

DESIGN PRINCIPLES AND CHARACTERISTICS OF FREQUENCY AND TIME STANDARDS

Helmut Hellwig

Frequency & Time Standards Section  
National Bureau of Standards  
Boulder, Colorado 80302

SUMMARY

High precision oscillators and clocks are discussed. They include cesium standards, rubidium standards, hydrogen masers, and quartz crystal oscillators. A brief review of their basic design philosophy and performance characteristics is given. Block diagrams of schematics of the physics packages as well as of the electronic systems are given, and it is pointed out quantitatively (where possible) which parameter changes cause frequency shifts and/or performance deterioration. Particular attention is focused on those parameters which are likely to change under nuclear radiation.

INTRODUCTION

This paper presents the area of precision frequency standards and clocks in three parts. The first part introduces the subject of precision frequency standards, and summarizes the present state-of-the-art in frequency stability and in time keeping. The second part discusses in detail the design of precision frequency standards which are available today: crystal oscillators, rubidium standards, cesium standards, and hydrogen standards. This discussion includes both the electronic circuitry, as well as the design of the physics package. The third part attempts to analyze known effects which may cause frequency shifts, instabilities, or malfunctions of these standards; components in the electronics and in the physics package are pointed out which may be critical in translating deleterious effects. Special emphasis is placed on effects possibly caused by nuclear radiation. Quantitative relationships are given where possible. The reader should understand that this topic has to be approached with caution since little is known experimentally about the effects of nuclear radiation on frequency standards, and much of what is said is only a best guess of what might happen, and more often is qualitative than quantitative.

I. PERFORMANCE OF PRECISION OSCILLATORS

The stability of precision oscillators is characterized by the square root of the pair variance (Allan variance) [1]. In Figure 1,  $\sigma_y(\tau)$  is plotted for

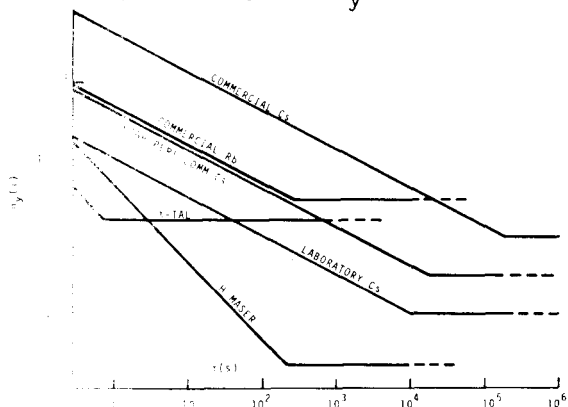


Fig. 1. Frequency stability of laboratory and commercial frequency standards

crystal oscillators and atomic frequency standards; the figure is adapted from Ref. 2. Plotted are typical or average performance for commercial standards and best measured performance for laboratory type devices. The inclusion of laboratory type devices helps to illustrate the potential for performance improvement possible with the commercial devices. Only the noise-dominated short-term performance and the noise-floor (best possible stability) for these standards are plotted. Omitted in this graph are drifts which should not be covered within the statistical measure  $\sigma_y(\tau)$ . Drifts have been measured in both cesium standards and hydrogen devices. However, they are typically very small, i.e., less than  $10^{-14}$  per day. Rubidium standards typically exhibit drifts which are of the order of  $10^{-13}$  per day. Crystal oscillators appear to exhibit drift or aging phenomena fundamentally which range from parts in  $10^2$  per day for the best crystal resonators, to parts in  $10^7$  for relatively inexpensive crystal devices.

One of the principal applications of frequency standards is their use as clocks. In a very real sense, any long-term frequency measurement is a time measurement. The stability performance and drift are related to the ability of frequency standards to operate as clocks and keep time [3].

The time error T at the elapsed time t after synchronization can be written as

$$T(t) = T_0 + R_0 t + \frac{1}{2} D t^2 + \dots + \epsilon(t) \quad (1)$$

where T is the time of the clock minus the time of the reference (ideal "true" time),  $T_0$  is the synchronization error at  $t = 0$  and R the rate (fractional frequency) difference between the two clocks under comparison averaged around  $t = 0$ . D is the linear (fractional) frequency drift term and  $\epsilon(t)$  contains all other fluctuations; e.g., those due to white noise, flicker noise, etc. The rms time dependence of  $\epsilon(t)$ ,  $\bar{\epsilon}(t)$ , can be calculated or estimated statistically [4], if one knows the power laws of the noise processes that model the clocks involved. For example, a drift of  $D = 10^{-12}$  per day, after 10 days, causes an accumulated time error of  $5 \times 10^{-11}$  days or about 4  $\mu$ s.  $\sigma_y(\tau)$  allows an estimate of  $\bar{\epsilon}(t)$ ; a reasonable approximation is simply  $\bar{\epsilon}(t) \approx t \sigma_y(\tau = t)$ . As an example,

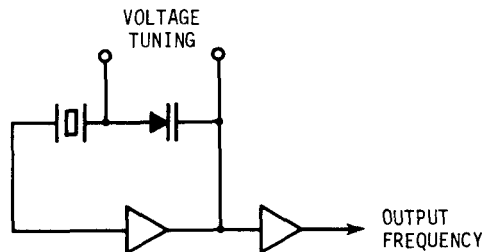


Fig. 2. Schematic of a quartz crystal oscillator

$\sigma_y(\tau = t = 10^4 \text{ s}) = 10^{-11}$  predicts approximately

$\bar{\epsilon}(t = 10^4 \text{ s}) \approx 0.1 \mu\text{s}$ .

## II. DESIGN PRINCIPLES OF PRECISION OSCILLATORS AND CLOCKS

The presentation of design principles in this chapter will be done in a simplified way. The standards are separated into functional blocks only to the degree necessary to discuss, in the following chapter, effects of parameter changes within the standard caused by aging or by external influences such as nuclear radiation.

Figure 2 shows a block diagram of a crystal oscillator. The crystal oscillator is basically a combination of the crystal resonator and a gain element with the crystal acting as a narrow band filter in the feedback. The oscillator usually features a varactor diode which provides voltage tunability. At this point it is worth noting that for any oscillator, not only commercial oscillators, the addition of tunability degrades stability because it introduces into the oscillator a variable element which is also frequency determining. Thus, the tuning element infringes on the primary function of the crystal as the only frequency determining element. Quantitative values for this degradation depend strongly on the particular engineering solution. As an example, a varactor tunability over a range of  $10^{-7}$  will likely preclude any possibility of reaching beyond  $10^{-12}$  in stability with a crystal oscillator.

As in all other frequency standards it is necessary to introduce isolation between the oscillator and its output. If the isolation is absent, any perturbation at the output would directly affect the oscillator. The most serious effect would be a frequency close to the oscillator resonance which would pull via injection locking. If this extraneous frequency is close enough to be within the bandwidth of the crystal resonator, the pulling in terms of the resonance linewidth will be approximately given by the power ratio of the extraneous signal to the oscillator signal measured at the resonator. Therefore, isolation of up to 140 dB is typically found in precision oscillators [5]. However, the wideband noise from the isolation amplifier may cause additional short-term frequency instability, especially in crystal oscillators.

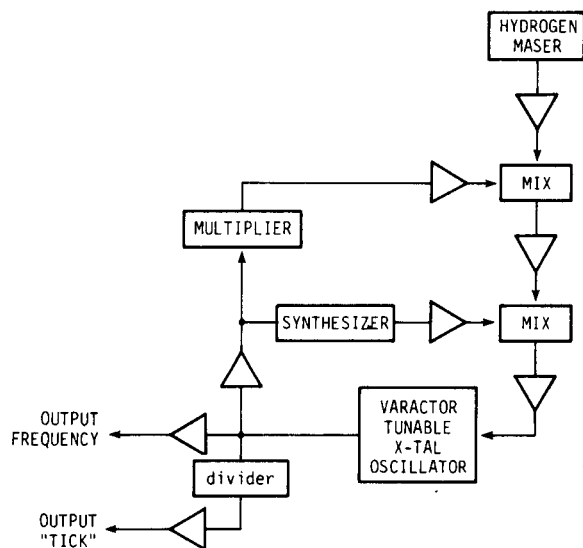


Fig. 3. Schematic of a hydrogen standard (maser oscillator)

A hydrogen frequency standard, based on a hydrogen maser [6], is depicted in Figure 3. The output of the hydrogen maser at 1.4 GHz is amplified in a wideband amplifier, and then fed into a double heterodyne receiver which ultimately translates the frequency down to dc. This voltage is used to control the frequency of the crystal oscillator which drives the double heterodyne system. In other words, the crystal oscillator is phase-locked to the hydrogen maser frequency. Again, the output frequency, typically at about 5 MHz, is buffered and a clock-tick can be obtained by passing this frequency through a divider and an output buffer. Hydrogen frequency standards are often called active devices because they are based on an active maser-oscillator and the standard 5 MHz is obtained via phase-locking techniques.

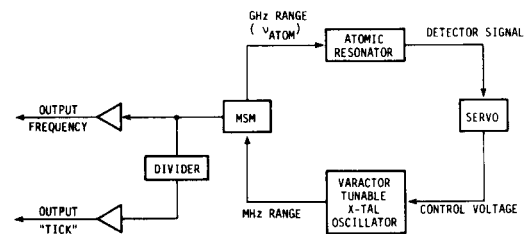


Fig. 4. Schematic of a passively operating atomic clock

The basic functional diagram of passive atomic frequency standards, e.g., the commercially available rubidium gas cell and cesium beam standards, is depicted in Figure 4. The atomic resonator acts as a frequency discriminator in a servo loop composed of a tunable crystal oscillator which feeds into a multiplier/synthesizer/modulator (MSM) electronics system. The MSM provides a frequency modulated microwave signal in the GHz range coinciding with the atomic resonance frequency. The output of the atomic resonator, the detector signal, contains the modulation of the microwave frequency which is phase-sensitively detected to produce a control voltage which keeps the crystal oscillator locked to the atomic resonance. Again outputs are obtained after buffering or frequency division.

The electronic components of Figure 4 are depicted in more detail in Figures 5, 6, and 7. Figure 5 shows the most simple solution to the MSM. The frequency modulation is imposed on the rf. This modulation can be a frequency modulation, or a phase modulation, and may be sinusoidal or squarewave. The modulation frequency must be lower than the linewidth of the atomic resonance. As an example, in some commercial cesium atomic standards the linewidth is 250 Hz. Thus, the modulation frequency typically is 100 to 200 Hz. The modulated rf is then multiplied to a frequency of several hundred MHz before it is fed into a step-recovery diode for further multiplication to the GHz range.

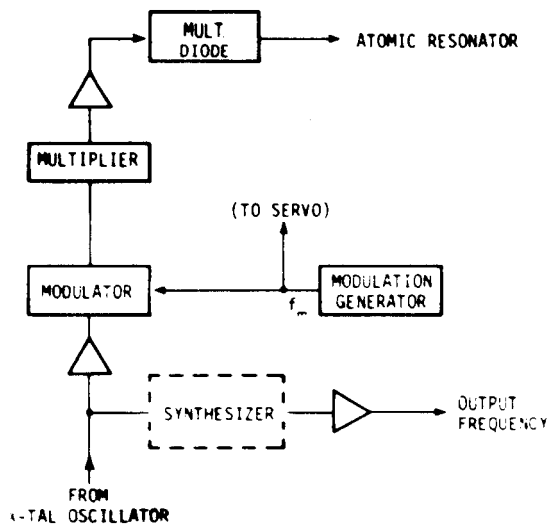


Fig. 5. Multiplier/Synthesizer/Modulator block diagram: synthesis in the secondary loop

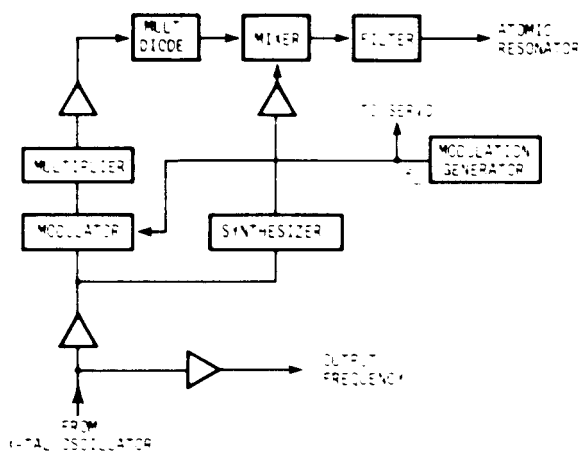


Fig. 6. Multiplier/Synthesizer/Modulator block diagram: synthesis in the primary loop

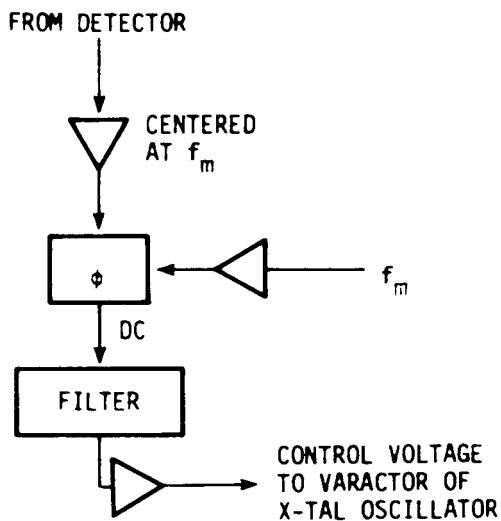


Fig. 7. Block diagram of the servo electronics

For optimum signal-to-noise the FM amplitude of the modulation is equal to half the linewidth of the atomic resonance. In this most simple synthesizing scheme of Figure 5, the crystal oscillator operates at a direct subharmonic of the atomic resonance frequency. This often means that its frequency is not a standard 5 MHz. In order to create a standard 5 MHz output, a synthesizer may have to be inserted before the output frequency is generated. The main loop containing the atomic resonator is often called the primary loop. The synthesized output, if another oscillator is used for spectral purity reasons, is called a secondary loop.

Figure 6 depicts an alternate MSM system which is often found in commercial standards. Here the synthesis is done in the primary loop, in other words, the crystal oscillator is at a standard (e.g., 5 MHz) frequency. The signal is again multiplied to several hundred MHz, then further multiplied in a step-recovery diode. The final frequency does not match with the atomic resonance frequency; therefore, a side-band has to be created at the atomic resonance frequency by mixing a synthesized lower frequency to the GHz carrier. A filter may be necessary to clean up the spectrum before the signal reaches the atomic resonator.

Figure 7 depicts a simple diagram of the servo system typically found in atomic frequency standards. The signal from the detector contains, in general, intensity at the modulation frequency; however, if the carrier frequency is exactly on the atomic resonance the output of the atomic resonator will contain only twice the modulation frequency (i.e., the second harmonic), and the fundamental vanishes. The intensity of the fundamental of the modulation depends on the detuning of the microwave signal from the atomic resonance signal. Its phase depends on the sign of the detuning. The phase detector where the signal is compared with the original modulation, allows the generation of a dc signal which will have a discriminator characteristic with zero corresponding to the center frequency of the atomic resonance. This signal can then be integrated and used to control the crystal oscillator which thus is locked to the atomic resonance.

It is important to note that although phase sensitive means are used, the whole system, as depicted in Figure 4, acts as a frequency lock and not as a phase-lock. This difference is the fundamental reason for the different stability characteristics of crystal and hydrogen standards, i.e., phase-lock systems, and cesium and rubidium standards, i.e., frequency lock systems, as depicted in Figure 1. The ultimate noise performance of a phase-lock system is such that the stability improves as  $\omega^{-2}$ , whereas in a frequency-lock system, such as rubidium gas cell or cesium beams, the stability improves only as  $\omega^{-1}$ .

The atomic resonators are depicted in more detail in Figures 8, 9, and 10. It is important to note that all three, rubidium, cesium, and hydrogen, are based on magnetic dipole transitions. In other words, the resonance is related to a magnetic property of the atom; it is excited by the magnetic component of the microwave field, and the transition frequency itself is sensitive to dc magnetic fields. The magnetic properties of atoms allow spatial separation of energy states in spatially inhomogeneous magnetic fields.

Figure 8 depicts a hydrogen maser [2,6]. The hydrogen usually is produced by a radio frequency discharge from molecular hydrogen. The beam emerges into a vacuum chamber, passes a state selecting magnet (hexapole), and enters a quartz storage

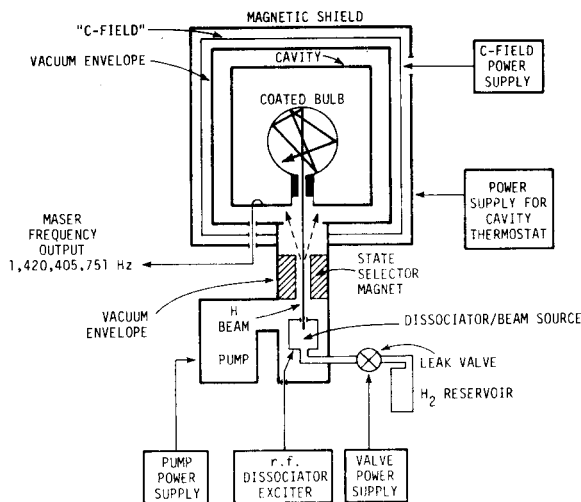


Fig. 8. Schematic of a hydrogen maser oscillator

vessel whose inside is lined with a fluorocarbon coating. The storage vessel is located inside a microwave cavity. If the cavity losses are low enough, and the intensity of the state selected hydrogen beam high enough, self sustained oscillations occur and the microwave output is generated (see Figure 3).

It is essential that the magnetic moments of the hydrogen atoms are spatially oriented in a region of low magnetic fields. For this purpose a so-called "C-field", a magnetic field with an orientation parallel to the rf magnetic is applied and several magnetic shields surround the cavity. The need for a high-Q cavity in order to achieve self sustained oscillations causes frequency shifts. They are related to the fact that the presence of the cavity is equivalent to the presence of an additional frequency determining element. The cavity has therefore to be stabilized, especially in temperature, in order to maintain frequency stability and accuracy. The required temperature stability is of the order of  $0.001^\circ \text{C}$  depending on the cavity material.

It is worth noting that usually a valve is inserted between the molecular hydrogen reservoir and the dissociator beam source in which the atomic hydrogen is created via radio frequency discharge. This leak valve is often a palladium leak having the property of passing only hydrogen and no other gas when heated. Therefore, a power supply is necessary to maintain adequate flow conditions.

The cesium atomic resonator or atomic beam tube [2,7], is depicted in Figure 9. The cesium beam emerges from an oven (at  $80^\circ \text{C}$  to  $120^\circ \text{C}$ ) into a vacuum. The beam passes the first state selecting magnet (A-magnet) and then traverses two interaction regions of a single cavity (Ramsey cavity) where it interacts with the microwave signal. The microwave signal changes the distribution of states in the atomic beam, i.e., the magnetic properties of the individual atoms. This is then analyzed in the state selecting magnet and detected at the atom detector. The detector consists of a hot wire ionizer which converts the impinging cesium atoms into cesium ions. The ions are then collected at an ion collector, which in its simplest form is an electrode followed by a field effect transistor. However, in most commercial standards, the collector is a mass spectrometer followed by an electron multiplier. Again, a C-field, i.e., a magnetic field orienting the

atoms has to be created in the cavity region, and a magnetic shield has to be used to reduce the influence of environmental fields.

The vacuum pump serves to keep low pressure in the cesium beam tube. However, most of the cesium is being absorbed by a suitable getter (typically carbon), which may be solid material but often is painted on the inside of the vacuum envelope.

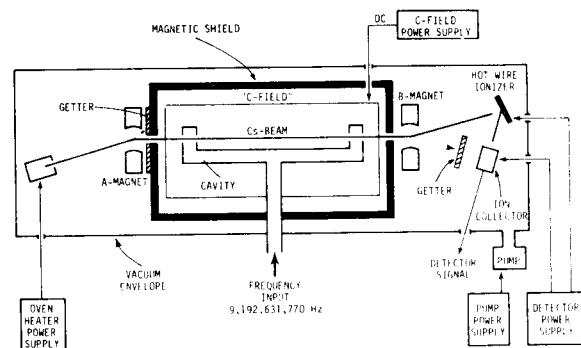


Fig. 9. Schematic of a cesium beam tube

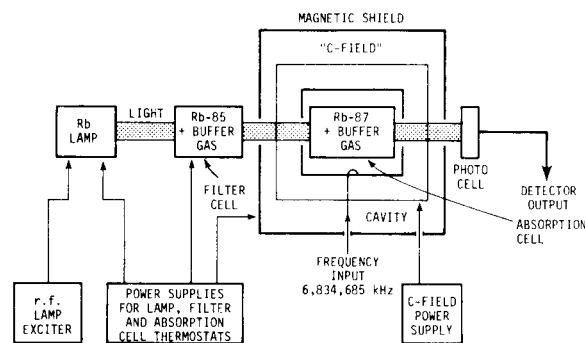


Fig. 10. Schematic of a rubidium gas cell system

A rubidium atomic resonator [2] is depicted in Figure 10. Rubidium and buffer gas is contained within a storage cell which is sealed off and located within a microwave cavity. The rubidium is created by an equilibrium between gas and liquid phase around  $70^\circ \text{C}$  temperature (a thermostat is needed for this). The corresponding partial rubidium pressure is of the order of about  $10^{-4} \text{ Pa}$  ( $10^{-6} \text{ torr}$ ). The buffer gas serves several purposes. It confines the rubidium atoms via frequent collisions to a very small region of space within the absorption cell, and thus reduces the first order Doppler effect and wall collision effects. This results in a much narrower line than otherwise possible; also re-radiation which would degrade the signal is suppressed. The rubidium lamp, excited by an rf oscillator, emits light at an optical transition of the rubidium atom. This light is transmitted through a filter which contains the rubidium isotope Rb-85 (Rb-87 is used in the absorption cell). The light then goes through the rubidium cell to a photodetector. If the microwave signal in the cavity coincides with the rubidium microwave transition, the light intensity is changed due to the simultaneous action of the microwave radiation and the light radiation on the same atomic energy level: light intensity

changes are the needed detector output signal.

It is possible, and has been commercially exploited, to combine the functions of filter cell and absorption cell into one cell, using a suitable isotope mixture [8]. This corresponds to a distributed filter/absorption action with the front part facing the rubidium lamp acting filter-like, and the part near the photocell acting absorption cell-like.

Not only the absorption cell, but also the filter cell and the rubidium lamp have to be heated, typically to higher temperatures than the absorption cell. The temperature stability of all three thermostats is critical to the frequency stability of the standard. Again, we find the need for a C-field, and for magnetic shields.

### III. POSSIBLE EFFECTS OF NUCLEAR RADIATION

Nuclear radiation can change the physical properties of materials or the functional parameters of electronic components. Both of these effects can lead to deterioration of the output signal with regard to the stability performance, as well as to systematic frequency shifts or drifts. Of course, a total malfunction of a clock can also be induced by nuclear radiation. In this chapter we will try to point out qualitatively where such influences can be expected and, if possible, give some quantitative relationships.

#### A. Crystal Oscillators

Only a cursory review of the effects in crystal oscillators is given. Effects in the electronics such as deterioration of gain, or deterioration of noise performance of transistors in the gain element of the oscillator or in the isolation output stage, cause deteriorating frequency stability of the standard. Both the short-term stability ( $\tau^{-1}$  region) and the noise floor (compare Figure 1) are affected.

Changes in the properties of the tuning element (varactor diode) affect the frequency directly; however, systematic frequency shifts and changes in the drift or aging behavior are largely related to the crystal resonator and quartz crystal properties themselves. Certain crystal materials are known to have much higher radiation tolerance than others. The reader is encouraged to study the literature existing on this topic [9,10].

#### B. Hydrogen Frequency Standard

The electronic components of a hydrogen frequency standard, of course, will change their properties under nuclear radiation. This includes the crystal oscillator itself. Being a phase-locked system no systematic frequency offset or aging should occur, but only changes in frequency stability. The effect of the deterioration of electronic components, whether it is multiplier, synthesizer, mixer, or amplifiers, will be that of degradation of the spectral quality of signals, and will be reflected in a deterioration of output frequency stability only. Since the short term stability of the hydrogen frequency standard ( $\tau^{-1}$  region of the stability) is determined by the noise of the electronics, whereas the flicker behavior of the hydrogen maser is probably determined by the hydrogen maser itself, a deterioration in the electronics will largely be reflected in the short-term stability ( $\tau^{-1}$  region).

It is probably a different story with the effects of nuclear radiation on the physics package, i.e., the hydrogen maser itself. If we study Figure 8, we should first analyze electronic effects

on the physics package via power supplies. The most critical power supply is probably the C-field supply since the required C-field stability is very high. An equation which translates C-field stability into maser frequency stability is given in the following [11]

$$\Delta\nu = 55 \times 10^{10} \text{ H } \Delta\text{H} \quad (2)$$

where  $\Delta\nu$  is the frequency change (in Hz) due to a field change  $\Delta\text{H}$  (in T); H is the C-field strength (in T). For typical C-fields of  $10^{-7}$  T a current change of 1 percent causes a fractional frequency shift of  $10^{-13}$ .

Next on the critical list of power supplies is the cavity thermostat. Cavity pulling is important in hydrogen masers and can be described by

$$\Delta\nu = \frac{Q_C}{Q_R} \Delta\nu_C \quad (3)$$

where  $\Delta\nu$  is the output frequency shift due to a cavity frequency shift  $\Delta\nu_C$ . The pulling factor is the ratio of cavity-Q to hydrogen resonance-Q; typically the pulling factor is of the order of parts in  $10^7$ .

For typical cavities, a cavity temperature change of approximately 0.01° C causes an output frequency change of  $10^{-13}$ . Thus, changes can be induced either via changes in the temperature servo but most likely via changes in the temperature sensor itself (usually a thermistor). Also, temperature changes in the bulk material could be induced by absorption of radiation.

Effects on the other power supplies, including the rf dissociator, may cause beam intensity changes or in extreme cases total failure of the unit. Beam intensity changes largely affect the frequency stability performance of the standard but can also cause small drifts via cavity pulling, i.e., change of  $Q_R$  due to spin-exchange [6].

With regard to material properties, changes in the shielding around the cavities could be important. Shielding factors of  $10^{-5}$  are typically employed, and thus changes in the shielding factor or in the residual magnetization of the shields would cause changes. Again, we use equation (2) to illustrate this. A change of  $10^{-9}$  T inside of the shielded region would cause a frequency shift of nearly  $10^{-13}$ .

Changes in the cavity tuning due to material effects which change the cavity resonance frequency are probably not important. However, the hydrogen atoms are stored in the fluorocarbon coated bulb for a time of about one second, equivalent to about  $10^4$  bounces. These bounces are not perfectly elastic, in other words, phase shift occurs at each collision resulting in a total frequency shift of the order of  $10^{-11}$  for typical bulbs. In order to maintain a frequency accuracy of  $1 \times 10^{-13}$  therefore, the properties of the coating have to remain stable to within one percent. Nuclear radiation may alter the properties of the fluorocarbon film and ultimately could destroy the film. Thus, frequency changes are to be expected, and under high radiation loads, total failure could occur. Total failure would already occur in typical masers, if the number of possible elastic bounces is reduced by a factor of 2 to 5, because the gain available from the hydrogen atoms would then be insufficient to maintain self-sustained oscillations.

#### C. Passive Atomic Standards

Rubidium gas cell devices and cesium beam frequency standards are passive devices. As such, they share

the principle of Figure 4, i.e., a frequency locked system using an atomic resonator. Frequency locked systems are sensitive against biases anywhere in the loop. For example, if the crystal oscillator is offset by a certain amount, i.e.,  $10^{-8}$ , and the total loop gain is  $10^6$  (this includes the electronic gain, as well as the equivalent gains of the varactor tuning and the detector), the systematic output frequency bias of the whole standard is  $10^{-14}$ . If in such a system, nuclear radiation causes the crystal oscillator to change its inherent frequency by approximately  $10^{-6}$ , the standard will experience a corresponding systematic output frequency shift of  $10^{-12}$ . Changes in gain of the whole servo loop correspondingly causes frequency shifts. Equivalent frequency shifts are to be expected if biases in the servo itself, such as dc voltages at the integrator or phase detector, are changed or produced by the action of radiation. Also saturation of electronic components could occur as a result of irradiation with resulting (temporary) failure of the servo loop as well as frequency offsets and (temporary) drifts.

Systematic frequency shifts can also occur via changes in the performance of the MSM. Changes in the electronic components of the MSM cause changes of the microwave spectrum. Systematic output frequency shifts can occur as a result of asymmetric microwave spectra [11]. This may be especially important for MSM systems such as pictured in Figure 6 where synthesis is done in the primary loop resulting in a naturally asymmetric spectrum which therefore may be much more sensitive to changes in electronic parameters including power, mixer performance and synthesizer performance.

Also, microwave power changes cause frequency shifts [12]. Depending on the particular properties of the individual physics package, shifts of up to parts in  $10^{12}$  may be caused by 1 dB power change. The step recovery diode may be an especially sensitive component in this regard. With the exception of a square-wave frequency modulation, the modulator could also cause systematic offsets, because any content of second harmonic in the output of the MSM is equivalent to a second-harmonic created by a frequency offset of the microwave signal from the atomic resonance frequency. Nuclear radiation effects in electronic components could change the relatively delicate balance needed in the modulator to suppress adequately second-harmonic components and thus create frequency shifts of the whole standard.

In addition to these systematic effects deterioration of the electronics in general may cause deterioration of the stability characteristics of the standard as was mentioned already in the case of the hydrogen standard. Since there is some evidence that not only the short-term stability ( $\tau^{-1/2}$  region) but also the noise floor is determined in part by electronic effects for both cesium and rubidium standards [13,14], the whole curve in Figure 1 could deteriorate as a result of deterioration of gain or noise performance of electronic components.

#### C-1 Cesium atomic resonator

As was discussed for the case of hydrogen, the C-field power supply is a sensitive component acting via the magnetic field sensitivity of the cesium resonance. The magnetic field sensitivity of cesium is given by [11]

$$\Delta\nu = 8.54 \times 10^{10} \text{ H } \Delta\text{H} \quad (4)$$

using units as noted in Eq. (2).

Typical C-fields in cesium standards are  $6 \times 10^{-6}$  T; therefore a change in the current generating the C-field of 0.1 percent may create a systematic frequency shift of the standard of the order of  $10^{-11}$ . The detector power supply is also sensitive since a change in its performance causes a change in the ionization efficiency which could not only lead to deterioration of stability but to systematic shifts via the reduction in servo loop gain as discussed above. Pump power supply and oven heater power supply are probably rather insensitive, short of total failure. The material properties of the magnetic shield may affect the frequency of the cesium resonance in a way very similar to the one discussed in connection with hydrogen above. Using equation 4, a change of  $10^{-9}$  T corresponding to a change of about 1 percent in the shielding factor creates a frequency shift of about  $10^{-13}$ .

If the ion collector is a combination of mass spectrometer and electron multiplier, the radiation sensitivity of the electron multiplier has to be watched. These effects act largely via reduced gain (see above) or may cause total failure. Heating effects due to nuclear radiation should not be of particular importance due to the inherent insensitivity of the cesium tube towards temperature changes.

#### C-2 Rubidium atomic resonator

The C-field considerations for the rubidium standard are similar to those for hydrogen and cesium above. The corresponding equation for rubidium is

$$\Delta\nu = 11.46 \times 10^{10} \text{ H } \Delta\text{H} \quad (5)$$

Typical C-fields are of the order of  $10^{-5}$  T. Therefore, a field change of  $10^{-9}$  T at the gas cell location, i.e., a C-field current change of 0.1 percent, leads to about  $10^{-12}$  frequency shift. The thermostats for lamp, filter cell, and absorption cell are critical. The lamp thermostat is the least critical and the absorption cell thermostat the most critical. As a quantitative example, temperature sensitivities of the absorption cell of parts in  $10^{11}$  to parts in  $10^{10}$  per degree are typical depending on the particular choice of buffer gas or buffer gas combination [15]. In this regard, heating of the physics package as a result of irradiation may be of considerable influence on frequency stability as well as frequency shifts and drifts.

The intensity and spectral distribution of the lamp intensity corresponds to a frequency shift of the order of  $10^{-11}$ . Thus, the power of the lamp exciter and the lamp temperature have effects which translate via this intensity shift. However, more important than intensity changes are spectral changes. The light is naturally not of symmetric spectral distribution because of the filtering action of the filter cell. Thus, changes in the temperature of lamp and filter can change the spectral distribution. Also the optical properties of the glasses involved are important. The glasses of lamp, filter cell and absorption cell could all change absorption coefficient and spectral distribution of absorption under nuclear radiation and thus cause frequency shifts. No reliable data on related effects are available to the best knowledge of the author at this time [16].

Changes in the glass structure of the lamp, filter and especially the absorption cell due to radiation may lead to the evolution of gasses as well as to changes in the absorption and diffusion properties. All of this ultimately may alter the rubidium density and the gas composition in kind and partial pressures of components. This could seriously affect all operational parameters of the standard.

Nuclear radiation can of course affect the sensitivity of the photo cell; in addition to the deterioration of the frequency stability performance of the standard, such effects of servo loop gain change as discussed above can result in frequency shifts. As in the case of cesium, rubidium standards are partly electronics - limited not only in the short-term performance, but also in the noise floor. Thus, the effects which were discussed so far giving rise to frequency shifts can also affect the fundamental frequency stability performance of Figure 1. Both rubidium gas cell and cesium beams are "passive" standards, therefore effects on the cavity tuning are negligible because of the fundamental insensitivity of the standard against cavity pulling. In today's rubidium and cesium standards, the pulling equation (comp. Eq. 3) is

$$\Delta\nu = \left(\frac{Q_C}{Q_R}\right)^2 \Delta\nu_C \quad (6)$$

The pulling factor is typically  $10^{-8}$  to  $10^{-10}$ , i.e., rather large  $\Delta\nu_C$  can be tolerated before  $\Delta\nu$  becomes of significant magnitude.

In conclusion, the author wishes to emphasize again that this paper is only an attempt at pointing out problem areas in precision frequency standards subjected to nuclear radiation. It is obvious that much remains to be done in addition to the very limited information which is presently available, especially regarding atomic clocks [16].

#### REFERENCES

- [1] J. A. Barnes, A. R. Chi, L. S. Cutler, D. J. Healey, D. B. Leeson, T. E. McGunigal, J. A. Mullen, Jr., W. L. Smith, R. L. Sydnor, R.F.C. Vessot, and G.M.R. Winkler, "Characterization of Frequency Stability," IEEE Trans. on Instrum. Meas., vol. IM-20, pp. 105-120, May (1971).
- [2] H. Hellwig, "Atomic Frequency Standards: A Survey," Proc IEEE, vol. 63, pp. 212-229, February (1975).
- [3] H. Hellwig, D. W. Allan, F. L. Walls, "Time and Frequency," Atomic Masses and Fundamental Constants 5, edited by J. H. Sanders and A. H. Wapstra, Plenum Press, pp. 305-311 (1975).
- [4] D. W. Allan, J. E. Gray, H.E. Machlan, "The National Bureau of Standards Atomic Time Scale: Generation, Stability, Accuracy and Accessibility," Nat. Bureau of Std. Monograph 140, pp. 205-232 (1974).
- [5] F. L. Walls, S. R. Stein, J. E. Gray, D. J. Glaze, "Design Considerations in State-of-the-Art Signal Processing and Phase Noise Measurement Systems," Proc. 30th Annual Symp. on Freq. Contr., Ft. Monmouth, NJ, to be published (1976).
- [6] K. Kleppner, H. C. Berg, S. B. Crampton, N.F. Ramsey, R.F.C. Vessot, H.E. Peters and J. Vanier, "Hydrogen Maser Principles and Techniques," Phys. Rev., vol. 138, No. 4A, pp. A972-A983, May (1965).
- [7] D. J. Glaze, H. Hellwig, D. W. Allan, S. Jarvis, Jr., "NBS-4 and NBS-6: The NBS Primary Frequency Standards," to be published in Metrologia 13 (Jan. 1977).
- [8] E. Jechart, "A New Miniature Rubidium Gas Cell Frequency Standard," Proc. 27th Annual Symp. on Freq. Contr., Ft. Monmouth, NJ, pp. 387-389 (1973).
- [9] B. R. Capone, A. Kahan, R. N. Brown, and J. R. Buckmelter, "Quartz Crystal Radiation Effects," IEEE Trans. on Nuc. Sci. NS-17, pp. 217-221, December (1970).
- [10] J. C. King and H. H. Sander, "Rapid Annealing of Frequency Change in High Frequency Crystal Resonators Following Pulsed X-Irradiation at Room Temperature," Proc. 27th Annual Symp. on Freq. Contr., Ft. Monmouth, NJ, pp. 113-119 (1973).
- [11] N. F. Ramsey, "Molecular Beams," Oxford, (1956).
- [12] H. Hellwig, D. W. Allan, S. Jarvis, Jr., and D. J. Glaze, "The Realization of the Second," Atomic Masses and Fundamental Constants 5, edited by J. H. Sanders and A. H. Wapstra, Plenum Press, pp. 330-336 (1975).
- [13] D. J. Wineland, D. W. Allan, D. J. Glaze, H. Hellwig, and S. Jarvis, Jr., "Results on Limitations in Primary Cesium Standard Operation," to be published in IEEE Trans. on Instr. and Meas. IM-26 (1976).
- [14] H. Hellwig, A. E. Wainwright, "A Portable Rubidium Clock for Precision Time Transport," Proc. 7th PTTI, Goddard Space Flight Center, Maryland, pp. 143-159 (1975).
- [15] P. Davidovits and R. Novick, "The Optically Pumped Rubidium Maser," Proc. IEEE, vol. 54, 155-170, February (1966).
- [16] T. M. Flanagan and R. E. Leadon, "Radiation Effects in Crystal and Atomic Frequency Standards," Proc. 7th PTTI, Goddard Space Flight Center, Maryland, pp. 125-140 (1975).