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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

FREQUENCY STANDARDS AND CLOCKS: A TUTORIAL INTRODUCTION

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Frequency Standards and Clocks: A Tutorial Introduction

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FREQUENCY STANDARDS AND CLOCKS:
A TUTORIAL INTRODUCTION

The topic of frequency standards and clocks is treated in a tutorial and non-mathematical way. The concepts of time, frequency, frequency stability, and accuracy are introduced. The general physical principles and design features of frequency standards and clocks are described. The design, performance, and limitations of quartz crystal oscillators and atomic devices (cesium, hydrogen, rubidium) are discussed in detail and critically compared for laboratory devices as well as for devices intended for field usage.

Key words: Cesium beam; clocks (atomic); crystal oscillator; frequency accuracy; frequency stability; frequency standards; hydrogen maser; quartz crystal; rubidium gas cell; timekeeping.

1. INTRODUCTION

Frequency standards and clocks: what do they have in common? A more complete answer will be given later. We note for the moment that most clocks and in particular the very accurate and precise ones are based on frequency standards. The reason for this is the intimate relationship between frequency (symbol ν , "nu") and time (symbol t). If we look at a series of events which are occurring in a somewhat regular fashion, e.g., the rise of the sun every morning, we can state how many of these events occur in a given time period: this number would be the frequency of this series of events. In our example we could say that the frequency of sunrises is $\nu = 7$ events per week or $\nu = 365$ events per year. "Events per week" or "events per year" would be called the unit which we used for our frequency number; this frequency number is different for different units. In our example we assumed that we know somehow what a week or a year is, i.e., we relied on some external definition for our unit of time.

We can now ask, what is the time between the events? The answer for our example is simple, one sunrise succeeds the other after $t = \frac{1}{7}$ week or $t = \frac{1}{365}$ year where we used "week" and "year" as two possible choices for our unit of time. We can rely on the regularity and precision of the occurrence of the events, in other words, on their precise periodicity. Hence, we could define: the unit of time is one week; one week is the time elapsed at the seventh sunrise following an initial sunrise.

We learned two things: (a) For periodic events, the time between the events t is related to the frequency ν of their occurrence in the following simple way

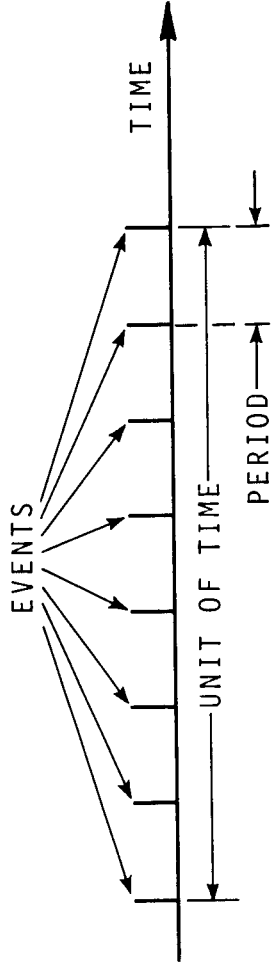
$$\nu = \frac{1}{t} \quad (1)$$

and (b) that periodic events can be used to define time, i.e., the generator of the periodic events - the frequency standard - can be used as a clock. The frequency standard becomes a clock by the addition of a counting mechanism for the events.

In our example above, the frequency standard is the rotating earth. The time between recurring events is one day. This frequency standard served mankind for thousands of years and remained until very recently the source for the definition of time. The counting mechanism which made it a clock was the recording of years and days.

The needs to interpolate time from day to day, to get along for many days without celestial observations, and to more precisely measure time-intervals which are very much shorter than a day brought about the invention of clocks. Although there are other types of clocks like the sand-clock or the decay in radiation intensity of a radioactive substance, we shall confine ourselves to the discussion of clocks based on frequency standards (i.e., systems based on periodic events).

The first clocks based on a frequency standard (a pendulum) were invented about 400 years ago. This type of clock is most widely used today. The pendulum may be a suspended weight (gravitational pendulum) like in "grandfather" clocks or the balance (torsion pendulum) or quartz



FREQUENCY = NUMBER OF EVENTS PER UNIT OF TIME

$$\text{ACCUMULATED CLOCK TIME} = \frac{\text{TOTAL NUMBER OF EVENTS}}{\text{NUMBER OF EVENTS PER UNIT OF TIME}}$$

POSSIBLE DEFINITION:

UNIT OF TIME = A SPECIFIC NUMBER OF PERIODS OF
A WELL-DEFINED EVENT GENERATOR

Fig. 1. Definition of time and frequency.

crystal of modern wristwatches. The objects of our discussion in this report are today's most advanced frequency standards and clocks; however, a close look at our traditional clocks will show all the essential features which we will recognize again in our later discussion of quartz crystal and atomic clocks.

The pendulum in our clock is the frequency determining element. In order to arrive at a frequency standard the pendulum has to be set in motion and to be kept in motion: A source of energy is necessary together with means to transfer this energy to the frequency determining element. In a wristwatch this source of energy is typically the winding spring, and the energy is transferred by mechanical means which are controlled by the pendulum itself in order to cause energy transfer in the proper amount at the proper time in synchronism with the movement of the pendulum. This is called "feedback" in electronic systems. We now have a frequency standard; the tick-frequency of its pendulum could be picked up acoustically, for example, and used as a standard frequency. This is actually being done commercially when adjusting the rate of a clock: the tick-frequency is compared to some (better) standard frequency. In order to arrive at a clock, a read-out mechanism is necessary which counts and accumulates the ticks (more accurately: the time between the ticks) and displays the result. In our example of a wristwatch, this is accomplished by a suitably dimensioned set of gears and the moving hands on the clockface.

The unit of time today is the second (symbol s). Very much in analogy to our sunrise example, the second is defined in reference to a frequency determining element. Since 1967 by international agreement this "natural pendulum" is the cesium atom. One second is defined in the official wording as "the duration of 9192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom". Accordingly, the frequency of the cesium pendulum is 9192 631 770 events per second (the cesium atom is a very rapidly oscillating pendulum). Following our eq (1) the unit of frequency is then defined as hertz (symbol Hz). One hertz equals the

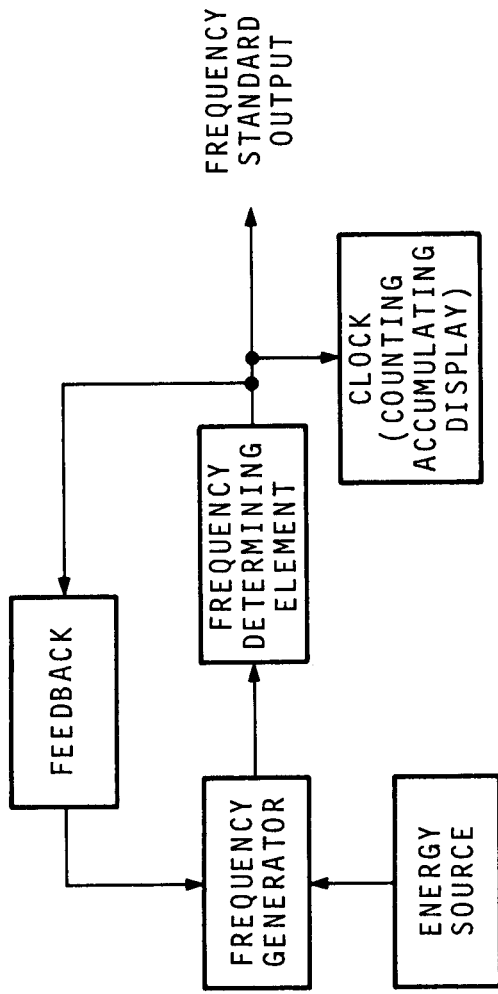


Fig. 2. Frequency standard and clock.

repetitive occurrence of one event per second. The use of "hertz" is preferred to the older term "cycle per second", cps, and was assigned in recognition of the exceptional contributions of the 19th century physicist Heinrich Hertz.

2. BASIC CONCEPTS

2.1 Accuracy, Reproducibility, Stability

The performance of frequency standards is usually described in terms of accuracy, reproducibility, and stability. We will use these terms in the sense of the following definitions:

Accuracy: the degree of conformity of a measured and/or calculated value to some specified value or definition.

Reproducibility: the degree of agreement across a set of independent devices of the same design after adjustment of appropriate specified parameters in each device. Alternately, it is the ability to reproduce, independently, a previous frequency value.

Stability: the frequency and/or time domain behavior¹ of a process. In the time domain (i.e., the measurement time or duration is the varied quantity) a frequently used measure of stability is the pair-variance (or Allan variance) (to be explained later) or its square root (the pair-stability).

It is obvious from these definitions that frequency accuracy will be largely of interest in scientific measurements and in the evaluation and intercomparison of the most advanced devices, but of little or no interest to the average user of frequency standards. A good reproducibility is an asset in applications where it is of importance to rely on some degree of conformity of the output frequency of several devices such as a factory-guaranteed frequency value. The characterization of the stability of a frequency standard is usually the most important information to the user. The frequency stability (symbol σ , "sigma") of a fre-

¹In this paper, for tutorial purposes, only the time domain stability is used. We note, however, that for many scientific applications the frequency domain stability measure is more useful.

quency standard will depend on a variety of physical and electronic influences both internal and external to the device which cause frequency fluctuations. The frequency stability depends also on the exact measurement procedure which was used to measure the stability.

We shall explain this in the following: Frequency stability can be measured by taking a reasonably large number of successive readings of an electronic counter which counts the frequency of the device to be evaluated. Each counter reading (in hertz) is obtained by measuring or sampling the counted frequency for some specified time, the sampling time (symbol τ , "tau"). This sampling time can usually be chosen by simply adjusting a knob on the counter; for example, a sampling time of 0.1s or 1s or 10s may be chosen. Everyone has had the experience that fluctuations tend to average out if observed long enough; however, this is not always so. Sigma will therefore usually depend on the sampling time of the measurement and tends to get smaller with longer sampling times; again, there are many exceptions to this.

It may be that the fluctuations at some later time are partially caused by, or depend to some degree on, the previous fluctuations. In this case, the actual value of σ will also depend on the particular way in which the many counter readings are averaged and evaluated. Also, it will be of influence whether the counter starts counting again immediately after completion of the preceeding count or if some time elapses ("dead-time") before counting commences again.

Finally, electronic circuits will have a finite response time, e.g., they cannot follow fluctuations faster than some given rate. For example, our eye can not register light fluctuations which occur faster than about every $\frac{1}{10}$ of a second; using eq (1), we say that the eye has a frequency response of 10 Hz, or that its bandwidth is only 10 Hz, i.e., the eye can not follow frequencies higher than 10 Hz. In order to measure frequency stabilities for sampling times larger than some value , we have to provide for an electronic frequency bandwidth which is larger than about $\frac{1}{\tau}$.

We summarize: a recommended way of properly measuring and describing frequency stability is the following: (a) make sure that the frequency bandwidth of the total measuring set-up is larger than $\frac{1}{\tau_{\min}}$ where τ_{\min} is the smallest desired sampling time; (b) use a counter with a dead-time as small as possible²; (c) take a sufficiently large number of readings at a given sampling time which is held constant and compute³

$$\sigma = \sqrt{\frac{\text{addition of the squares of the differences between successive readings}}{2 \times \text{total number of differences used}}}$$

In the scientific literature this σ is called the square root of the pair (or Allan) variance; (d) repeat (c) at other sampling times τ and tabulate or plot σ as it depends on τ . See Appendix I (fig. 26).

Commonly, σ will be given as a fractional or normalized value, i.e., the value obtained for the frequency stability is divided by the carrier frequency. For example, if a frequency stability of $\sigma_{\delta\nu} = 10$ Hz were measured at a carrier frequency of $\nu = 5$ MHz (MHz = megahertz = million Hz) then the fractional frequency stability would be

$$\sigma_y = \frac{10}{5 \times 10^6} = 2 \times 10^{-6}.$$

We denote the kind of σ by a subscript, $\delta\nu$ ("delta nu") referring to frequency fluctuations (measured in Hz) or $\frac{\delta\nu}{\nu} = y$ referring to fractional or normalized frequency fluctuations (dimensionless). A stability of one part in a million is thus

$$\sigma_y = 1 \times 10^{-6},$$

and one part in a trillion is written as

$$\sigma_y = 1 \times 10^{-12}.$$

²The dead-time should be less than the reciprocal bandwidth; if not, computation procedures exist to account for larger dead-times.

³The counter readings can be taken in Hz, σ will then have the dimension of Hz.

The common usage of the fractional frequency stability σ_y instead of the frequency stability $\sigma_{\delta\nu}$ (given in Hz) has its good reasons. In many applications of frequency standards their nominal output frequency is used after multiplication or division, i.e., the standard frequency is used to synthesize electronically other frequencies. Also, frequency standards themselves already synthesize several output frequencies, and different frequency standards offer different output frequencies. In such a usage of frequency standards as well as in the comparison of their performances it would be extremely inconvenient to state $\sigma_{\delta\nu}$ because this number (in Hz) would change with any alteration in frequency due to synthesis. This is not the case with σ_y because $\delta\nu$ as well as ν change in the same way in synthesizing procedures. Of course, we assume here that synthesis does not cause additional instabilities, an assumption which is mostly valid with today's electronic capabilities.

2.2 Time Accuracy

In clocks, time accuracy is of importance. In accordance with the definition for accuracy at the beginning of this section, the accuracy of a clock is the conformity of its reading (the date shown) with the reading of a standard time scale (a standard or reference date). A clock can be initially set (synchronized) with respect to a reference clock with some accuracy T_0 . Its reading then gradually deviates by an amount $T(t)$ from the reading of the reference clock. $T(t)$ indicates that the deviation or error T is a function of the time t which elapsed after synchronization with the reference. This deviation, i.e., the accuracy of the clock, depends on the stability performance $\epsilon(t)$ ("epsilon of t ") of the frequency standard in the clock, the fractional frequency offset R_0 of the clock⁴ with respect to the reference clock, and on the change D of the fractional frequency of the clock with time (D = fractional frequency drift). Other parameters may be important; however, those mentioned are most commonly encountered. The time reading of the clock then has a degraded accuracy $T(t)$ which is given by

⁴The counter readings can be taken in Hz; σ will then have the dimension of Hz.

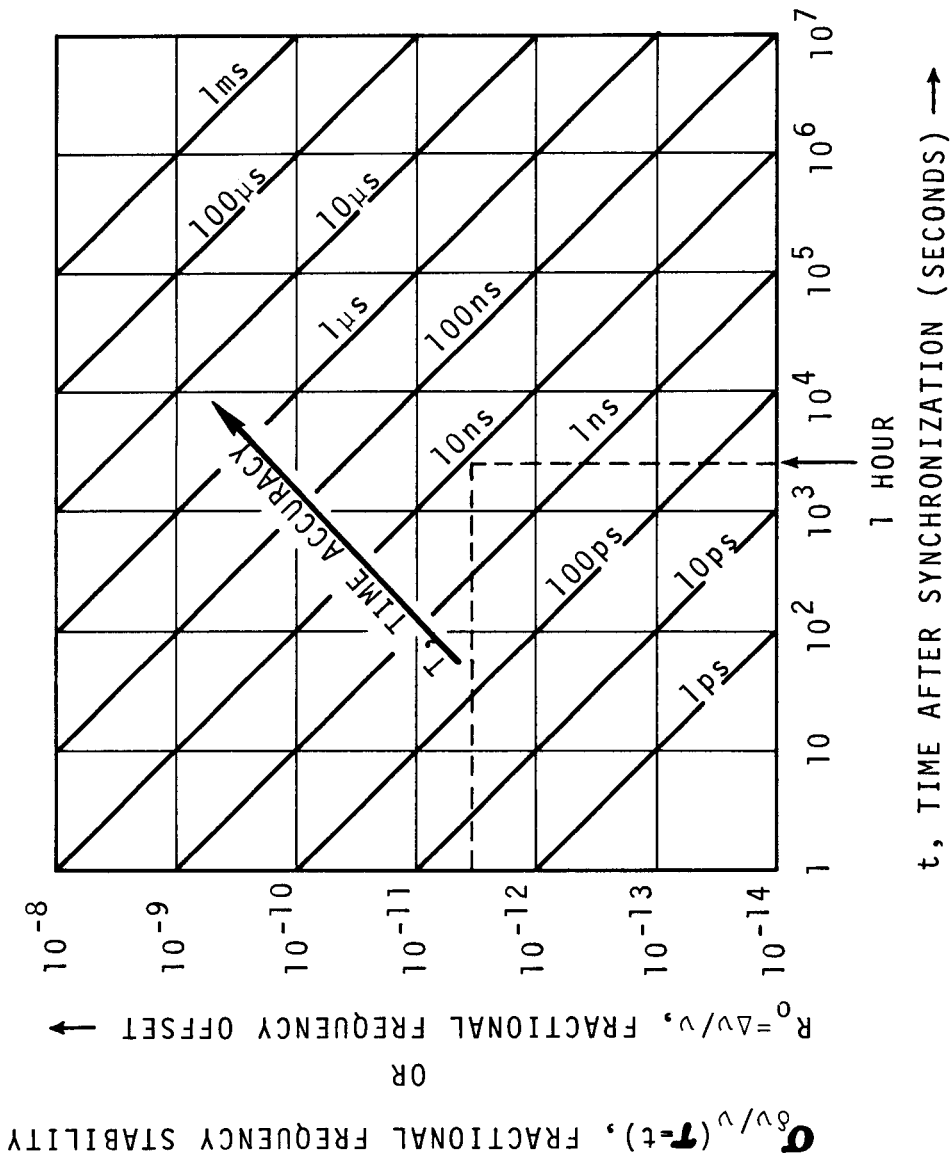


Fig. 3. Relationships between clock accuracy, frequency stability, and frequency offset.

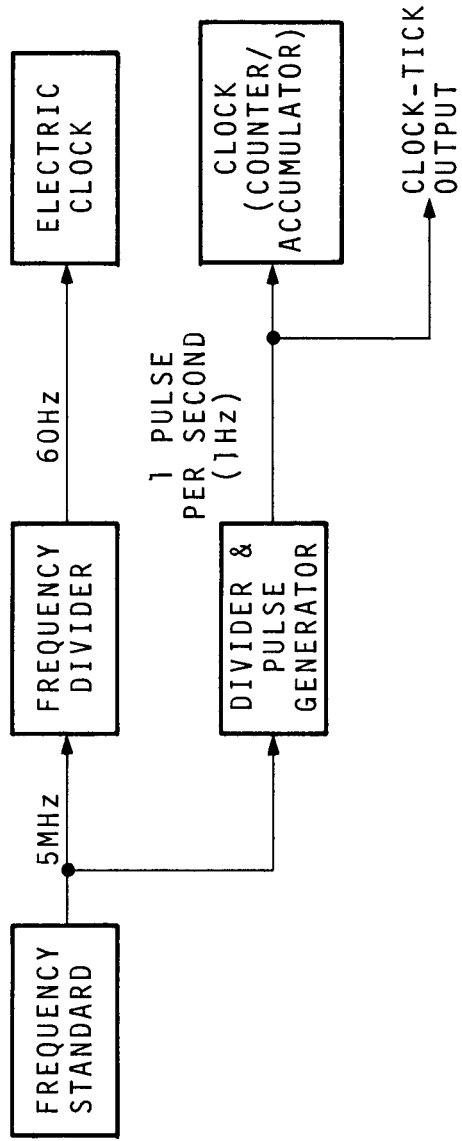


Fig. 4. Example of a clock system.

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

The presence of a frequency drift D can rapidly deteriorate clock accuracy because the corresponding time error "accelerates" following the square of the elapsed time t . If T_0 , R_0 and D are not present (i.e., zero), only the random fluctuations can cause a time error $T(t) = \epsilon(t)$. $\epsilon(t)$ of course can be calculated from the frequency stability σ_y . This can be a rather complex mathematical problem and is often called "clock modeling" or "time prediction". For most practical uses, however, a very simple, quite good approximation may be used:

$$\epsilon(t) \approx t \times \sigma_y (\tau = t) \quad (2a)$$

where $\sigma_y (\tau = t)$ means the fractional frequency stability evaluated for a sampling time τ equal to the time t which elapsed after the last setting of the clock. For example, a clock with a fractional frequency stability of $\sigma_y = 10^{-11}$ for sampling times of 10^5 seconds (about 1 day) would be accurate to $T = \pm 10^5 \times 10^{-11}$ second = ± 1 microsecond per day (again we assume T_0 , R_0 and D to be zero).

A clock with a fractional frequency offset of $R_0 = \Delta\nu/\nu = 10^{-9}$ would be accurate to $T = 100$ microseconds after 1 day (assuming T_0 , D and $\epsilon(t)$ to be zero). And, finally, a clock with $D = 10^{-9}$ per day would be accurate to only $T = 5 \times 10^{-6}$ day ≈ 0.4 second after 100 days.

2.3 Clocks

In the Introduction we discussed that the addition to a frequency standard of a mechanism, which counts and accumulates and possibly displays the result, creates a clock.

This task can be performed by a frequency divider which, for example, derives a frequency of 60 Hz directly from a 5 MHz crystal oscillator. The 60 Hz voltage can be used to drive an electric clock similar to those driven by the 60 Hz power line frequency which we use at home or at work. Or, an additional electric pulse generator may be used which generates one very sharp electrical pulse per second. The time interval of 1 second

between the pulses (corresponding to a frequency of 1 Hz) is directly derived from the output of our frequency standard. The pulses can be used in time comparisons with those of other, similar clocks; or a counter/accumulator/display (clock-face) can be driven by them.

3. FREQUENCY STANDARDS, GENERAL ASPECTS

3.1 Resonators

The performance of a frequency standard is to a considerable degree, but not exclusively, given by its frequency determining element. It determines the frequency by its resonance behavior. Some examples for resonance phenomena are (a) a rod, clamped only at one end, which can vibrate, (b) a block of solid material which can contract and expand and thus vibrate, (c) a capacitor-coil combination (tank circuit) in which the electro-magnetic energy can oscillate back and forth between these two elements, (d) an antenna (a dipole) where the distribution of electric charges can oscillate back and forth, and (e) a coil in which an electric current can create a magnetic field which can oscillate between its two possible polarities (a magnetic dipole). All these devices have in common that they can vibrate or oscillate if they are excited. The method of excitation may be a mechanical pulse for (a) and (b) or an electrical pulse for (c) or a sudden surge of an electric field for (d) or of a magnetic field for (e). The devices exhibit a resonance, i.e., they are resonators with a well-defined frequency which is characteristic of the physical dimensions of the device: the length of the rod, the thickness of the block, the size of the capacitor and coil, the length of the antennas. Once excited, the oscillations will die out gradually with a decay time which is determined by the losses of the resonator. Some of these losses are internal friction as in our cases (a) and (b), and electrical resistance for (c) through (e); in any case, the oscillation energy is ultimately transformed into heat. If there were no losses, the oscillations would never stop; we would have an ideal resonator. The more losses, the faster the oscillations decay and the resonance is less pronounced. It is now obvious that we could use the decay t_d of the oscillations to describe the quality of our resonator. The larger t_d the better the resonator.

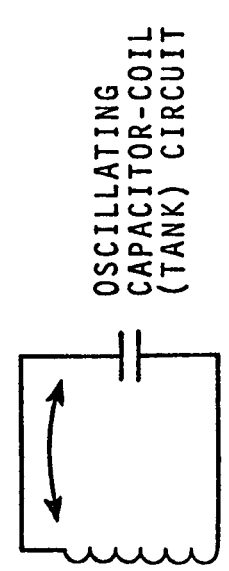
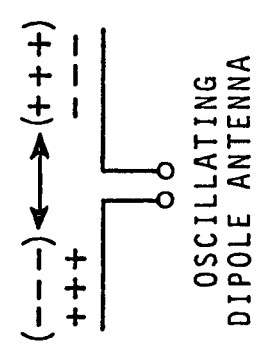
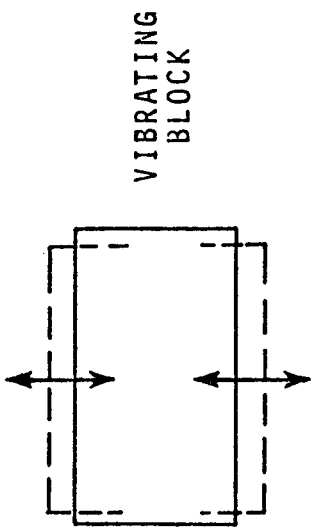


Fig. 5. Examples of resonators.

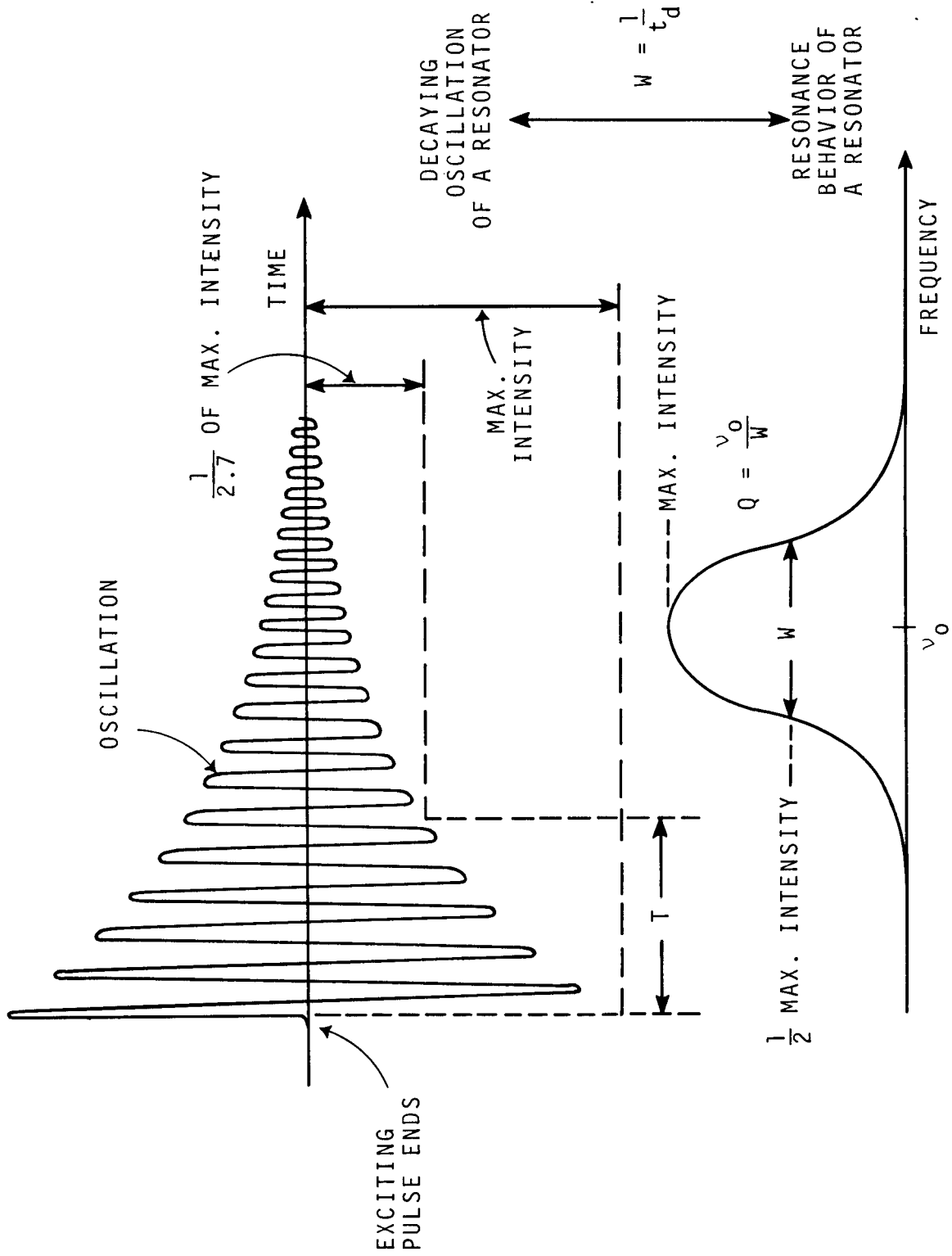


Fig. 6. Decay time, linewidth, and Q-value of a resonator.

An alternate way of measuring the resonance behavior is to use an external oscillator, to couple it to the resonator, and to sweep slowly the frequency of the external oscillator across the resonance. We will find again a resonance frequency at which the resonator will oscillate most pronounced, i.e., with the greatest intensity. On both sides of the resonance frequency, the response of the resonator will lessen until it ceases to respond. We can define a frequency interval around resonance in which the resonator response is relatively strong; we call it the resonance linewidth (symbol W). There is a simple relationship⁵ between W and the decay time t_d

$$W = \frac{1}{t_d} . \quad (3)$$

Again, as in the case of σ , it is of advantage to state the linewidth in a fractional way. The fractional linewidth would be $\frac{W}{\nu_0}$ where the symbol ν_0 is used for the resonance frequency. More widely used is the quality factor of the resonance (symbol Q) which is defined as the reciprocal fractional linewidth

$$Q \equiv \frac{\nu_0}{W} . \quad (4)$$

In frequency standards we obviously like to have large values for the Q of the frequency determining element. As an example, if $Q = 10^6$, then a fractional accuracy of 10^{-10} would imply that we can determine the center of our resonance curve to a small fraction (10^{-4} or one hundredth of a percent) of its width. In the same example, a stability of 10^{-12} for some sampling time would correspond to an ability to keep the frequency to within 10^{-6} (one millionth) of the resonance linewidth around a given value. It is clear, therefore, that the frequency stability and accuracy of a frequency standard may be expected to become the better the higher the Q -value of the frequency determining element.

Many kinds of frequency determining elements have been and are being used in frequency standards. They can be grouped into three classes:

⁵Equation (3) is only an approximation. Depending on the particular shape of the resonance curve we would have to insert a factor into this equation; however, this factor is never far from unity. t_d is defined as the decay to $\frac{1}{e}$ of the original amplitude. e is a number, $e \approx 2.7$.

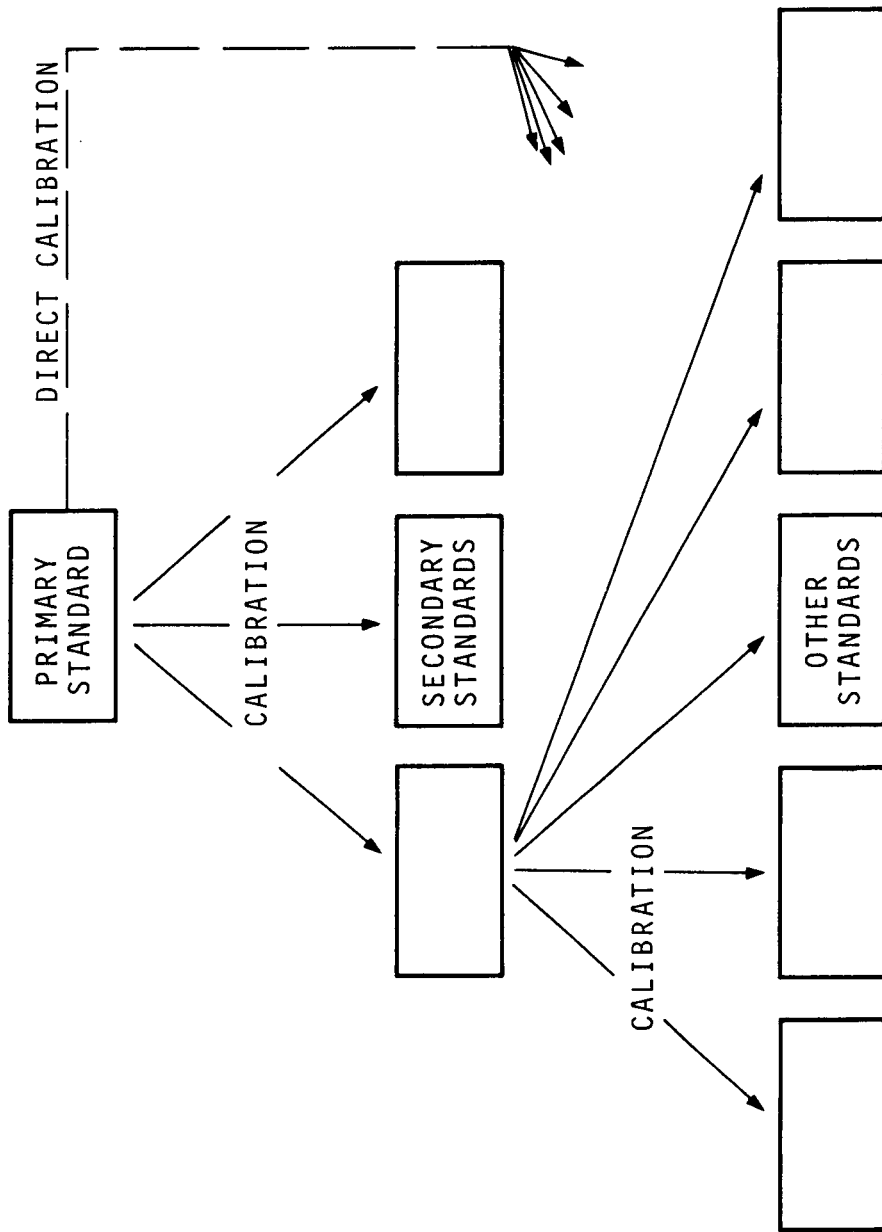


Fig. 7. Hierarchy of frequency standards.

Mechanical resonators;
electronic resonators;
atomic resonators.

As far as mechanical resonators are concerned we will only discuss one group in detail, the quartz crystals. Other mechanical resonators like the pendulum and the tuning fork are of no importance in today's high performance frequency standards although they have been historically very important and are still used in low performance devices (e.g., in watches). For similar reasons we will also omit the discussion of electronic resonators like the tank circuits (our device (c) of above) and microwave cavities.⁶ Atomic resonators form the heart of our most accurate frequency standards and clocks and will, therefore, be extensively discussed.

3.2 Primary and Secondary Standards

At this point, we should briefly discuss the frequently used terms "primary frequency standard" and "secondary frequency standard". These terms should refer to the systems-use of the devices; any frequency standard, regardless of its accuracy or stability, can be a primary frequency standard, if it is used as the sole calibration reference for other frequency sources. A secondary frequency standard is a device which is occasionally calibrated against a primary frequency standard but operationally serves as the working reference for other frequency sources. The use of the terms "primary" and "secondary" to describe the performance and/or the design of a frequency standard itself is not helpful, often misleading and therefore discouraged. These aspects can be described adequately and accurately by stating accuracy, reproducibility, and design features.

One class of frequency standards can be separated from the rest. We call those the evaluable or "primary" frequency standards, which, by virtue of their basic physical operation as well as their design, allow the experimental evaluation of all known influences which might alter the output frequency. The accuracy of the evaluable frequency standard can thus be stated for the single device without reference to any other frequency

⁶We will touch on one very interesting example of a standard using a microwave cavity, the superconducting cavity oscillator (See Section 8)

standard and the term "primary" is then permissible because they are by virtue of their design the top of a calibration hierarchy. Some (but not all) cesium and hydrogen standards fall in this category.

4. QUARTZ CRYSTAL DEVICES

4.1 Quartz Crystal Resonator

The quartz crystal is a mechanical resonator much like our examples (a) and (b) of section 3.1 The resonator's oscillations have to be excited and sensed externally. In the case of a quartz crystal this is done by taking advantage of its piezoelectric properties. The piezoelectric effect is a special property of a certain class of crystals. Compression or dilatation of the crystal generates a voltage across the crystal, and conversely, the application of an external voltage across the crystal causes the crystal to expand or contract depending on the polarity of the voltage. A crystal is not a homogeneous medium but has certain preferred directions; thus, the piezoelectric effect has a directional dependence with respect to special, preferred directions of the crystal. In order to take advantage of the piezoelectric effect one has to cut the crystal resonator from the crystal block in a well defined way with respect to these crystallographic directions. The raw material today is both natural quartz and synthetic quartz. The crystal is cut out of the raw crystal in the desired orientation with the aid of optical techniques which allow the determination of the crystallographic axes. The high precision final orientation of the cut and the tuning to the desired frequency is then done by grinding and etching under control of x-ray methods.

The quartz crystal can be cut and electrically excited in a variety of ways. The most common types of vibrations (modes) are the longitudinal and thickness modes, the flexure (bending) mode, the torsional mode, and the shear mode. In order to use the piezoelectric effect, electrodes have to be put on some of the crystal surfaces such that the desired mode is excited. The electrodes are typically created as extremely thin metallic coatings by vacuum evaporation of metals. Electric leads are attached to the electrodes, (e.g., by soldering), which usually also serve as the mounting support thus suspending the quartz crystal. In order to least perturb the mechanical vibrations of the crystal, the electrode-support leads are attached at points where no vibrational motion occurs (modes). The crystal is usually encased (in metal or glass) and the enclosure is sometimes filled with a protective gas or is evacuated.

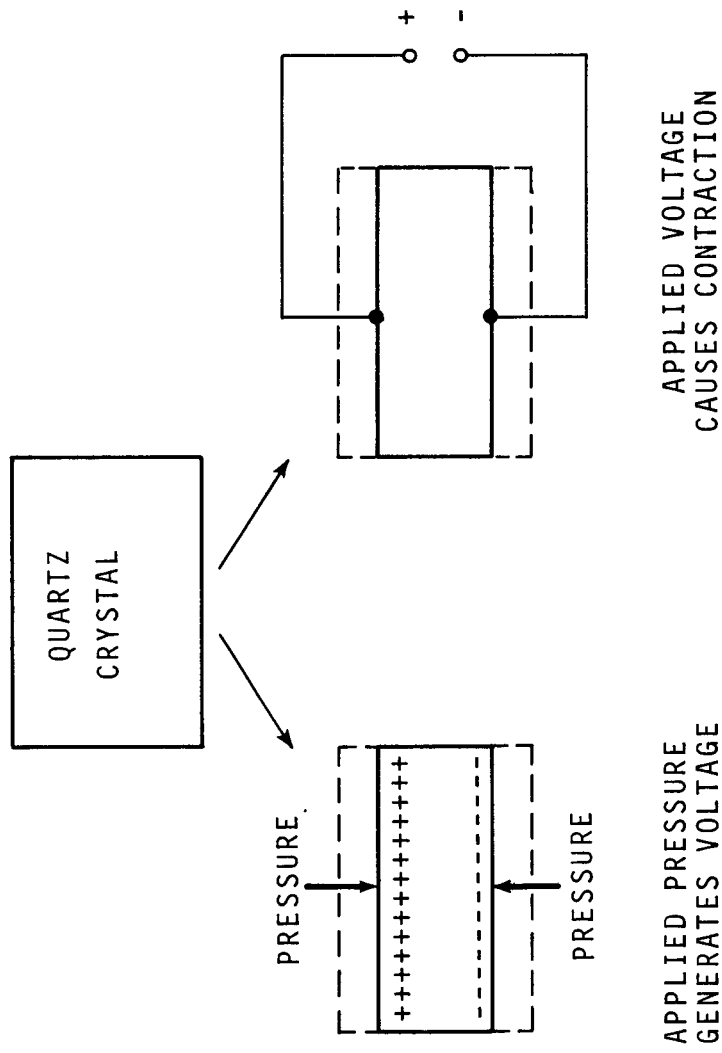


Fig. 8. The piezoelectric effect.

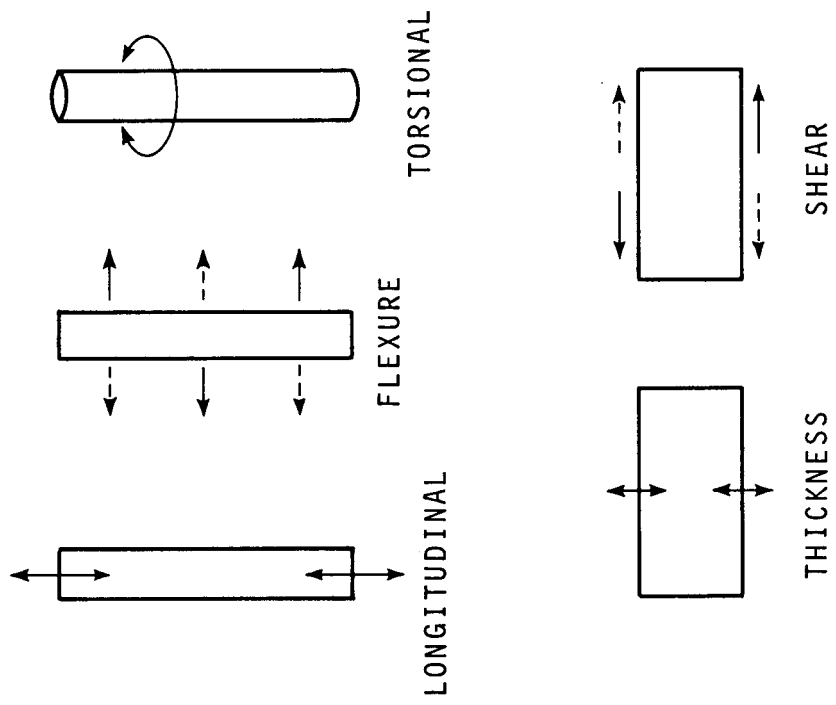


Fig. 9. Principal vibrational modes of quartz crystals.

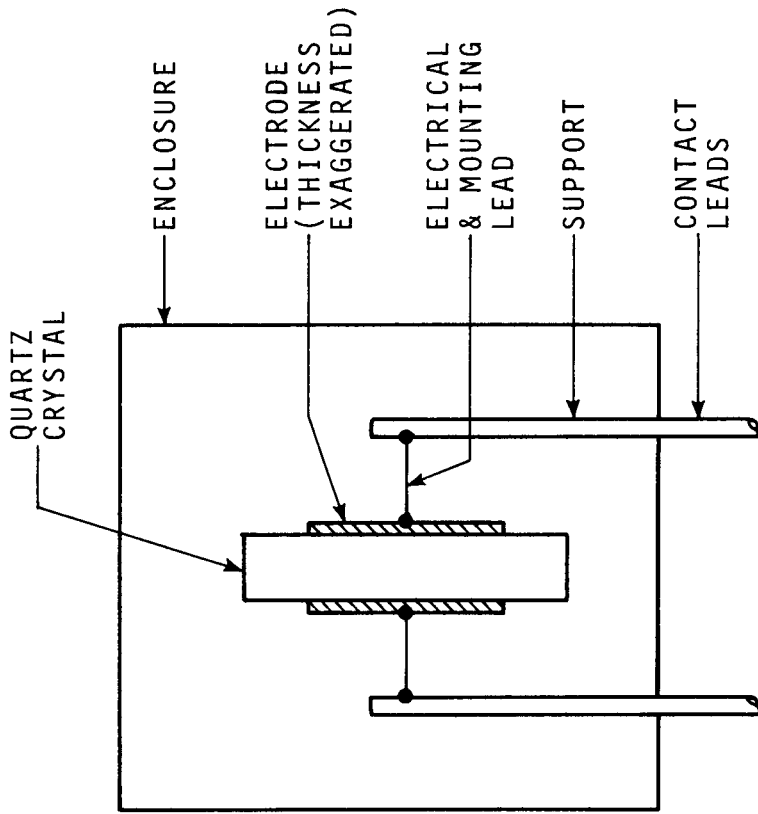


Fig. 10. Typical quartz crystal mount.

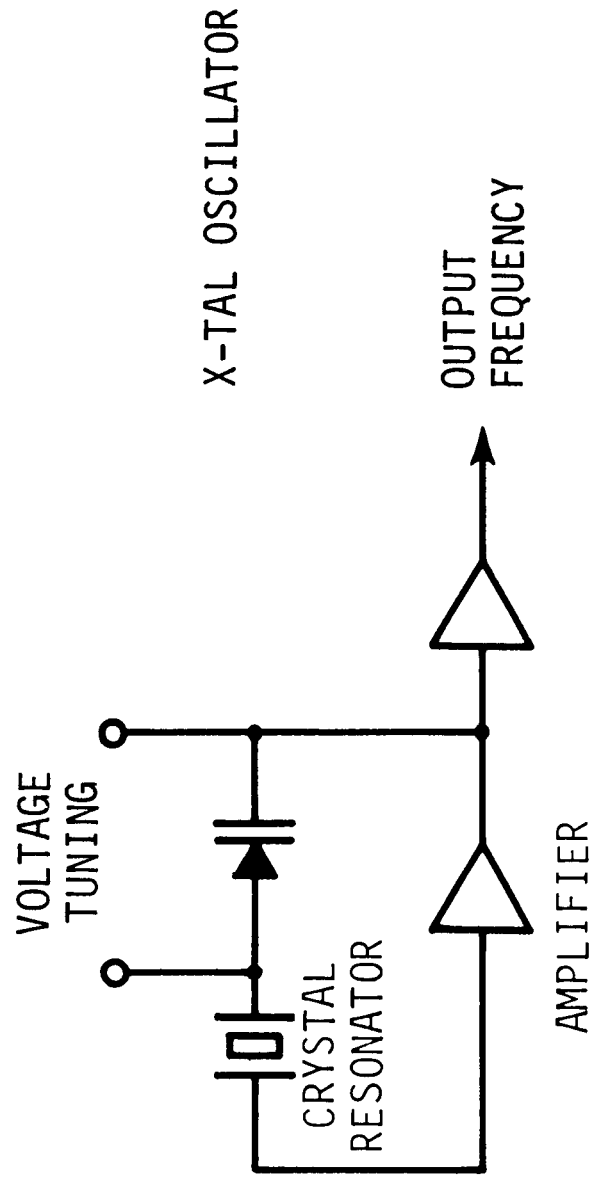


Fig. 11. Block diagram of a quartz crystal oscillator.

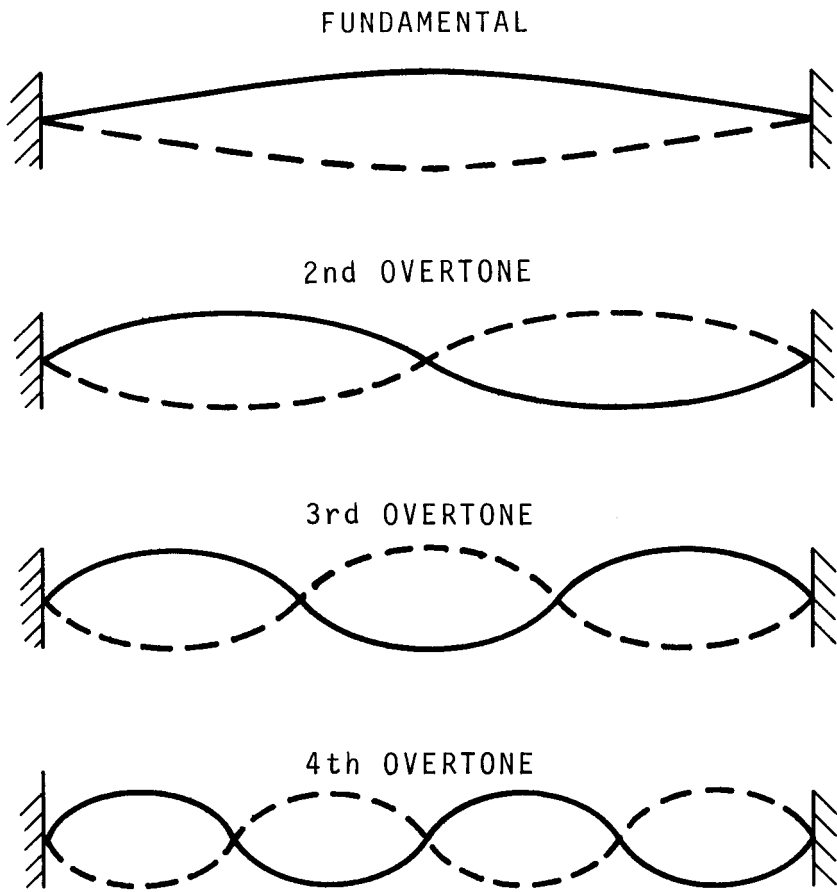


Fig. 12. Fundamental and overtone resonance frequencies.

A frequency standard can now be built by adding an electronic amplifier (energy transfer), and feedback. We call such a device a quartz crystal oscillator. Its output frequency is determined by the quartz crystal resonator whose frequency in turn is determined by the physical dimensions of the crystal together with the properties of crystalline quartz. The resonance frequency thus depends on the orientation of the cut, the particular mode, and the dimensions of the crystal. As an example, we find that the resonance frequency for a longitudinal mode of vibration is approximately given by

$$\nu_o = 2.7 \times 10^3 \times \frac{1}{\ell} , \quad (5)$$

where ℓ is the length of the crystal. Equation (5) is written such that the use of meters to express ℓ will give the resonance frequency ν_o in hertz. Equation (5) allows us to estimate the size of crystals. For example, a 100 kHz crystal has a length which is of the order of a few centimeters and a 10 MHz crystal has a length (thickness) of just a few tenths of a millimeter. We see from this that the production of quartz crystals with resonance frequencies much above 10 MHz is hardly possible. However, one can excite resonators not only in their so-called fundamental mode (which we discussed so far) but also at multiples (overtones) of this fundamental resonance frequency. The best example for this is the violin string which also can be made to oscillate at frequencies which are multiples of the fundamental frequency; the violinist depends on this. Quartz crystals which are designated for the excitation of multiples of their fundamental resonance are called overtone crystals.

4.2 Effects on the Crystal Resonator Frequency

Two deleterious effects, among others, are important in the design of crystals and crystal oscillators and limit their usefulness. The first is the temperature dependence of the quartz crystal resonance frequency, the second is a slow change of the resonance frequency as time goes on (frequency drift or aging).

The temperature dependence is caused by a slight change in the elastic properties of the crystal with temperature. This can easily be imagined from the general behavior of matter: the packing density of atoms increases with lowering the temperature. However, certain cuts, i.e., certain crystallographic orientations of the crystal, minimize this effect over a rather wide range of temperatures, most notably the so-called "AT" and "GT" cuts. Temperature coefficients of less than one part in 100 million per degree (celsius or kelvin) are possible. In other words, the fractional frequency change is less than 10^{-8} with one degree of temperature change. Nevertheless, this effect demands certain precautions in the design of a crystal oscillator if very high frequency stabilities over longer times (hours or days) are desired and/or if large environmental temperature fluctuations are to be tolerated. Hence, crystals are enclosed in electronically regulated ovens which maintain a constant temperature; in certain crystal oscillators this is done to better than $\frac{1}{1000}$ of a degree.

A different solution to the temperature problem is the so-called temperature compensated crystal oscillator or TCXO. An additional frequency determining element in the oscillator, which can essentially be just a small capacitor (see fig. 11 and our example (c) of sec. 3.1), gives the opportunity to tune the oscillator over a limited range by varying this additional element. If a temperature sensor is added which causes a change in this capacitor one can adjust the response in such a way that the change in resonance frequency of the crystal resonator is just compensated by a suitable adjustment of the added capacitor. Bimetal springs have been used which mechanically change the setting of the capacitor much in the same way as the automatic choke in many automobiles works. Today, capacitors whose value changes with an applied voltage (varactors) are used, as shown in figure 11; the applied voltage is derived from a temperature sensing circuit. The TCXO thus does not necessarily require further temperature control by an oven. However, we see the drawback of this approach. In adding a further frequency determining element, the crystal resonator has to relinquish a corres-

ponding part of its control on the output frequency of the whole oscillator. We, therefore, realize that the stability performance of a TCXO will degrade the more, the wider the temperature range of compensation is made.⁷ The long-term stability (days) of TCXO's is therefore below that of crystals with a good oven control. We find TCXO's in small, usually portable units of relatively low performance; i.e., for applications where frequency stabilities from day to day and frequency changes over some tens of degrees of temperature of not better than 10^{-9} are needed.

The drift, or aging, is a common behavior of all crystal oscillators. It is a nearly linear (uniform) change in resonance frequency with time, which frequently is negative (i.e., the resonance frequency decreases). A frequency decrease could be interpreted as an increase in the crystal size according to eq (5). Many physical mechanisms have been considered as the cause: contamination of the surfaces (deposition of foreign material); changes in the electrodes or the metallic plating or the mounting; reformation of loose (from grinding and etching) surface material; changes in the internal crystal structure; etc.; all of this possibly caused or enhanced by the vibrating motion of the oscillating crystal. Careful fabrication and electrode design combined with clean vacuum enclosures have led over the years to a reduction of the aging to about 10^{-11} per day and better for the best crystals. This aging corresponds to 10^{-11} fractional thickness change per day, as we can see from eq (5). For a 5 MHz crystal with a thickness of a little less than a millimeter this aging corresponds to an absolute thickness change of only 10^{-11} of a millimeter or less than $\frac{1}{10}$ of one percent of the diameter of an atom. It seems surprising that mechanical resonators can be built which change their dimension by so little.

Three more effects on crystal resonators are to be considered. One is its relative sensitivity to gravitational forces and acceleration:

⁷This is also true for any tuning (frequency adjustment) capability which is added to any frequency standard. The larger the tuning range, the less the stability. The best frequency standards and clocks can not directly be adjusted; however, adjustment can be done external to the device via frequency synthesizers or time steppers (phase shifters).

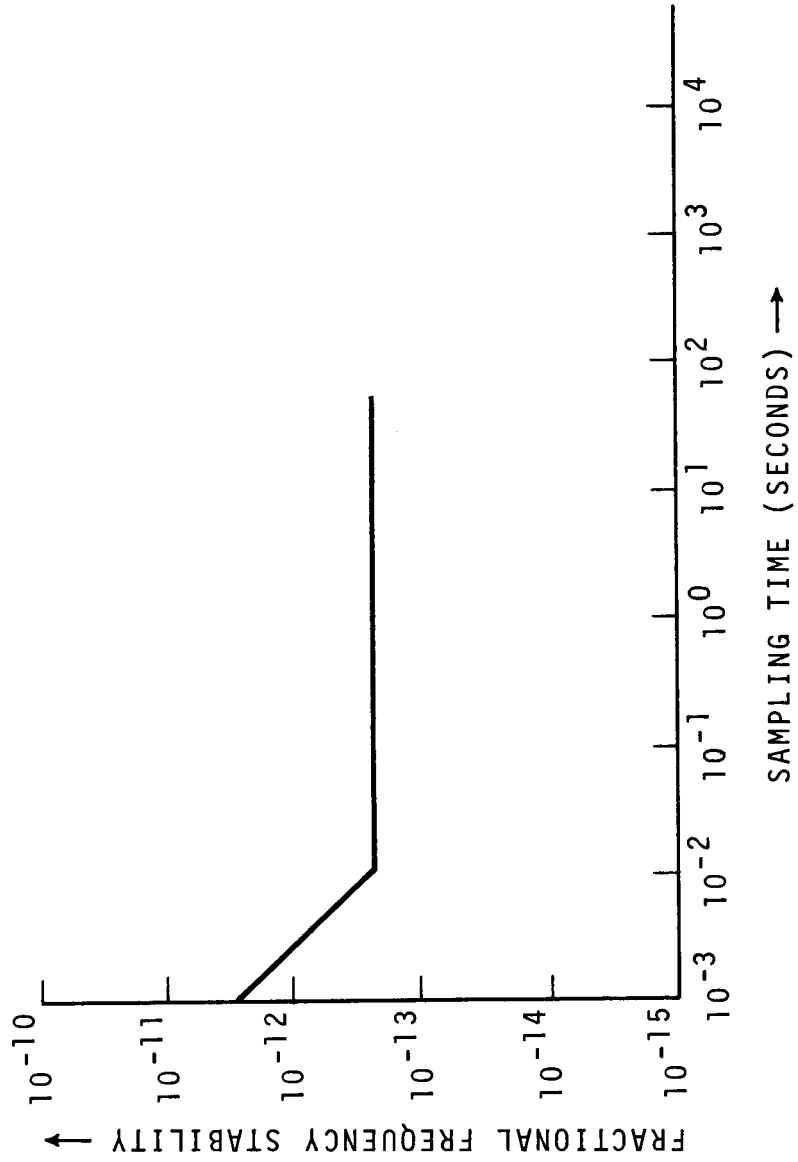


Fig. 13. Frequency stability of the better quartz crystal oscillators.

frequency changes will occur because of the stresses in the crystal caused by these forces. This influence depends on the direction of the force relative to the crystallographic axes and thus can be minimized for certain orientations. The magnitude of the effect is typically of the order of 10^{-9} for accelerations corresponding to the earth's gravitation.

The second effect is related to intermittent operation. If a crystal oscillator is turned off and, after some time, put back into operation it will not oscillate immediately at the original frequency but will exhibit first a "warm-up" due to temperature stabilization of the crystal resonator and its oven and then for some time (as long as many days) a large but diminishing drift until it reaches its previous aging performance. The frequency at which it will then operate might also be substantially different (as compared to its stability and aging performance) from its frequency before the interruption. The third effect is the sensitivity of the crystal to ionizing radiation (x-rays, nuclear radiation): transitory and lasting frequency changes are produced via radiation-induced changes in the crystal lattice.

4.3 Quartz Crystal Oscillator Performance

Crystal resonators have Q -values which are typically in the range from $Q = 10^5$ to almost $Q = 10^7$ (around room temperature; at very low temperatures much higher Q values can be obtained). These are very high Q -values as compared to most other resonators except, most notably, atomic resonators.

These high Q -values are an essential prerequisite for the excellent stability performance of crystal oscillators. The best presently available devices show stabilities of about one part in 10^{13} for sampling times from one second to hundreds of seconds. There is some experimental evidence that some crystal resonators may perform better and that limitations are primarily caused by noise in the electronic components in the oscillator circuits. This noise (flicker noise) may possibly be reduced by a special selection of low noise components (transistors, capacitors, etc.) and by some special circuit design. Thus there is a reasonable chance that the

stability may reach values of better than 10^{-13} for sampling times of seconds to hours. For times shorter than one second, the stability is often determined by additive noise in the output amplifiers and can then be reduced by other better electronic circuits or by a (crystal) filter in the output. The long-term stability beyond several hours sampling time is determined by the aging and by external influences such as line voltage variations, temperature fluctuations, etc. The immediate environment of the resonator, i.e., the mounting, enclosure, etc., probably are of substantial influence in this regard and improvements appear possible. A specification of accuracy is not very well possible with crystal oscillators. Without any frequency calibration they possibly can be fabricated via thickness-determination (not very practical) to about 10^{-6} frequency accuracy. If they are calibrated against a high accuracy frequency standard they maintain this calibration (accuracy) according to their long-term stability performance, e.g., a crystal with the low aging of 10^{-11} per day will be accurate to a few parts in 10^8 for the duration of a year.

We realize, therefore, that crystal oscillators require calibration, which may be rather frequent depending on the requirements. The frequency adjustments are being made with a small added capacitor in much the same way as we discussed before in connection with the TCXO. The most stable ones with the lowest aging rate cost more than \$1000, have a volume of a few hundred cubic centimeters, and require a power of several watts. They have a crystal oven for temperature control, well-designed electronics, and usually several output frequencies which are derived from the oscillator frequency with the aid of frequency dividers and multipliers. These high performance devices presently use crystal resonators in the 1 to 10 MHz range with Q-values of more than one million.

Crystal oscillators which are cheaper and/or smaller are available in an immense variety of designs at certain sacrifices in frequency stability and/or environmental insensitivity. Costs can go down to below \$100, sizes to a few cubic centimeters, and power requirements to less than 0.1 watt. The reliability of crystal oscillators is usually not limited by the crystal, the mean time between failure (MTBF) being that of any electronic circuit of equivalent sophistication.

5. ATOMIC RESONANCE DEVICES

5.1 Atomic Resonators

The basis of commercially available atomic frequency standards are resonances in atoms at microwave frequencies (range 1 to 100 GHz, GHz = gigahertz = 10^9 hertz). Resonances in molecules and resonances at higher frequencies in the infrared and visible regions are being studied for frequency standard applications but have not yet led to practical devices; however, their potential is high (see Section 8). We will confine ourselves, therefore, to the discussion of microwave resonances in atoms. We may picture such a resonance as a little magnetic dipole antenna as was discussed in our example (e) in Section 3.1. We typically deal with a great many of these dipole antennas (atomic resonators), and we can separate them into two kinds⁸: (1) receiving antennas, which will absorb energy from a field at their resonance frequency, much like our TV antenna at home, and (2) transmitting antennas which radiate energy at their resonance frequency in a fashion analogous to the action of the transmitting antenna of a broadcasting station. A physicist might say that the atoms which act like a receiving antenna are in the "lower state" and those acting like a transmitting antenna are in the "upper state"⁹. In a natural ensemble of a great many atoms (a gas), we find that the total number of upper state atoms is nearly equal to the total number of lower state atoms. This has an important consequence: if this gas is placed in an external magnetic field, which oscillates at the atomic resonance frequency, all atoms may resonate; however, nearly half of the atoms receive (absorb) energy from the field, the other half emit (add) energy of an equivalent amount to the field. It is obvious that the net effect is almost zero; the gas as a whole acts as if it has almost no resonance although the individual atoms each may resonate.

⁸Of course, this is a simplification

⁹There is a peculiarity with atoms: an atom changes from the upper to the lower state upon emission of a well-defined amount of energy, and, correspondingly, an atom changes from the lower to the upper state after receiving an equal amount of energy at the atomic resonance frequency.

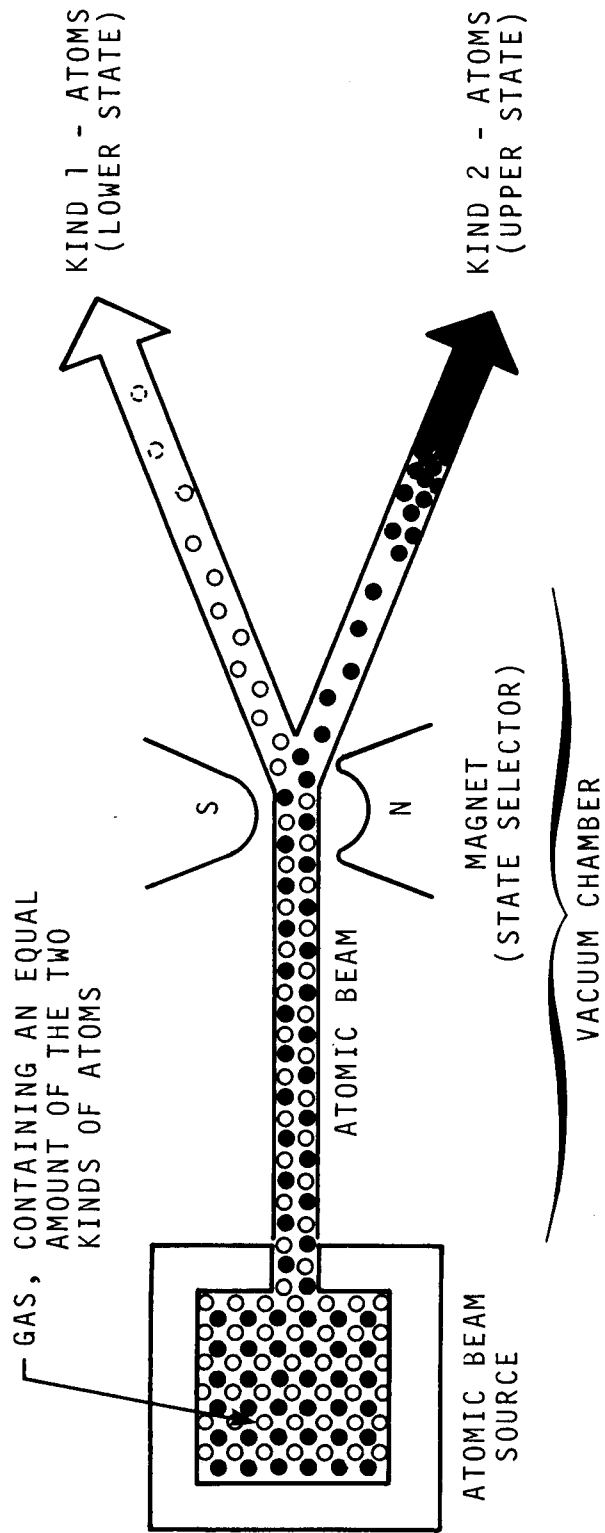


Fig. 14. Spatial state selection.

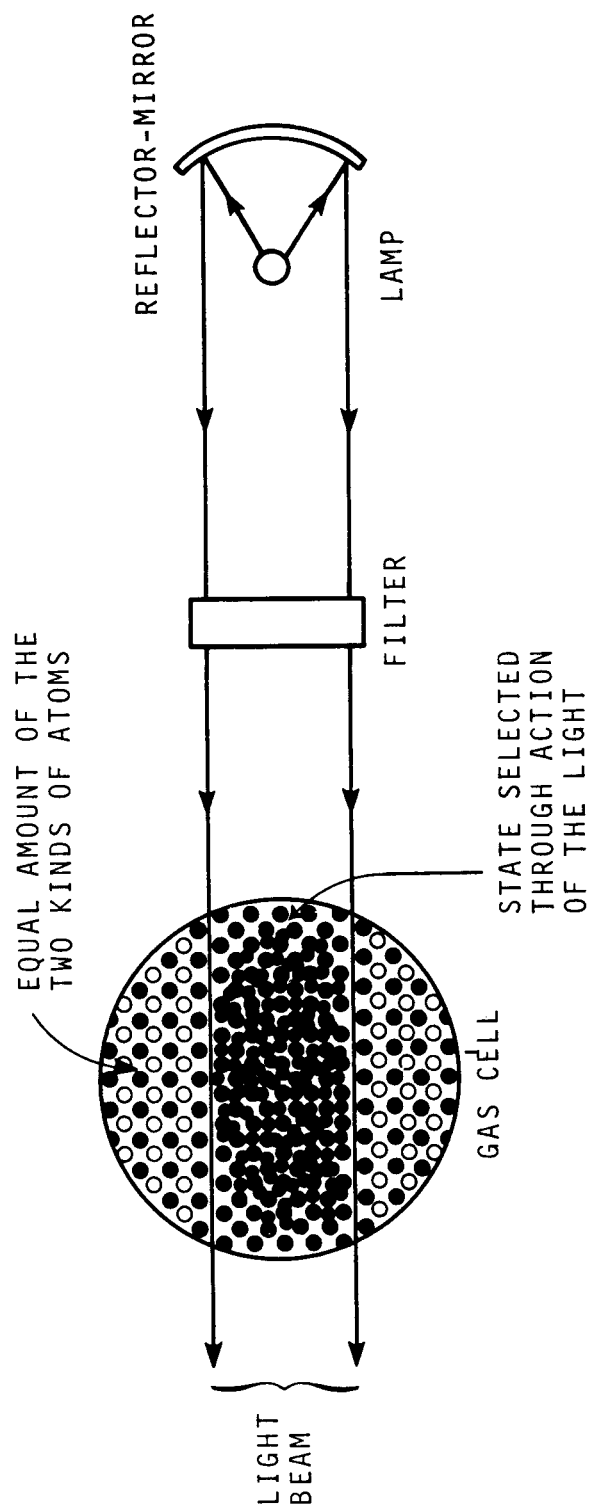


Fig. 15. Optical state selection.

From this we see that in order to observe the atomic resonance we have to change somehow the relative amounts of the two kinds of atoms; the upper or the lower state has to be in the majority, corresponding to a net emission or absorption of energy. The way in which this is done determines the design of an atomic resonance device, which is the frequency determining element in our atomic frequency standard.

5.2 State Selection

We will now discuss the two most important methods to accomplish what is called state selection: the change in the relative numbers of the two kinds of atoms.

(a) Spatial state selection: This method relies on an actual sorting procedure where the two atomic states are sorted into different directions in space. One of the states can then be used, the other is discarded. As an example, an actual system may produce an atomic gas by heating the substance in an oven to a suitable temperature. The atoms leave the oven through a hole and form an atomic beam in an adjacent vacuum chamber. The atomic beam is then passed through a rather strong magnet which causes the separation of the beam into two beams, each of them containing only one kind of atoms. We remember that our picture of an atom is that of a little magnetic dipole antenna. The magnet exerts a force on these magnetic dipoles, which acts in opposite directions for the two different atomic states (we note this without further explanation).

(b) Optical state selection: This technique takes advantage of the fact that the atoms have more than just one resonance. Other resonances typically correspond to infrared or visible (light) frequencies. We can excite one of these resonances by shining intense light of the corresponding frequency on the atoms. If the light is filtered carefully, very monochromatic (one color, i.e., a very well-defined frequency) light is obtained. If the light frequency is chosen properly, only one kind of the atoms resonates. At the same time, this light frequency is too far away from the corresponding light resonance of the other kind of atoms. The light resonance can thus "remove" one kind of the atoms and provide for the desired majority of the other kind.

5.3 Interrogation of the Atoms

We are now almost in a position to assemble our atomic frequency standard. We still need some means to observe the atomic resonance. A microwave cavity is typically used. Such a cavity has microwave resonances which are determined by its physical size. The (electrical) losses of this cavity are given by the electrical conductivity of the cavity material. Such a cavity may have the shape of a cylinder or that of a box. It resonates in a way quite similar to the working of an organ-pipe in the case of acoustic waves. The best known example of a microwave cavity is the microwave oven where food is heated by placing it into the resonance field of a cavity. In order to observe the atomic resonance we have to place the state selected atoms inside of this cavity and subject them for some specified time to a microwave signal at their resonance frequency. The microwave signal will change the relative number of atoms in the two states, e.g., if all atoms were initially in the upper state we find some in the lower state after the microwave signal acted upon them for some time (see footnote 9). If the frequency of the external microwave signal is exactly at the atomic resonance frequency, this transfer of atoms from one state to the other reaches a maximum. The center of the atomic resonance is thus found by monitoring the number of atoms in one of the two states and by varying the microwave frequency until the number of atoms in the lower state reaches a maximum, or the number of atoms in the upper state a minimum. A proportional electric signal can be derived which is fed back to the oscillator generating the microwave signal. Thus an automatic servo can be built which keeps the oscillator (usually a crystal oscillator) locked to the atomic resonance.

5.4 Signal Detection

The detection of the effect of the microwave signal on the atoms can be done in basically three ways, two of which relate to the two methods of state selection.

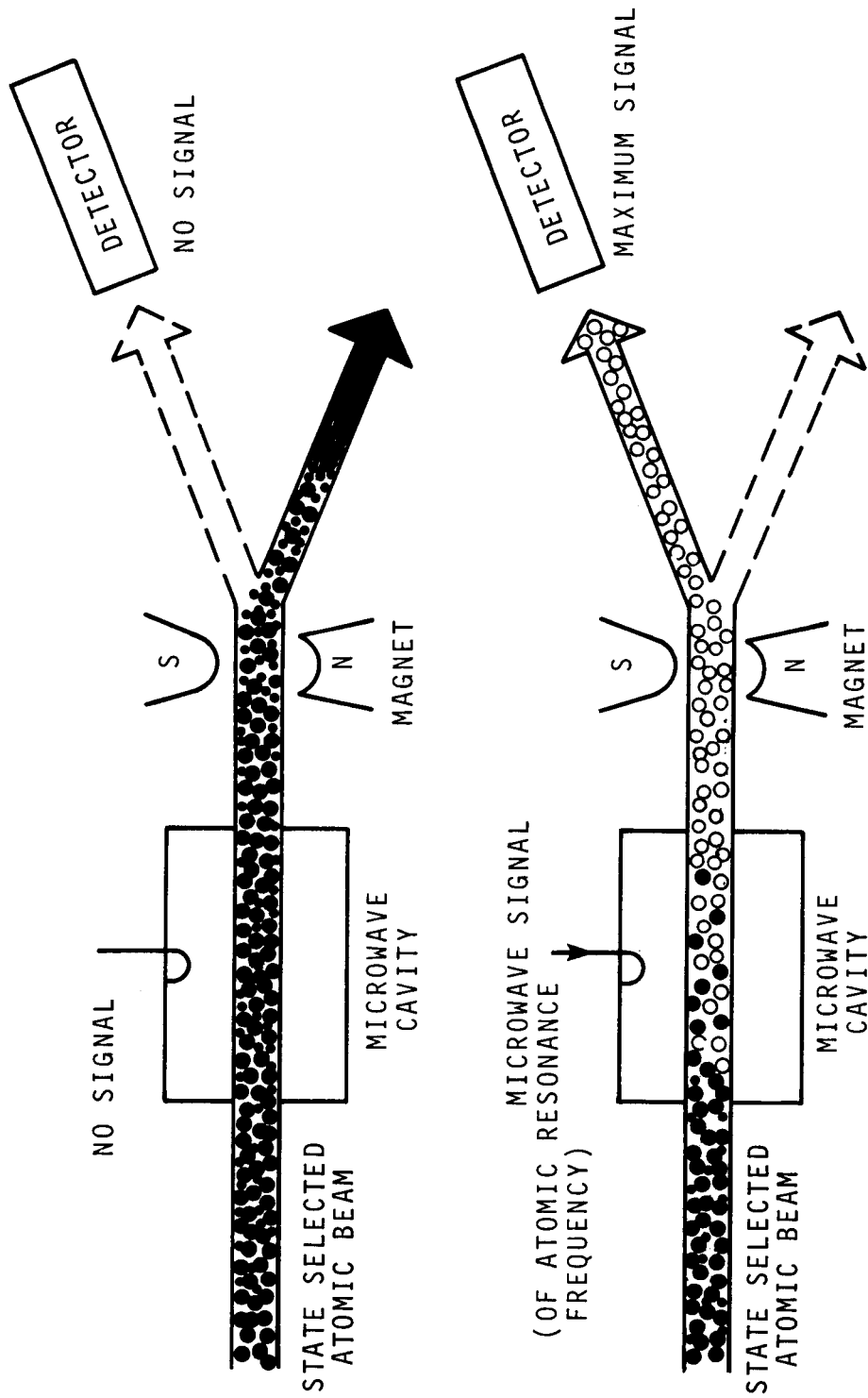


Fig. 16. Atom detection.

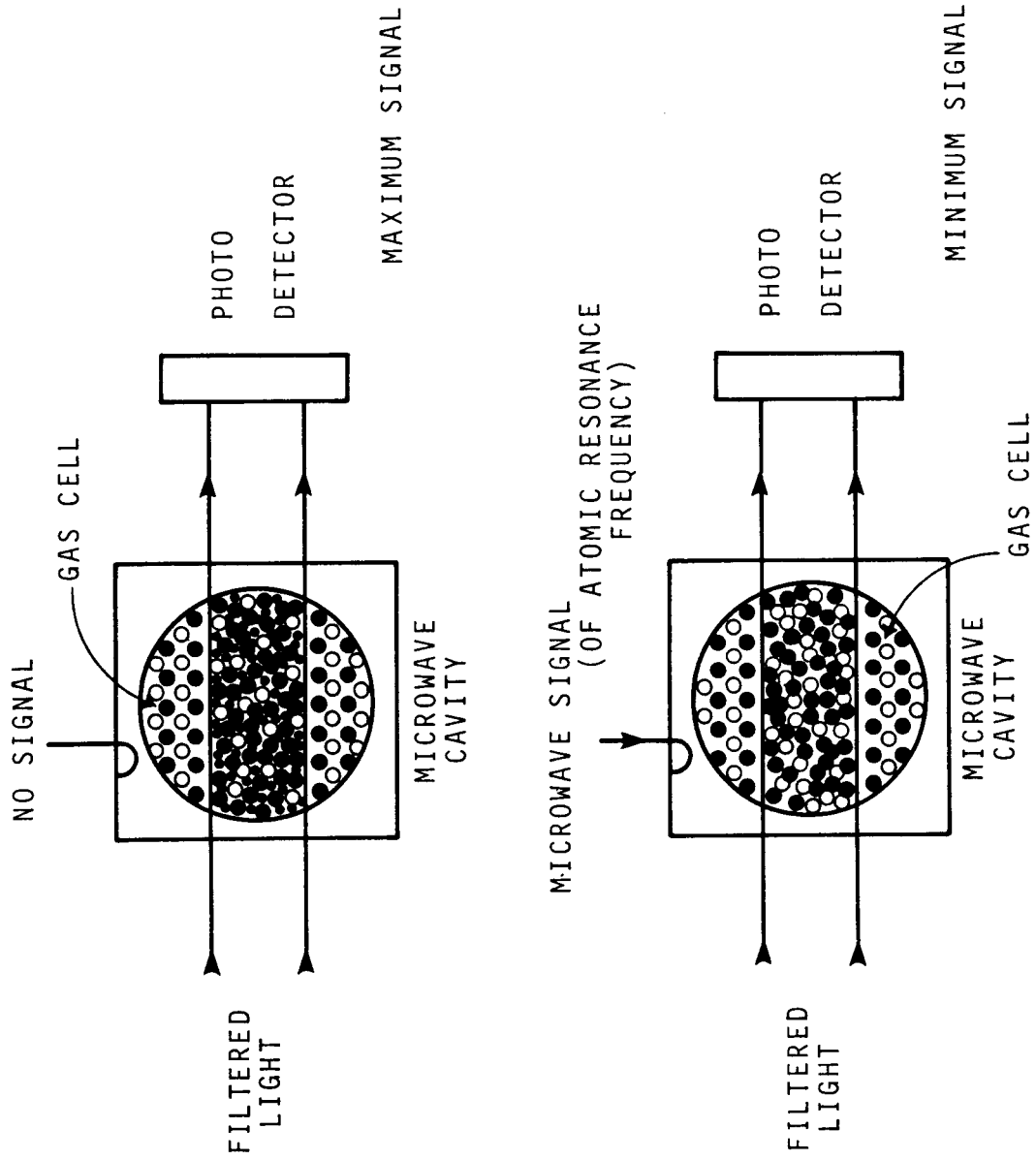


Fig. 17. Optical detection.

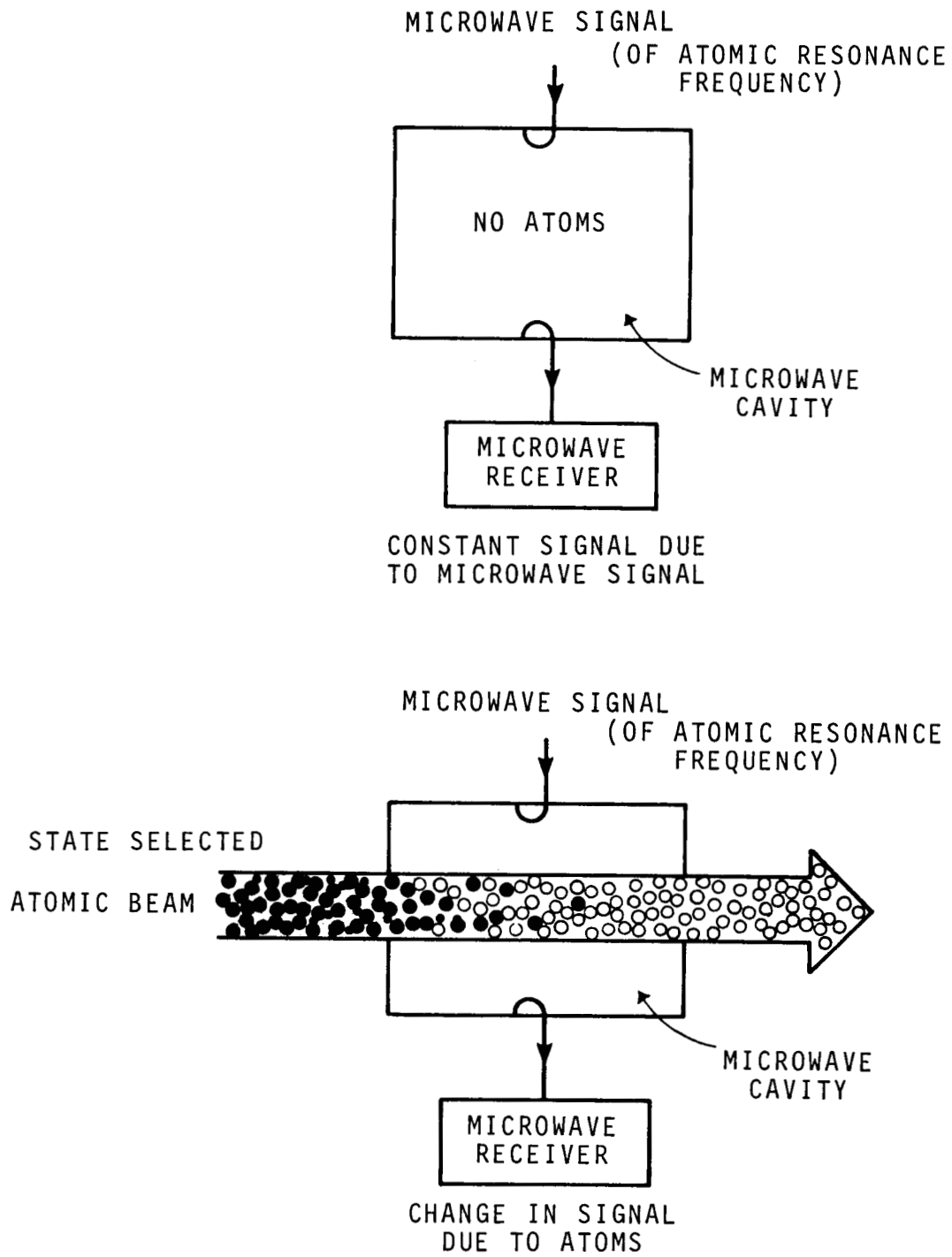


Fig. 18. Microwave detection.

(a) Atom detection: The atoms which leave the cavity as an atomic beam are passed through the field of a magnet which spatially sorts the two states. An atom detector is placed to intercept one of these states. The output of the detector thus indicates the number of atoms in the upper (or lower) state.

(b) Optical detection: If the atoms are optically state selected, a detector for light (photo-detector) can be placed in a position such that the light which has interacted with the atoms is detected. Since the light removes atoms from one of the states, its intensity will change if atoms which resonate at the light frequency are added. Such an addition takes place as a result of the microwave signal which, in effect, transfers atoms from one state (with no light interaction) to the other (taking part in the light resonance). The light at the photo-detector therefore is a measure of the number of atoms in one of the states.

(c) Microwave detection: In this type of detection, the microwave signal is transmitted through the cavity to a microwave detector. Since the atoms will either add energy to the signal (if initially in the upper state) or subtract energy (if initially in the lower state), the microwave power level at the detector is a measure of the number of atoms changing state.

5.5 Atomic Frequency Standard

The analogy to our mechanical frequency standard, the wrist watch, which we discussed in Section 1, may now be drawn: the frequency determining element is the atomic resonator which consists of a cavity containing the state selected atoms, and some means of detecting the change in the number of atoms in the two states. A control signal, related to the number of atoms which changed their state due to the action of the microwave signal is fed back to the (crystal) oscillator. The oscillator and the associated frequency multiplier or synthesizer¹⁰

¹⁰As we discussed before, good crystal oscillators are available at frequencies of several MHz; the atomic resonances are at GHz frequencies. The crystal oscillator frequency therefore has to be multiplied by a factor of about 1000.

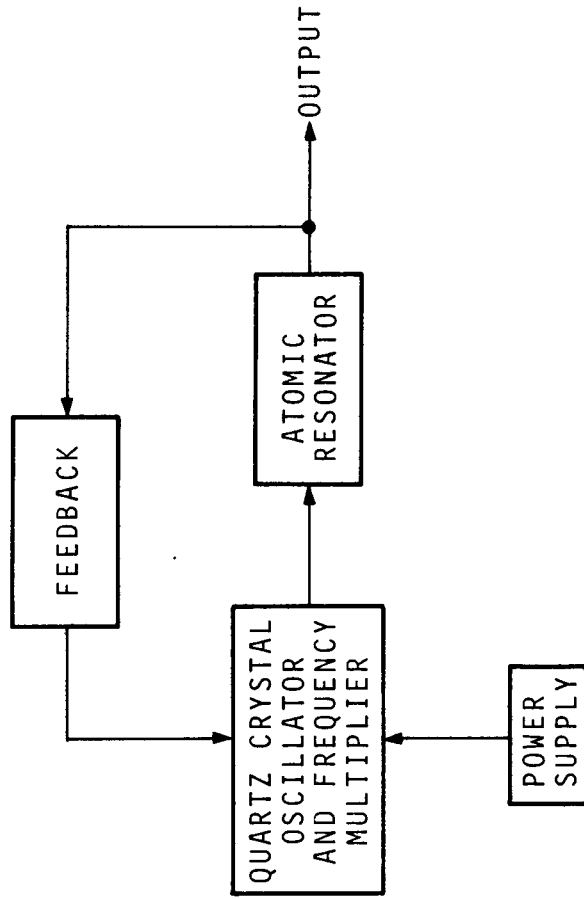


Fig. 19. Atomic frequency standard.

correspond to the energy transferring means in our wrist watch (see Sec. 1).

Some power supply has to provide the energy necessary to drive the oscillator, multiplier, and possibly the atom state selector. Very high Q-values can be achieved with atomic resonators. To understand this, we have to recall our eqs (3) and (4).

The Q is related to the time t_d , which describes the average duration of oscillations of the resonator. In atomic resonators we find two chief causes for the termination of oscillations. The first one is collisions of the resonating atoms with each other and with surrounding walls; each collision usually terminates the oscillation. The second one is a rather obvious cause: the atoms may simply leave the region of microwave signal interaction. In an atomic beam apparatus, the atoms enter the cavity, traverse the cavity in a certain time, and then leave the cavity. As an example, let us assume that we have a cavity of 1 meter length which is traversed by atoms with an average speed of 100 meter per second (a typical value). We assume an atomic resonance frequency of 10 GHz. The interaction time t_d is then $\frac{1}{100}$ second, the linewidth 100 Hz (from Eq (3)), and the Q-value is 10^8 (from eq (4)). We arrived at a Q-value which is considerably better than that of a quartz crystal oscillator!

5.6 Effects on the Atomic Resonator Frequency

Before we discuss effects which might cause changes in the output frequency of an atomic standard, we should make a very important statement: The atomic resonance frequency itself is given to us by nature, it will not drift or age. Hence, atomic resonators with Q-values of 10^8 or higher may be expected to have accuracies of one part in 10^8 or better because we will not be able to pull the resonance frequency further away than the linewidth of the resonance.

In the following, we are not exhaustive but list only the major perturbing effects:

- (a) Noise: Random noise in the crystal oscillator, the detector, the microwave cavity, and the frequency synthesizer cause corresponding fluctuations of the output frequency.
- (b) Cavity pulling: The microwave cavity is itself a resonator. Thus we have an additional frequency-determining element besides the atoms. It influences the output frequency by pulling the combined resonance frequency to a value which usually lies between the resonances of atom and cavity. This necessitates the tuning of the cavity to the atomic resonance. The requirements for tuning will be relaxed if the Q-value of the atomic resonance is as high as possible and the cavity-Q as low as possible.
- (c) Microwave spectrum: If the exciting microwave signal has not a symmetric but an asymmetric distribution of frequencies,¹¹ a frequency pulling occurs which conceptually is related to the mechanism of cavity pulling. By careful design in the electronics, this effect can be made negligible.
- (d) Collisions: Collisions between the atoms and between the atoms and the walls of a vessel (gas cell) in which the atoms may be contained, not only shorten the duration of the oscillation but also cause a frequency shift. Obviously, these effects can be minimized by having low atom densities and no walls, if possible.
- (e) Doppler effect: The apparent change in frequency if the emitter moves relative to an observer is called Doppler effect. Everybody knows this for acoustic waves from the experience of an approaching, whistling locomotive or from automobile racing. Here, the moving objects are the oscillating atoms and the observer is the microwave cavity. The Doppler effect can be highly reduced by choosing a particular direction of the atomic beam with respect to the direction of the flow of microwave power in the cavity; in our acoustic example, this corresponds to the passing of the whistle at some large distance instead of having the whistle move directly

¹¹ The microwave signal will never be just one single frequency but will have a certain distribution of frequencies (spectrum).

towards the observer. An alternate way of reducing the Doppler effect is the containment of atoms in a region small compared to the wavelength of the microwave radiation, e.g., by placing a gas cell inside of the cavity.

(f) Magnetic field: Of the effects which we discuss here, this is the only one which directly affects the atomic resonance. We remember that we used a small magnetic dipole antenna as the model for the atomic resonance. If this antenna is placed in an external static magnetic field (as that of a permanent magnet) the tuning of the antenna changes, i.e., the atomic resonance frequency changes. This necessitates magnetic shielding, which is a characteristic design feature of all presently used atomic frequency standards. The shielding is usually quite elaborate and reduces the external magnetic fields, e.g., the earth's magnetic field, to 1%, or less of its external value. This residual magnetic field can then be measured quite precisely by using the atomic resonance itself. In fact, the associated measurement precision is so good that magnetic field effects do not seriously impair the accuracy of atomic frequency standards. However, fluctuations of the external magnetic field, or the movement of the device through a varying field, e.g., as in a relocation, may perturb the frequency of the atomic standard. Generally speaking, one tries to minimize all of the effects listed above, and to keep their influence as stable with time as possible. Such an approach suffices for most applications¹². For laboratory standards, however, where frequency accuracy is the primary purpose, all effects must be evaluated in a series of experiments, and reevaluations must be done occasionally in order to detect changes with time.

6. AVAILABLE ATOMIC FREQUENCY STANDARDS

We will now discuss the design and performance of the three types of atomic frequency standards which are currently in operational use.

¹²The magnetic effect is an exception. The residual magnetic field inside of the shields must be evaluated and possibly reset any time after changes in the external field occur, e.g., after moving the device. The magnetic shields may also have to be demagnetized.

CESIUM ATOMIC RESONATOR

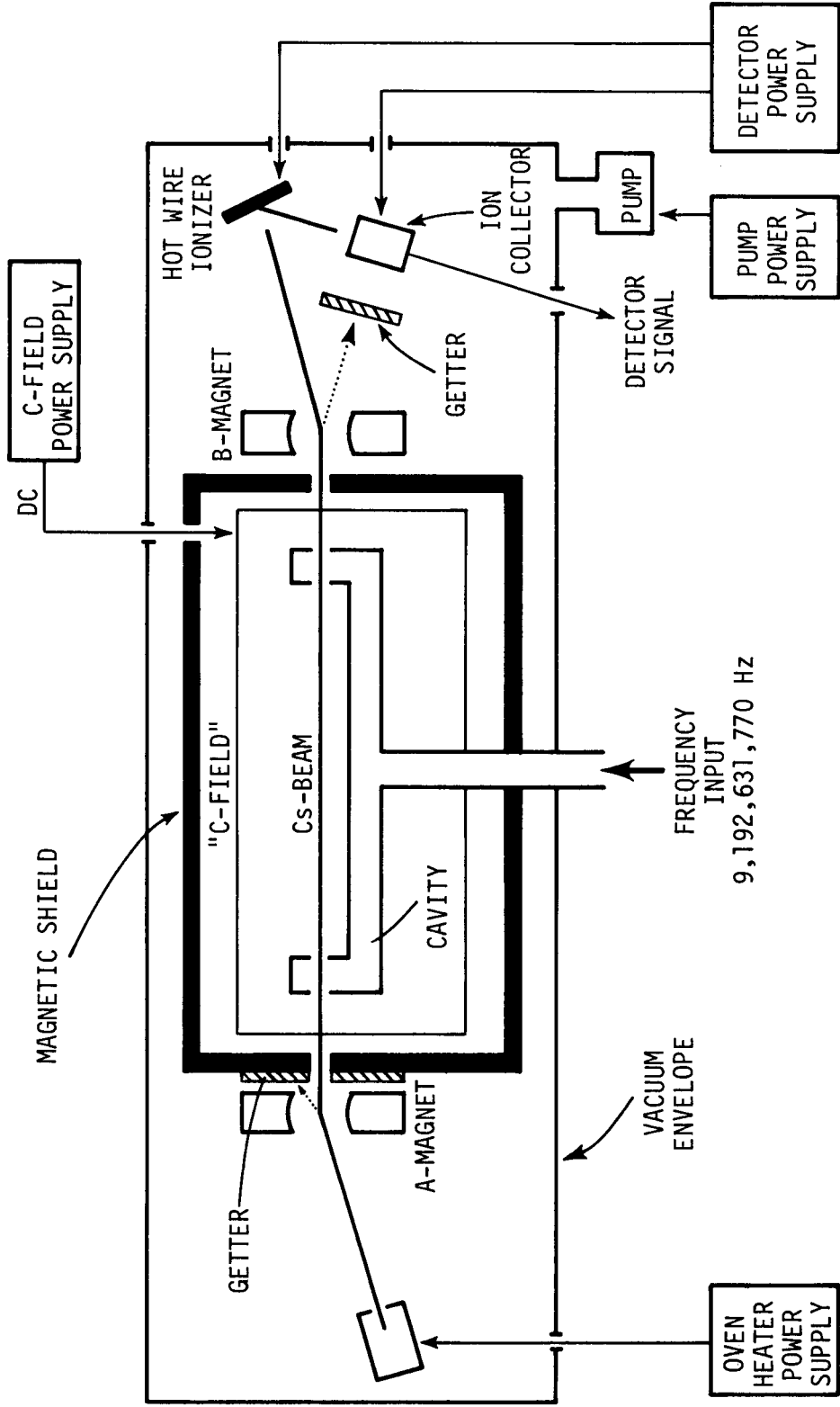


Fig. 20. Schematic of a cesium beam tube. Typically, a cavity with separated interrogation regions is used. This design offers certain advantages over a simple cavity of a length equivalent to the separation of the two regions. See Appendix II.

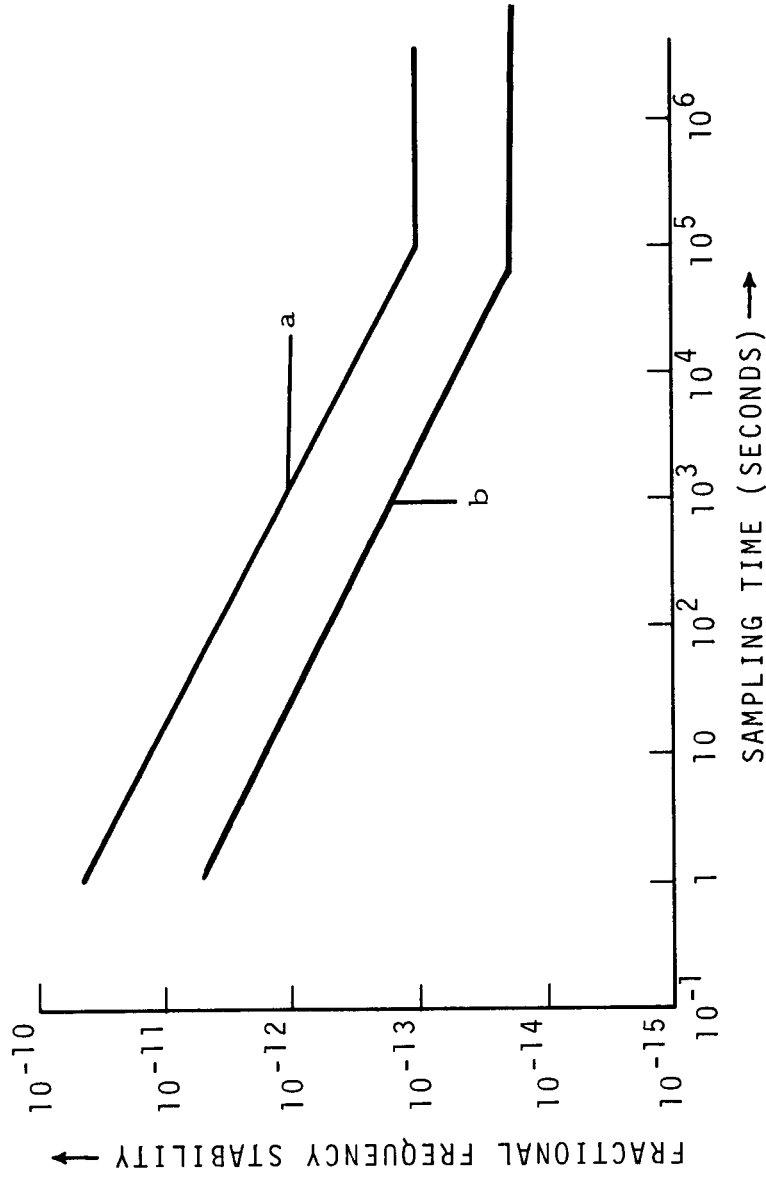


Fig. 21. Frequency stability of commercial cesium beam frequency standards.

a) typical performance

b) typical performance of high beam intensity tubes

Individual units may perform slightly worse or better than shown.
Modern laboratory standards perform still better.

6.1 Cesium Beam Frequency Standard

The atomic resonance is at 9192 631 770 Hz. The standard is based on the atomic beam method using spatial state selection and atom detection. An oven contains the cesium metal. If heated to about 100°C, enough cesium gas will be produced to form an atomic beam which leaves the oven through one or many channels into a vacuum chamber. This chamber is evacuated to a pressure of less than 10^{-9} of atmospheric pressure. The beam traverses first the state selecting magnet, then the microwave cavity where an external microwave signal acts on the beam, and finally reaches the atom detector after passing another state selecting magnet. The atom detector is simply a wire or ribbon (typically made from tungsten or platinum) which is heated to about 900°C by passing an electric current through it. Cesium atoms which impinge on this wire (which is biased with a few volts dc) become electrically charged (ionized) and can be collected on an auxiliary electrode. The stream of electrically charged atoms at this electrode represents an electric current which is amplified, detected, and fed into the feedback network.

The speed of the atoms and the length of the cavity determine the Q-value of the atomic resonator. Typical atom speeds are 100 meters per second. In commercial devices which have to be reasonably small the cavity is about 0.1 to 0.2 meter long; the corresponding interaction time t_d is two thousandths of a second. From eqs (3) and (4), we calculate a linewidth of a few hundred hertz and a Q-value of a few 10^7 . In laboratory devices one can go to very long cavities. Cavities of up to 4 meter long are used, leading to Q-values of a few 10^8 . The fractional frequency stability of laboratory and commercial devices can reach one part in 10^{14} at sampling times of less than one hour to days. The frequency stability for less than a few hours is limited by fluctuations in the atomic beam intensity which are basic and unavoidable ("shot noise"). These fluctuations affect the frequency stability less if more intense atomic beams are used. This approach which is becoming available in both commercial and laboratory devices, improves the stability (compare Sec. 7). In contrast to commercial devices, the laboratory standards are designed

RUBIDIUM ATOMIC RESONATOR

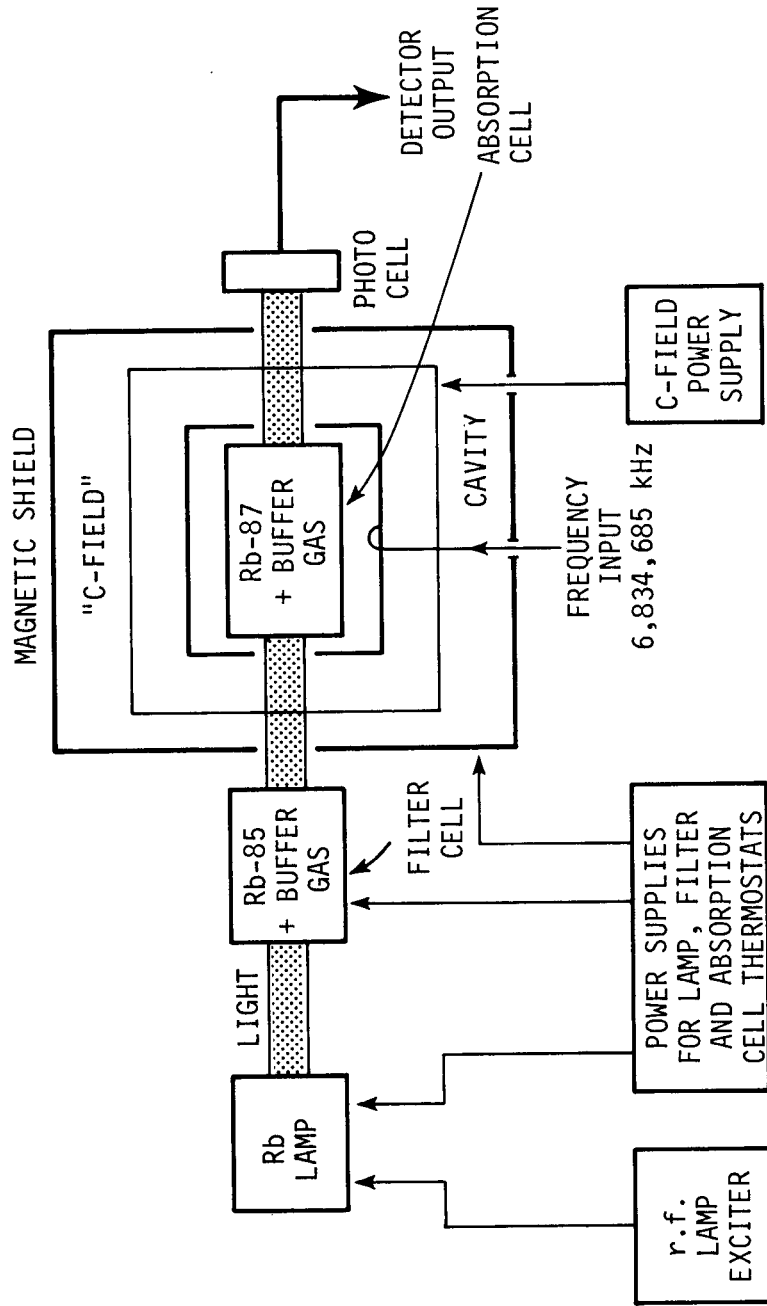


Fig. 22. Schematic of a rubidium gas cell.

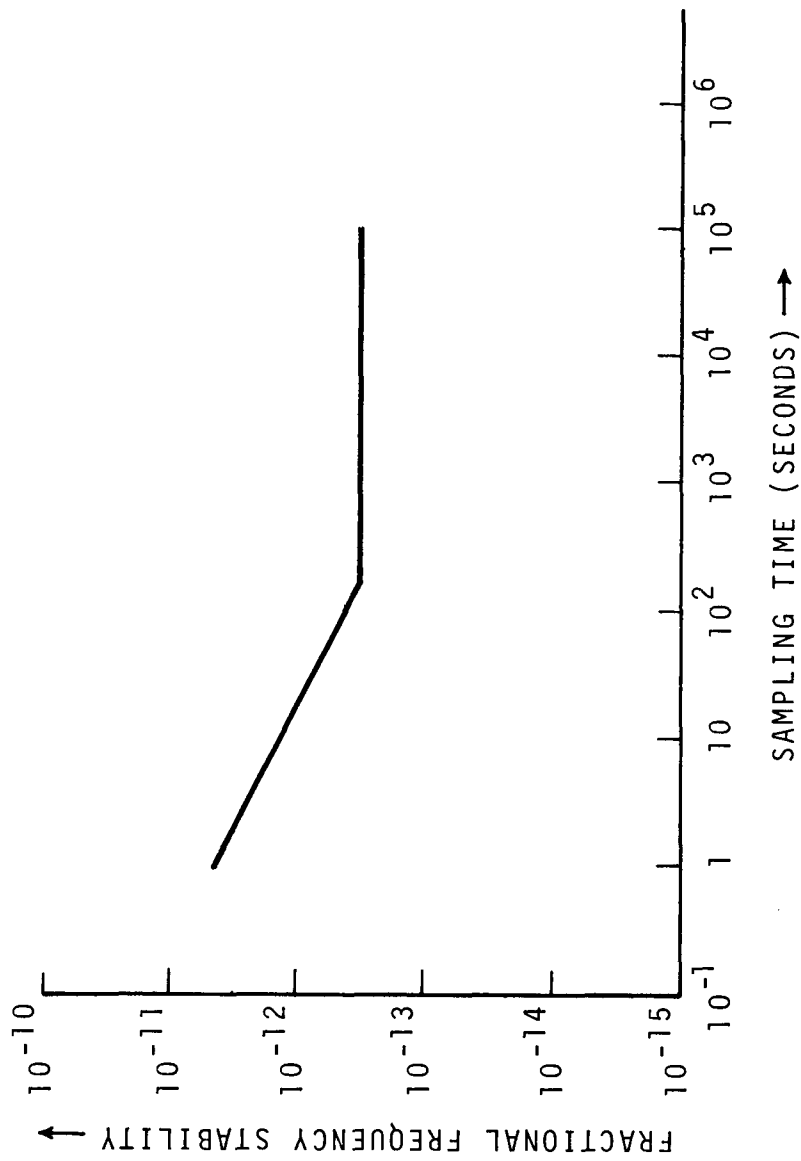


Fig. 23. Frequency stability of commercial rubidium gas cell frequency standards.

to allow a more complete and easier evaluation of all effects on the frequency. Cesium standards are used extensively where its high reproducibility and long-term stability (sampling times of more than a day) are needed. For most applications, cesium standards need not be calibrated. They are the work horses in most of today's standard frequency and time services. The laboratory standard serves to realize the definition of the second (see Sec. 1).

6.2 Rubidium Gas Cell Frequency Standard

The atomic resonance is at 6834 682 608 Hz. The standard is based on the gas cell method using optical state selection and optical detection. The gas cell contains rubidium gas at a pressure of only about 10^{-9} of atmospheric pressure. In order to reduce the effect of wall collisions on the rubidium atoms, an inert buffer gas (e.g., argon or nitrogen) is introduced into the cell at a pressure of about 1/1000 of atmospheric pressure. This allows lifetimes of the rubidium atom oscillations (the oscillation lifetime t_d is still limited by atom collisions) of about 1/100 second. From eqs (3) and (4) we calculate a corresponding linewidth of about 100 Hz and a Q-value of several 10^7 . Atomic collisions as well as the simultaneous action of the light and the microwave signals on the same atom cause frequency shifts of the order of 10^{-9} . These frequency shifts depend strongly on the composition, temperature, and pressure of the buffer gas and on the intensity of the light. As a result, rubidium gas cells vary in their resonance frequency by as much as 10^{-9} depending on the particular setting of the frequency shifting parameters during manufacturing. Since these influences cannot be expected to stay unchanged as time goes on, rubidium standards need not only initial calibration but also recalibration because they exhibit a frequency drift, i.e., an aging analogous to crystal oscillators. The stability performance of rubidium standards is nevertheless quite spectacular. At one second sampling time they display a stability of better than 10^{-11} and perform near the 10^{-13} level for sampling times of up to a day. For longer times the frequency stability is spoiled by

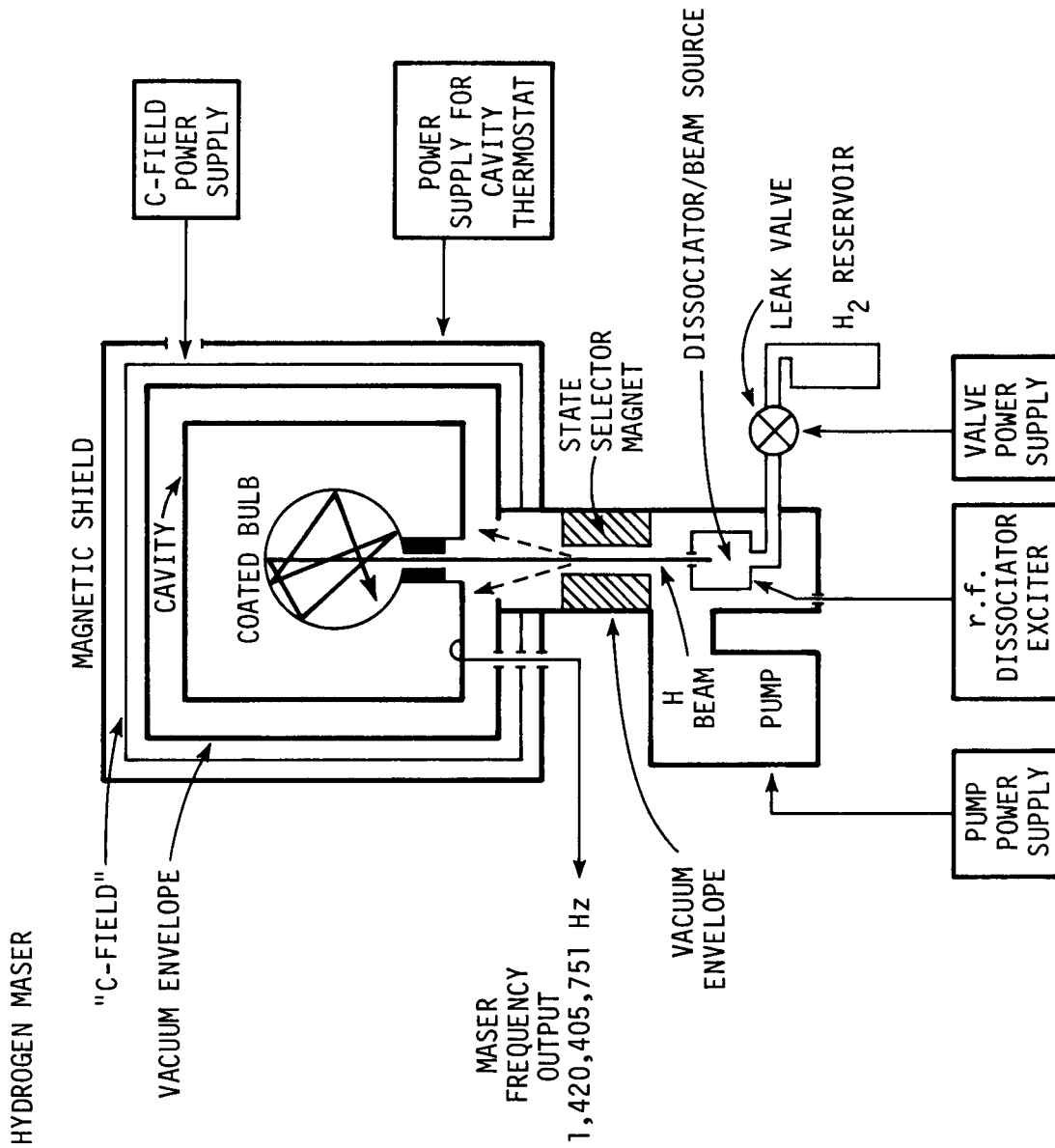


Fig. 24. Schematic of a hydrogen maser oscillator.

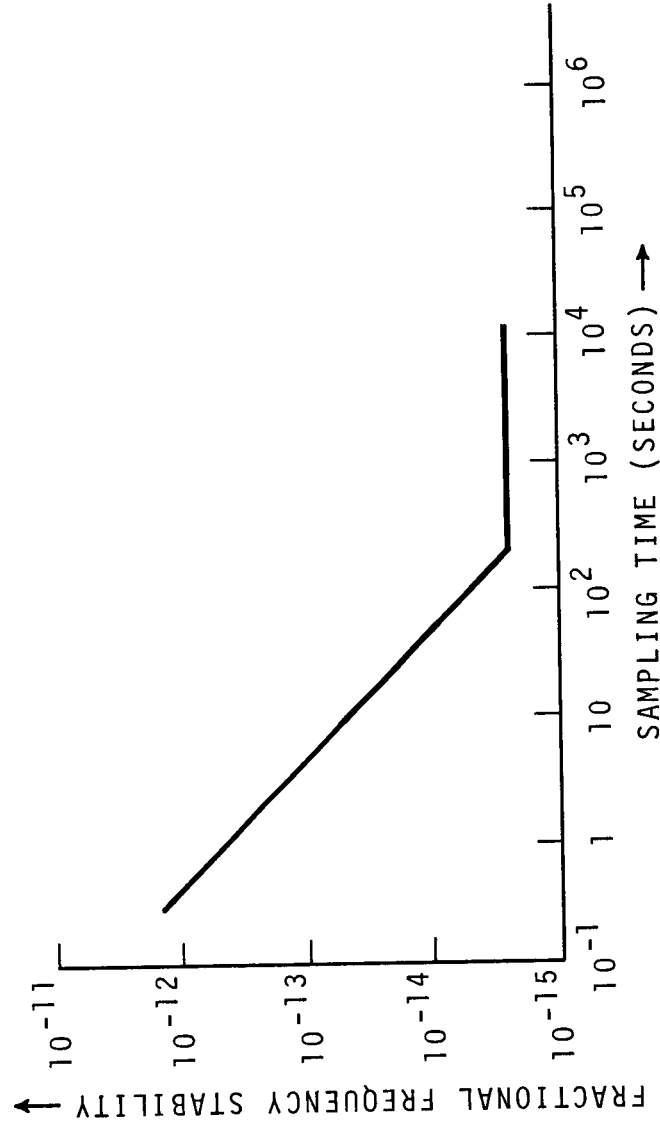


Fig. 25. Frequency stability of a hydrogen maser oscillator.

the frequency drift which is typically 1×10^{-11} per month (but much less than the drift of crystal oscillators). Commercial devices with the above mentioned performance are available. Rubidium standards are used where excellent medium term stability (minutes to a day) is needed, where its reduced costs, size, and weight, as compared to cesium standards, are important, and where a crystal oscillator with its more frequent needs for recalibrations and its greater environmental sensitivity does not suffice.

6.3 Atomic Hydrogen Maser¹³

The atomic resonance frequency is at 1420 405 752 Hz. The standard is based on the atomic beam method using spatial state selection and microwave detection. The beam source is a radio frequency gas discharge in molecular hydrogen¹⁴ which produces atomic hydrogen with high efficiency. The atomic hydrogen beam leaves the source through one or many channels into a vacuum chamber. The beam then traverses a state selecting magnet and enters a storage bulb in the microwave cavity. The storage bulb is made from quartz glass which has low electric losses and thus does not spoil significantly the cavity-Q. The storage bulb is evacuated to a pressure of less than 10^{-11} of atmospheric pressure. Its inner walls are lined with a fluorocarbon coating, a substance similar to the non-stick coating in cookware. This coating allows many collisions of the hydrogen atoms with the walls without significantly disturbing the oscillations of the atoms. The underlying physical mechanisms are not yet fully understood. The storage bulb is typically 0.15 meters in diameter and dimensioned to keep hydrogen atoms for a time of about one second. Then they leave the bulb and thus leave also the microwave cavity. From eqs (3) and (4) we calculate a linewidth of about 1 Hz and

¹³Maser is an acronym meaning "microwave amplification by stimulated emission of radiation". Laser is a derived acronym with "light" substituted for "microwave".

¹⁴All natural hydrogen gas is composed of hydrogen molecules; each hydrogen molecule is formed by chemical bonding of two hydrogen atoms.

a Q-value of about 10^9 , the highest Q-value in all presently used atomic standards.¹⁵ If the intensity of the hydrogen beam, which consists only of upper state atoms (emitting atoms), is sufficiently large and if the cavity losses are sufficiently low, self-oscillation will start in the cavity; i.e., the maser itself will generate a microwave signal. We have a maser-oscillator with an output frequency directly derived from the atomic resonance. A crystal oscillator can be locked to this frequency by frequency comparison techniques. As compared to the cesium standard, the hydrogen maser is not quite as accurate because of experimental difficulties in the evaluation of the frequency shift due to the collisions of the hydrogen atoms with the fluorocarbon surface of the storage bulb. In order to obtain self-oscillation the cavity-Q must be relatively high. Thus cavity pulling is relatively strong, and it limits the long-term stability (over times longer than about one day) to values not better than those of cesium standards. In the region from a few seconds to nearly a day the hydrogen maser has the best stability of all existing standards. Its application is rather limited to uses where these stabilities are critical and where a rather bulky device is no handicap. Unlike cesium and rubidium standards, hydrogen masers have not yet been evaluated under adverse environmental conditions.¹⁶ The number of hydrogen masers in use is very small compared to the numbers of cesium beam devices and of rubidium devices.

¹⁵ Higher Q-values are realized in experimental devices such as methane stabilized helium-neon lasers and ion storage devices as well as in microwave cavities which are cooled to the superconducting state (compare Sec. 8).

¹⁶ Relevant data have been accumulated in 1976 in connection with the use of a hydrogen maser in a space probe in order to gain scientific data on the general theory of relativity. This program was sponsored by NASA and carried out by the Smithsonian Astrophysical Observatory.

7. SUMMARY AND COMPARISON OF AVAILABLE FREQUENCY STANDARDS

Table 1 gives a summary of the performance characteristics of the frequency standards discussed in sections 4 and 6. Individual units may give better (or worse!) performance than indicated by the numbers in the table. The table may be used to compare the four types of devices.

Table 1. Summary and Comparison of Available Frequency Standards

Device	Resonance Frequency	Q
Crystal Oscillator	TCXO Oven controlled	10^5 to 10^6
	High performance type (oven controlled)*	a few 10^6
Cesium Beam	Small commercial	10^7
	Typical commercial	a few 10^7
	High performance commercial	several 10^7
	Laboratory type	a few 10^8
Rubidium Gas Cell	6 834 682 608 Hz	a few 10^7
Hydrogen Maser Oscillator	1 420 405 752 Hz	10^9

* Values for selected units in parentheses.

** The design of some units approaches a commercial design.

Table 1 (contd.)

Principle causes for long-term instability	Fractional frequency stability*				Time between resynchronization for timekeeping of**	
	one second	one hour	one day	ten days	1 μ s	1 ms
Aging of crystal resonator & electronic components; environmental effects	Cannot be specifically stated (typically ranging from 10^{-6} to 10^{-9})					
	1×10^{-11}	1×10^{-10}	5×10^{-10}	5×10^{-9}	one hour	several days
Aging of components, environmental effects; some units continue to improve in stability without apparent limitation	(2×10^{-13})	(2×10^{-13})	(5×10^{-13})	(5×10^{-12})	several hours	one month
	1×10^{-12}	1×10^{-12}	1×10^{-11}	1×10^{-10}	several days	one year
	4×10^{-11}	7×10^{-13}	1×10^{-13}	1×10^{-13}	month	many years
	2×10^{-12}	3×10^{-13}	7×10^{-14}	6×10^{-14}	month	many years
	6×10^{-12}	1×10^{-13}	4×10^{-14}	4×10^{-14}	month	many years
Aging of light source, filter, and gas cell, environmental effects	1×10^{-12}	2×10^{-14}	1×10^{-14}	1×10^{-14}	months	many years
	1×10^{-11}	3×10^{-13}	1×10^{-12}	3×10^{-12}	few days	few months
Cavity pulling, environmental effects	5×10^{-12}	3×10^{-13}	3×10^{-13}	3×10^{-13}	month	many years
	5×10^{-13}	2×10^{-15}	1×10^{-14}	2×10^{-14}	month	many years

* The data can also be regarded as the time required between recalibrations to achieve the (calibrated) time accuracy which corresponds to the stated stability figure (assuming no frequency offset). It should be noted that aging or drift (if "well-behaved") does not limit the systems-usage of a device since it can be measured and predicted.

** Based on the assumption that data and equipment are properly utilized.

Table 1 (contd.)

Fractional Frequency Drift (Aging)	Fractional Frequency Reproducibility	Fractional Frequency Accuracy**	Principal Environmental Effects
10^{-9} per day	10^{-6}	As manufactured worse than 10^{-6}	Accelerations (g-forces, shock, vibration), temperature changes, ionizing radiation, changes in crystal drive level.
5×10^{-10} per day	10^{-9}		
1×10^{-11} per day (5×10^{-13})	10^{-10}		
In some units, drift of as much as 1×10^{-12} per year may occur.	1×10^{-11}	3×10^{-11}	Strong magnetic fields*, strong accelerations, large temperature changes
In many units, none detectable with resolution of 1×10^{-13} per year. (In some units drift of as much as 1×10^{-12} per year may occur.)	5×10^{-12}	1×10^{-11}	
Can be reset to better than 1×10^{-13}	3×10^{-12}	7×10^{-12}	
1×10^{-11} per month	3×10^{-14}	1×10^{-13}	
None detected with resolution of 1×10^{-12} per year	5×10^{-11}	5×10^{-10}	Strong magnetic fields*, temperature changes, atmospheric pressure
	5×10^{-13}	1×10^{-12}	Strong magnetic fields*, temperature changes

* As compared to earth magnetic field.

** The data given for hydrogen and all cesium standards are likely to improve in the future.

Table 1 (contd.)

Behavior under intermittent operation	Reliability	Size* vol. in cm ³	Weight* in kg	Power demand* in watts	Estimated selling price in k\$* (for frequency standard)
Fast warm-up Warm-up requires min. to hours	Not limited by crystal resonator	>10	>0.1	>0.1	several 0.1
		>100	>0.5	several watts	0.3 - 1.0
		10,000	5-10	15	several 1.0
Warm-up in 10 - 30 minutes	Life of the cesium resonator (beam tube) is at least 3 yrs. (continuous operation)	10,000	16	30	20
		30,000	30	40	20
					22
Warm-up in 10 - 30 minutes	Lifetime of the cesium resonator is 3 mo. - 3 yrs. (continuous operation) depending on particular devices.	700,000	1000	100	200
		1,000	1	12	3-6
		20,000	10-20	35	7-10
Warm-up in hours	Insufficient no. of units. Some have operated continuously for much longer than 1 yr.	200,000 - 700,000	50-200	40	200

*These figures are rounded to one significant digit. For single unit purchase, under current availability conditions.

8. TRENDS

All devices which were discussed in this report have improved over the past years in one or more of the following aspects: reliability, size, weight, stability performance, and environmental insensitivity. A considerable amount of effort is now being expended in research and development to go further in this direction; however, it would be inappropriate here to try to estimate the improvement of performance specifications which might (or might not) be achieved in the future.

There are several other devices, designs, and concepts which have been studied or are being investigated with some potential for future use in frequency standards. Most of these are summarized in Table 2.

Table 2. Additional Promising Items Under Investigation

Resonator	Resonance Frequency	Q (incl. projected values)	Comments
Ammonia absorption	Around 22 GHz	10^5 to 10^6	Sensitive to (inter- nal) electric fields; relatively low Q
Ammonia maser oscillator	Around 22 GHz	a few 10^7	First maser oscillator (1955), problems with relatively strong Doppler effect & molecular collisions
Thallium atomic beam	21 GHz	10^7 to 10^8	Less sensitive to external magnetic fields, detection problems. Pursued in the 1960's but discontinued.
Barium oxide molecular beam	19 GHz	10^7 to 10^8	Sensitive to (internal) electrical fields. Insensitive to external magnetic fields, detection problems. Pursued in the late 1960's but discontinued.
Hydrogen atomic beam	1.4 GHz	10^8 to 10^{10}	Storage principle & microwave detection (no self oscillations), "passive" maser. Stabilities of almost 10^{-15} documented for 4 days averaging.
Ion storage	In the GHz to visible region depending on chosen ion	10^8 to 10^{15}	Storage principle & atom detection, or straight beam (as in cesium) & atom detection. Detection problems with this approach.
Saturated molecular absorption	In the THz region* depending on chosen atom or molecule	10^9 to 10^{11}	Storage in electric & magnetic fields (no walls!). Problems with storing a sufficient number of ions. Helium and mercury ions have been used.
2-photon absorption	In the THz region* depending on chosen atom or molecule	10^9 - 10^{15}	Exciting oscillator is a laser. Problems in usage because of very high frequency (infrared & visible radiation). Methane and iodine are two of the several molecules being used.
Rubidium maser oscillator	6.8 GHz	a few 10^7	Some promising results with hydrogen and alkali. Problems because of needed very high frequency (comp. saturated absorption).
Cesium maser/gas cell	9.2 GHz	10^7	Similar to rubidium gas cell with similar limitations, but self-oscillations with microwave detection.
Superconducting microwave cavity	In the GHz region	10^8 - 10^{11}	Performance and design similar to rubidium maser/gas cell (see above and main text).

* THz = one trillion hertz = 10^{12} Hz.

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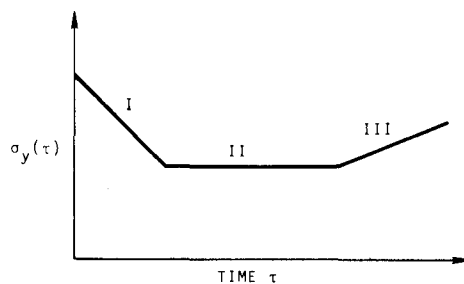
SPECIFYING AN OSCILLATOR IN THE TIME-DOMAIN

A stability plot of a frequency standard typically shows the characteristic as shown in Fig. 26. The first part, "I" with $\sigma_Y \sim \tau^{-1/2}$ (white frequency noise) or $\sigma_Y \sim \tau^{-1}$ (white or flicker of phase noise) reflects the fundamental noise properties of the standard. This behavior continues with increasing averaging time until the so-called flicker "floor" is reached where $\sigma_Y(\tau)$ is independent of the averaging time (curve "II", flicker of frequency noise). This behavior is found in all frequency standards; it depends on the particular frequency standard and is not fully understood in its physical basis. Examples for probable causes for the flicker "floor" are power supply voltage fluctuations, magnetic field fluctuations, changes in components of the standard, microwave power changes, etc. Finally in the third section, "III", of the generalized curve, the stability deteriorates with increasing averaging time. This occurs typically at times ranging from minutes to days, depending on the particular kind of

standard. A behavior $\sigma_Y(\tau) \sim \tau^{+1}$ usually corresponds to linear frequency drift or aging D. A slope in the range from τ^0 to τ^{+1} is found in most frequency standards due to a variety of internal and environmental parameter instabilities. Thus the third part of the curve can be improved by better control of the standard in the laboratory or its protection against environmental influences.

It is recommended to characterize a standard in the time-domain by giving the following data:

1. fundamental stability (curve "I") $\sigma_Y(\tau) = k\tau^\mu$ stating k and μ .
2. stability limit or flicker floor (curve "II") stating σ_{YF}
3. frequency drift or aging, if any, stating D (fractional frequency change per day).
4. characteristic values of $\sigma_Y(\tau)$ in the range of curve III after subtracting linear frequency drift or aging D from the data.



- | | |
|---|--|
| I. $\sigma_Y(\tau) \sim \tau^\mu$ | $\mu = -1$; WHITE OR FLICKER OF PHASE NOISE |
| | $\mu = -1/2$; WHITE FREQUENCY NOISE |
| II. $\sigma_Y(\tau) = \sigma_{YF} = \text{CONST}$ | FLICKER "FLOOR" (FLICKER OF FREQUENCY) |
| III. $\sigma_Y(\tau) \sim \tau^\mu$ | $0 \leq \mu \leq 1$ TYPICAL |
| | $\mu = 1$; PURE FREQUENCY DRIFT (AGING) |

Fig. 26

RAMSEY CAVITY

Figure 27 shows the cavity with two separated interaction regions (Ramsey cavity) and a typical corresponding cesium resonance spectrum. The broad pedestal (or "Rabi" resonance) is a result of the coherent interaction of the atoms with either interaction region alone; therefore, the corresponding linewidth is $W \approx v/\ell = \frac{1}{t_{d\ell}}$ where v is the speed of the atoms, ℓ the length of one interaction region and $t_{d\ell}$ the atomic time-of-flight through it.

The more rapidly oscillating pattern (Ramsey pattern) on top of the pedestal is a result of the coherent interrogation by both interaction regions. This pattern can be explained as follows (we assume that there is no phase difference of the electromagnetic field between the two cavity regions): If the interrogating frequency is equal to the cesium resonance frequency, the atomic oscillations will remain in phase with the interrogating signal while the atom flies from the first to the second region; the driving signal in the second region will reinforce the action of the first cavity and we obtain maximum signal (center of the resonance). If the signal frequency is offset from the atomic resonance frequency we can observe two extremes: (a) the frequency offset, $\Delta\nu$, is such that $\Delta\nu \times t_L = 1, 2, 3, 4, \dots$ where $t_L = L/v$ is the atomic time-of-flight between the interaction regions.

(b) $\Delta\nu \times t_L = 1/2; 3/2; 5/2; \dots$

In cases (a) the atoms arrive "in-phase" at the second interrogation region; we obtain reinforcement and maximum signal. In cases (b), the atoms arrive "out-of-phase" at the second region; we obtain negative reinforcement with minimum signal as a result.

Since t_L depends on the atomic velocities (see above), the cases (a) and (b) will "wash-out" with increasing $\Delta\nu$ due to the fact that the beam contains a spectrum of velocities (velocity distribution) and a corresponding range of t_L . This is the reason why the Ramsey pattern rapidly attenuates on either side of the central peak.

As compared to a normal, single cavity of the length L , the main advantages of the Ramsey cavity relate to the fact that the atoms are freely oscillating while flying between the two interaction regions; i.e., they are not subject to effects from cavity imperfections and they average all other deleterious effects; e.g., magnetic field effects. Also, the linewidth of the center peak of the Ramsey pattern is about one half that of the single cavity.

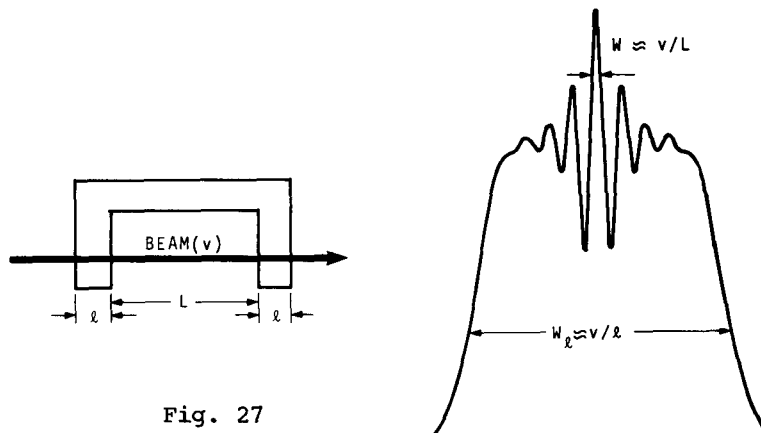


Fig. 27

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