluctuations. A better understanding and control of the aging of rubidium cells due to improved control of the lamp intensity, as well as the gas composition in the cell appears possible. In cesium, an understanding of the flicker noise performance is expected as well as improved signal levels. Flicker noise effects may be due to cavity temperature gradients, microwave interrogation power fluctuations, magnetic field variations etc., all of which can be controlled to higher precision [1,2,16].

Table 3 lists five new concepts of devices. The cesium gas cell device is very much like the rubidium gas cell device except that cesium is used which necessitates a different lamp filter arrangement [17,18]. There is the potential that some aging effects may be better controllable with a cesium device because its different filter permits better control and higher symmetry of the optical spectrum. However, aside from this, the cesium gas cell device is expected to have characteristics similar to the projected performance of rubidium gas cell devices.

The dual-crystal concept is depicted in Fig. 2. The device consists of a crystal oscillator which is locked to a crystal resonator with a reasonably long time constant. The lock between the crystal oscillator and the passive crystal resonator can be envisioned as being rather simple using the dispersion lock technique studied in its basic feasibility with the hydrogen maser [19,20]. The advantage of a combination of a passive crystal with an active crystal oscillator lies in the realization of exceedingly high short-term stability in the oscillator, while the crystal resonator can be specifically designed for excellent long-term stability. In crystal oscillators short-term and long-term stability have been opposing goals, because high short-term stability typically requires rather high driving levels whereas excellent long-term stability requires low drive levels at the crystal resonator. A combination using two crystals could optimize on both in the same package.

The passive hydrogen device has been studied in detail and has demonstrated feasibility [19,20]. Its advantages rely to a high degree on the significant reduction of cavity pulling. As was mentioned already, cavity pulling serves as the transducer for temperature fluctuations, pressure fluctuations, mechanical stress fluctuations, etc., into frequency fluctuations. The passive device allows cavity Q's of 100 times or more below that of an oscillator and thus leads to a corresponding reduction in the cavity pulling effect. An increased environmental insensitivity coupled with a simplified design and excellent long-term stability without very high demands on the temperature stability can be realized. Figure 3 shows a block diagram of such a device. The hydrogen resonance is interrogated by a signal derived from a crystal oscillator. The signal is used to lock the crystal oscillator to the hydrogen resonance. In Fig. 3, dispersion locking is depicted which could simplify the overall system. A low cavity Q can be realized by using a lossy cavity but it appears advantageous to realize the low Q by using a very high cavity Q with a well defined mode, and lowering the Q electronically with negative feedback. This concept is shown in Fig. 3. In order to discriminate against long-term phase shifts in the electronics, an amplitude modulation of the hydrogen signal may be added. As shown in Fig. 3, this could be a hydrogen beam modulation.

Figure 4 shows the concept of a small and inexpensive atomic frequency standard. Traditionally, atomic frequency standards have been devised, designed, and built in order to achieve performances impossible to reach with crystal oscillators. In other words, the atomic resonance was used in the past to achieve excellence in performance. Thus, the selection of the atomic resonance as well as the whole design concept was directed towards achieving the utmost in stability and accuracy. A different design philosophy, however, appears possible. The weaknesses of a crystal oscillator are certainly not its size, weight, or power. They are the fact that crystals do not have a precise frequency without calibration,and that the crystal shows environmental sensitivity, in particular, with regard to temperature and acceleration (constant load, vibration, shock, etc.). If the atomic resonance is viewed only as a means to reduce or eliminate these negative performance characteristics of a crystal oscillator we are not necessarily constrained to resonances which lead to utmost stability and accuracy performance but others may be considered that lead to simpler designs. We therefore propose that a simple atomic standard could be built based on the well known inversion transition in ammonia*. Ammonia will not permit the design of a standard exceeding signicantly a 10^{-10} performance level in stability, accuracy, and environmental insensitivity, however, up to the 10^{-10}level a rather simple design concept should be realizable. Such an ammonia standard is depicted in Fig. 4 and its projected performance is depicted in Table 3. Again one could use the simple dispersion lock concept to control the frequency of the oscillator. The oscillator has not necessarily to be a crystal oscillator. If the standard is to operate under severe acceleration and vibration, the sensitivity of a crystal against these influences may cause loss of lock to the atomic resonance. Therefore, it may be advantageous to use other oscillator concepts such as a conventional LC or a Gunn effect oscillator. The device will have a performance which is in certain ways inferior to that of laboratory type crystal oscillators but it is projected that a combination of low cost, size and environmental insensitivity can be obtained which is not presently available with any other design solution.

Finally, in Fig. 5, we depict the superconducting cavity oscillator. This oscillator concept has been recently developed and studied, and it has demonstrated stability performance which exceeds that of any other known oscillator [23,24]. In fact, stabilities in the 10^{-16} region have been realized at averaging times of hundreds of seconds [25]. The superconducting cavity oscillator appears adaptable to commercial design and would be the best oscillator for medium-term stabilities (averaging times of 10 to 1000 s). It could therefore be of interest to users such as those engaged in very long baseline interferometry. It appears, however, unlikely that the superconducting cavity oscillator can become a very small and rugged device and it is equally unlikely that its environmental sensitivity can be reduced significantly from those values projected in Table 3.

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* The ammonia molecule has served in the first "atomic clock" device [21] as well as in the ammonia maser [22] which opened up the modern field of quantum electronics. Ammonia was discarded for clock applications because 25 years ago it was technologically cumbersome to reach K-band and because ammonia is inferior with regard to the realization of superior accuracy and stabilities.

So far, we have only discussed stabilities for averaging times of 1 s or longer. Stabilities in the millisecond region correspond to very high spectral purity. This spectral purity is especially needed in the generation of frequencies in the infrared and visible radiation region from microwave sources. The two oscillators which play a crucial role in this regard are superconducting cavity oscillators and crystal oscillators. Studies of both of these devices have shown that significant improvement in the millisecond stability region should be possible which, in turn, should allow multiplication of these signals into the infrared region without the need for intermediate oscillators. Such oscillators (lasers) presently serve as spectral filters in the infrared synthesis work and speed of light measurements [9].

It has been projected that linewidths of less than about 100 Hz in the near infrared region should be possible without intermediate oscillators using either improved crystal oscillators or superconducting cavity oscillators, or using today's crystal oscillator paired with today's superconducting cavity as a filter at X-band [26]. Such linewidths would be totally adequate to do high precision metrology, since 100 Hz in the near infrared region represents parts in 10^{13}.

Thus the realization of a unified standard for length and time [27,28] and a control of frequencies in the infrared and visible region is crucially tied to the availability of new oscillators.

Acknowledgements

The author is indebted to the many individuals, laboratories and companies who provided information which made possible the compiling of data of Tables 1 and 2 and Fig. 1. D. W. Allan and F. L. Walls contributed important information in many discussions. S. R. Stein provided data on the superconducting cavity oscillator; Fig. 5 is adapted from his thesis [25].

Tables 1-3

The listed data are average values for the respective types of standards taken from publications, reports and manufacturers specifications. There may be significant deviations towards better or worse data for certain models under certain operating conditions. The listed data for one type have generally been realized in at least one existing device. Therefore, some stability data are not as good as those of Fig. 1 which refer to the best achieved values (regardless of operational, physical, or environmental characteristics). The following is an explanation of the terms used in the second half of the Tables (the terms in the first part of the Tables are self-explanatory): Warmup is the time required to reach a frequency within 10^{-9} of the "final" frequency (i.e., after several days). In atomic standards it is practically equivalent to the time required for reaching a locked condition. Retrace is the ability of the device to reproduce - after a complete turn-off (long enough to return to shelf storage temperature) - the frequency before the power interruption. Temperature and acceleration sensitivities are self-explanatory, however, it must be noted that crystals are inherently sensitive to these effects due to the fact that the crystal resonator itself changes frequency under these environmental loads, whereas atoms are inherently unaffected. However, the proper design of temperature control can reduce these effects significantly. Acceleration refers quantitatively to constant g-loads; however, the values indicate qualitatively the related sensitivities to vibration and shock. Barometric effects are transduced into frequency variations via design features, and thus are reducible by improved design. Magnetic effects are acting directly on the atoms changing their frequency, but - as in the case of temperature for crystals - this effect can be reduced almost arbitrarily by shielding (though affecting cost and size) for all atomic standards.

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AVAILABLE TODAY

	COST (K$)	SIZE (ℓ)	WEIGHT (lb)	POWER (W)	STABILITY		
					1s	FLOOR	DRIFT (per day)
X-tal	0.7 – 3	1	1	3	10^{-11}	10^{-11}	10^{-10}
Rb(gas cell)	3.5 – 8	1	2	15	10^{-11}	10^{-12}	10^{-12}
Cs (tube)	15	20	40	30	10^{-11}	10^{-13}	10^{-14}
H (maser)	100	100	90	20	10^{-12}	10^{-14}	10^{-14}

	WARM-UP		ENVIRONMENT			
	TIME for 10^{-9}	RETRACE	TEMP (per °C)	ACCL. (per g)	BAROM. (per mbar)	MAG. FIELD (per G)
X-tal	1h	10^{-10}	10^{-11}	10^{-9}	–	–
Rb (gas cell)	10 min.	10^{-11}	10^{-11}	10^{-12} (est.)	10^{-12}	10^{-12}
Cs (tube)	30 min.	10^{-12}	10^{-13}	10^{-13}	10^{-14}	10^{-12}
H (maser)	1 min.	10^{-12}	10^{-13}	10^{-12} (est.)	10^{-14}	10^{-12}

TABLE 1 Available devices

POTENTIALLY AVAILABLE

	COST (K$)	SIZE (ℓ)	WEIGHT (lb)	POWER (W)	STABILITY 1s	FLOOR	DRIFT (per day)
X-tal	0.7 – 3	0.5	0.5	2	10^{-11}	10^{-12}	10^{-10}
Rb (gas cell)	2	1	2	10	10^{-12}	10^{-13}	10^{-13}
Cs (tube)	10	10	20	20	10^{-12}	10^{-14}	10^{-15}
H (maser)	80	100	90	20	10^{-12}	10^{-15}	10^{-15}

	WARM-UP TIME (for 10^{-9})	RETRACE	ENVIRONMENT TEMP (per °C)	ACCL (per g)	BAROM (per mbar)	Mag Field (per G)
X-tal	1 hr.	10^{-10}	10^{-11}	10^{-9}	- -	- -
Rb (gas cell)	10 min	10^{-12}	10^{-12}	10^{-13}	10^{-13}	10^{-12}
Cs (tube)	15 min	10^{-12}	10^{-13}	10^{-13}	10^{-14}	10^{-12}
H (maser)	1 min	10^{-12}	10^{-13}	10^{-12}	10^{-14}	10^{-12}

TABLE 2 Potential of presently available devices for the near future.

POTENTIALLY AVAILABLE

	COST (K$)	SIZE (ℓ)	WEIGHT (lb)	POWER (W)	STABILITY 1s	FLOOR	DRIFT (per day)
Dual X-tal	1 - 3	1	1	2	10^{-13}	10^{-13}	10^{-11}
Cs (gas (cell)	4 - 8	2	3	10	10^{-12}	10^{-13}	10^{-13}
H (passive)	50	60	70	15	10^{-12}	10^{-15}	10^{-16}
Utility atomic standard	1 - 2	1	2	2	10^{-9}	10^{-11}	10^{-12}
SCC-Osc.	20	100	100	100	10^{-13}	10^{-15}	10^{-13}

TABLE 3a Potential of new design concepts judged realizable in the near future.

POTENTIALLY AVAILABLE

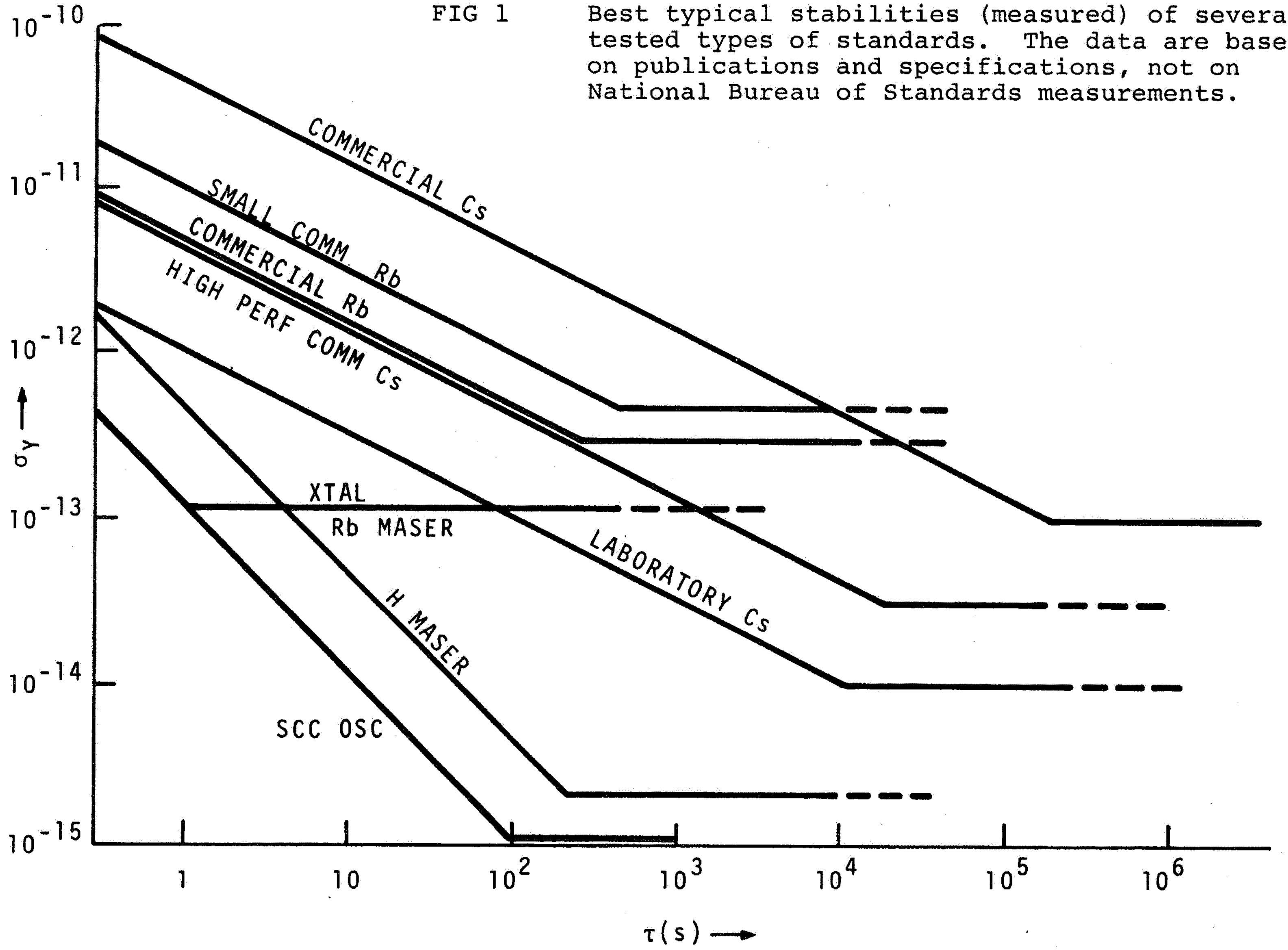
	WARM-UP		ENVIRONMENT			
	TIME (for 10^{-9})	RETRACE	TEMP (per °C)	ACCL. (per g)	BAROM. (per mbar)	MAG. FIELD (per G)
Dual X-tal	10 min	10^{-11}	10^{-11}	10^{-9}	- -	- -
Cs (gas cell)	10 min	10^{-12}	10^{-12}	10^{-13}	10^{-13}	10^{-12}
H (passive)	1 min	10^{-13}	10^{-15}	10^{-14}	10^{-15}	10^{-12}
Utility atomic standard	1s	10^{-12}	10^{-12}	10^{-14}	10^{-15}	10^{-13}
SCC-Osc	3h	10^{-15} *	(10^{-12})	10^{-9}	(10^{-14})	- - - -

* assuming that the device stays at superconducting temperatures, otherwise 10^{-7}

TABLE 3b Potential of new design concepts judged realizable in the near future.

C-2

FIG 1 Best typical stabilities (measured) of several tested types of standards. The data are based on publications and specifications, not on National Bureau of Standards measurements.



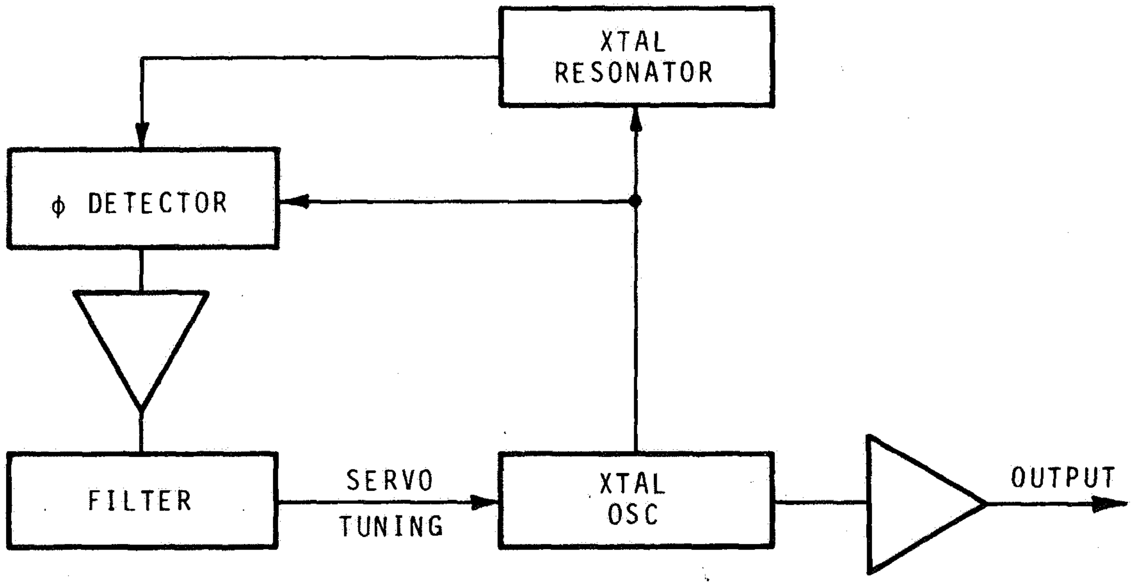


FIG. 2 Dual crystal concept. The crystal oscillator (high-level drive) is servoed to a passive crystal resonator (low drive level) using the phase sensitive dispersion lock technique.

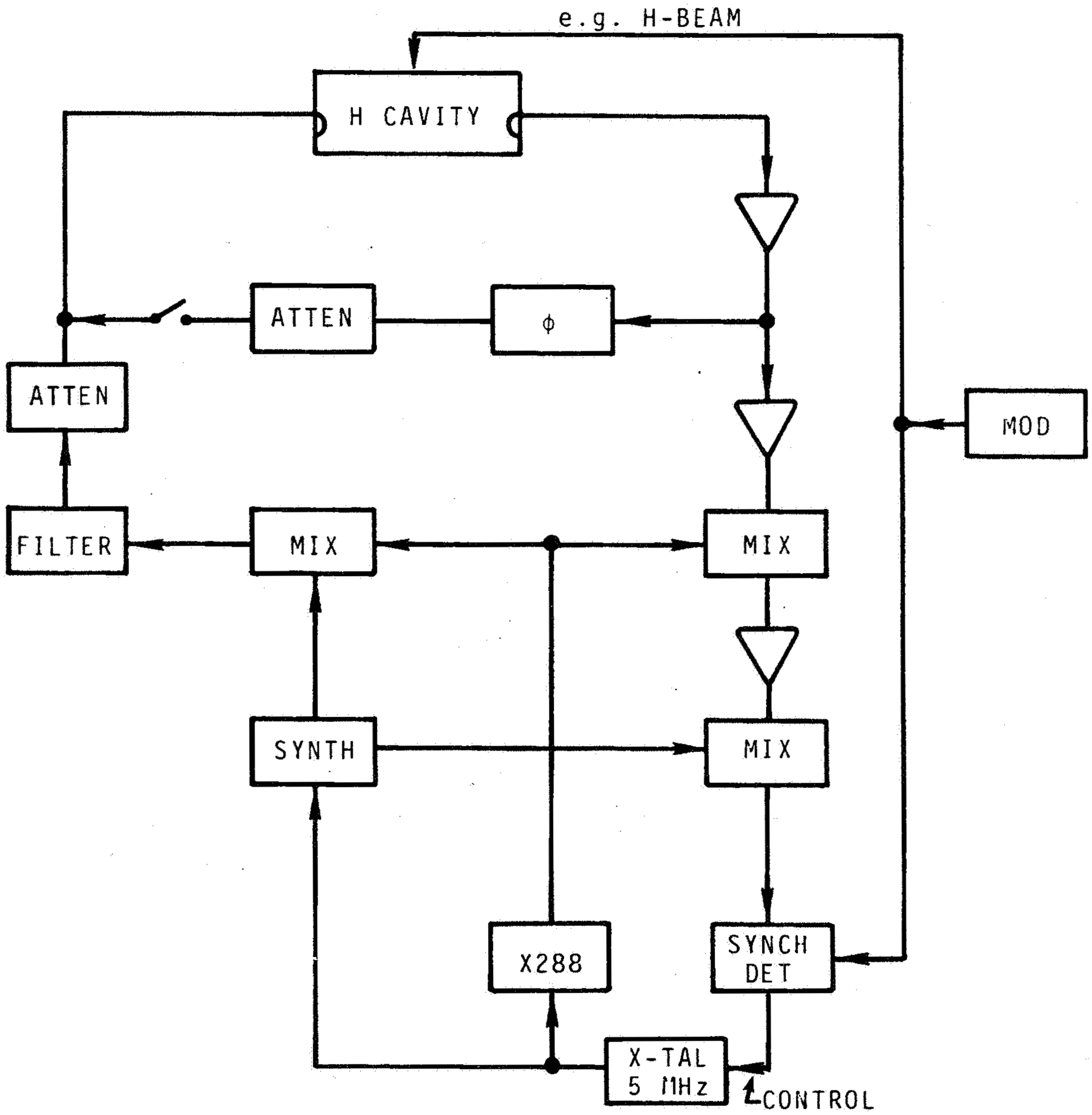


FIG. 3 Passive hydrogen concept. The crystal oscillator is locked to the hydrogen resonance using the phase sensitive dispersion lock technique. The cavity-Q is lowered using negative electronic feedback.

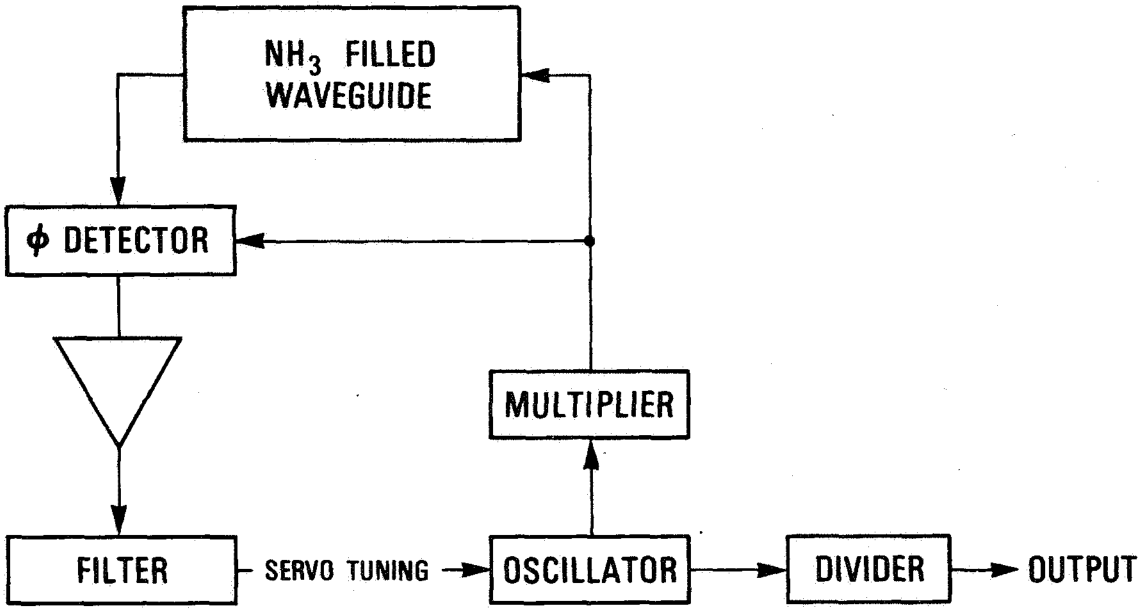


FIG. 4 Utility standard concept. The oscillator is locked to a resonance in ammonia (K-band) using the phase sensitive dispersion lock technique. The oscillator may not necessarily be a crystal oscillator but a Gunn effect oscillator or other conventional source.

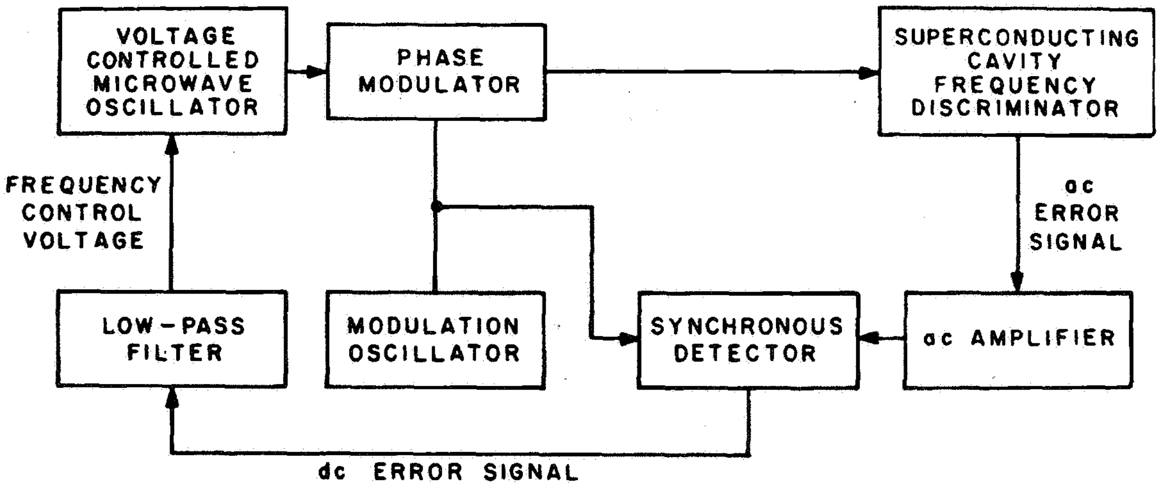


FIG. 5 Superconducting cavity oscillator. A Gunn effect oscillator is servoed to a superconducting cavity using conventional lock loop techniques [23,24].

QUESTION AND ANSWER PERIOD

DR. REDER:

I wonder why Dr. Winkler doesn't have a question on the inclusion of different standards in the general time scale.

DR. WINKLER:

I agree. I think that would be very desirable. But I have indeed a question or a comment regarding your slide No. 2.

There is a comment that region III really is not a drfit region, but a random walk frequency modulation. That is physically something completely different from a drift.

DR. HELLWIG:

If I remember what I said, I said that this is a deterioration of stability with increasing averaging times which may contain a drift or aging.

DR. WINKLER:

Yes. Well, the drift variations come with a true slope of plus one whereas you have indicated here a slope of plus one-half which would be a random walk frequency modulation, something quite reasonable to assume or even to see when you talk about atomic standards where you have some random variations. They occur presumably with a Poisson frequency, Poisson distribution. And for a lifetime, they will cause drifting away of frequency, but not necessarily in a continuous, monotonous way.

And I think it is important for us to realize that.

Another thing, of course, is I believe to understand what you have said concerning the combination of two standards or two frequency generators is really capable of widest generalization. That is, if you need very high, long-term stability. you must have a passive resonator. And if you must have very high or extreme short-term stability, you must have an active resonator, whatever it is. A passive one could be a crystal resonator, but also a cesium beam standard. And the active one could be a hydrogen maser or a crystal designed for very high short-term stability.

Indeed, I am quite certain that you are right that these approaches should be more pursued, particularly the combination of phase-locked filter to cesium standard, I think, which is closest to the practicability.

DR. HELLWIG:

Yes, I fully agree with all your comments. And just to defend myself once more, the fact that this slope is one-half indicates that I had the same opinion as you. But it makes it very difficult to give data for this region. And that is why I omitted them in my next slide.

DR. KARTASCHOFF:

Peter Kartaschoff, Swiss Post Office, Telecommunications Research Division.

For the user, data on

—Reliability

—Expected lifetime

of the various frequency standards would be very valuable and should be collected and made known.

DR. HELLWIG:

I fully agree; however, (a) not enough data are available readily to make general statements, and (b) the data on reliability would necessarily be tied to specific models of specific manufacturers. It does not behoove NBS to publicly state such data which would imply a relative quality rating of different commercial units. A general statement on lifetime can be made: The crystal or atomic resonators do not principally limit the design lifetime because better or different engineering can always lead to improvements. However, in the case of cesium and hydrogen devices, there is the basic mechanisim of exhaustion of the atom source and of the vacuum pump capacity.

LT. PARKIN:

Larry E. Parkin, U.S. Coast Guard.

If the quartz crystal within the cesium standard can be improved such that its output (stability) is 10^{-13} , will the long term stability of the cesium standard be significantly increased?

DR. HELLWIG:

No; the short-term stability may increase up to the crystal performance. However, a longer servo-attack-time is to be used which may affect the environmental sensitivity.

MR. LIEBERMAN:

Ted Lieberman, NAVELEX.

I was wondering about your warm-up times on your slides, first in the present-day cesium, rubidium and crystal. You talked about 30 minutes for cesium and 15 minutes for crystal. Isn't it essentially how long it takes to lock?

I think the cesium, rubidium come on much less time and in the future, will it be dependent on how soon you could lock or are you talking about different design?

DR. HELLWIG:

No. I think I did not project any change in cesium or rubidium for the future, any significant change, because, as you correctly said, this is the time required to produce your atomic resonance. You have to produce rubidium gas and cesium gas in a sense. And this first requires a time to warm up a device, an oven.

So there is fundamentally a problem in speeding that up. You could speed it up, of course, if you increase your initial power substantially.

MR. LIEBERMAN:

What we are talking about is five minutes or six minutes, not fifteen minutes or thirty minutes.

DR. HELLWIG:

What I quoted is the time to reach a certain performance. And some devices will reach lock within five—well, five is a little fast—7, 10 minutes. What I tried here again is not to describe particular devices, but sort of an average. And all the numbers I gave, stability of these numbers, give them the benefit of a good variance, really.

MR. TURLINGTON:

Tom Turlington, Westinghouse Electric.

Why do you think your proposed dual crystal oscillator will warm up about six times more rapidly than single crystal oscillator?

DR. HELLWIG:

Because a good long-term stability and low aging requires a careful oven design which makes a rapid warm-up difficult. In single crystal oscillators, usually the long-term performance is important. Thus rapid warm-up is usually not found in so-called precision oscillators. Good short-term stability requires only a rather simple temperature control; thus, rapid warm-up is possible. Therefore, in a dual crystal where the tasks of good short-term and good long-term performance are assigned to different crystals, rapid warm-up is possible without sacrifice in long-term stability, i.e., stability for one-day and longer.