

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.

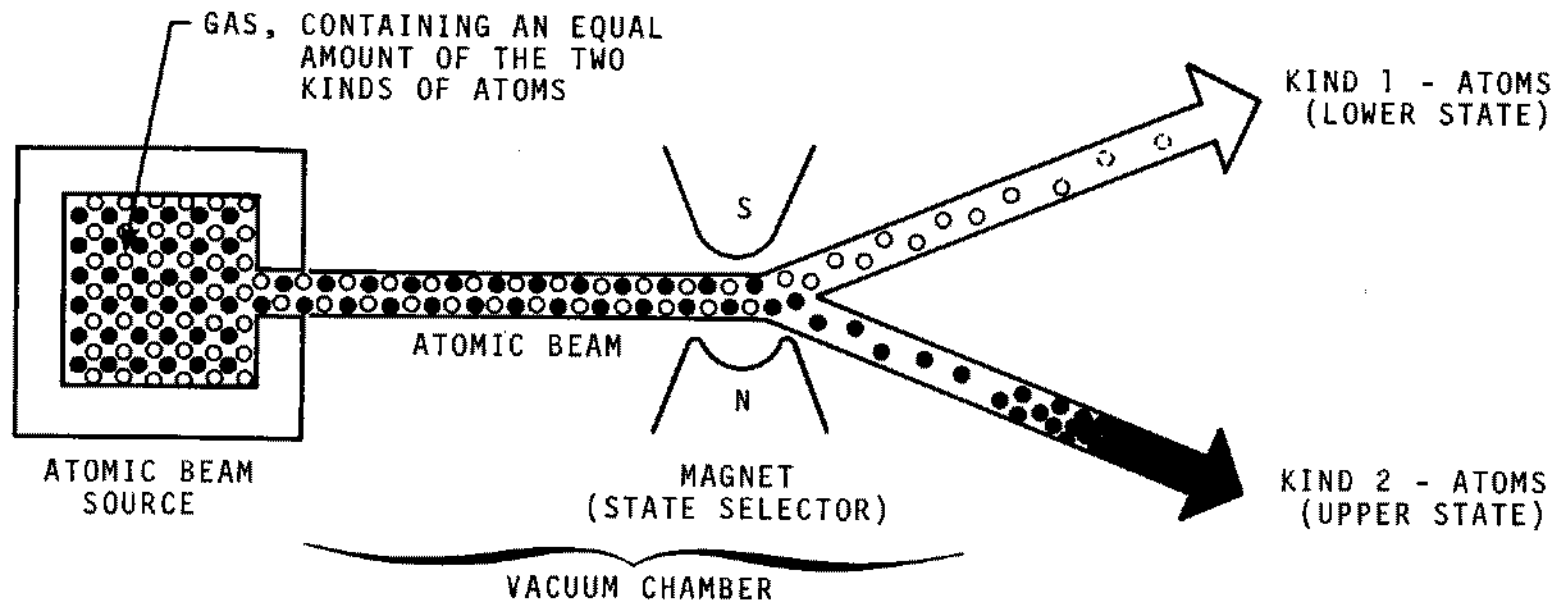


Fig. 14. Spatial state selection.

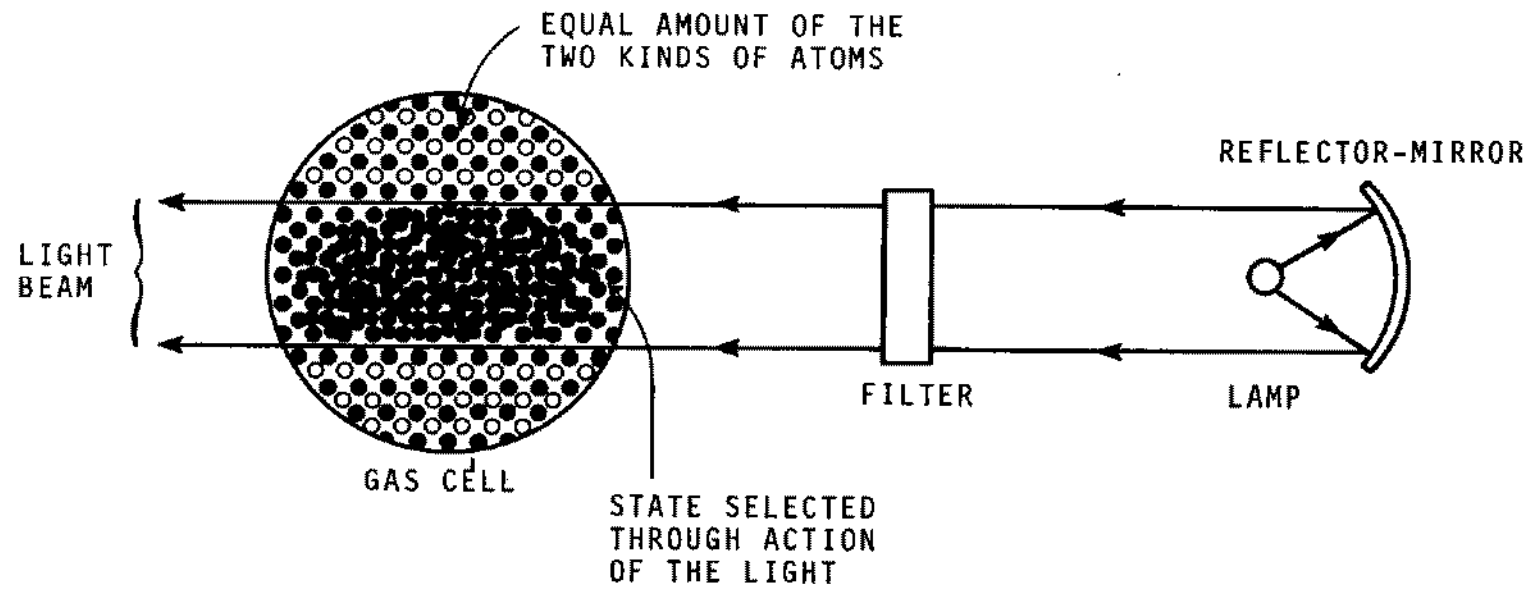


Fig. 15. Optical state selection.

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.

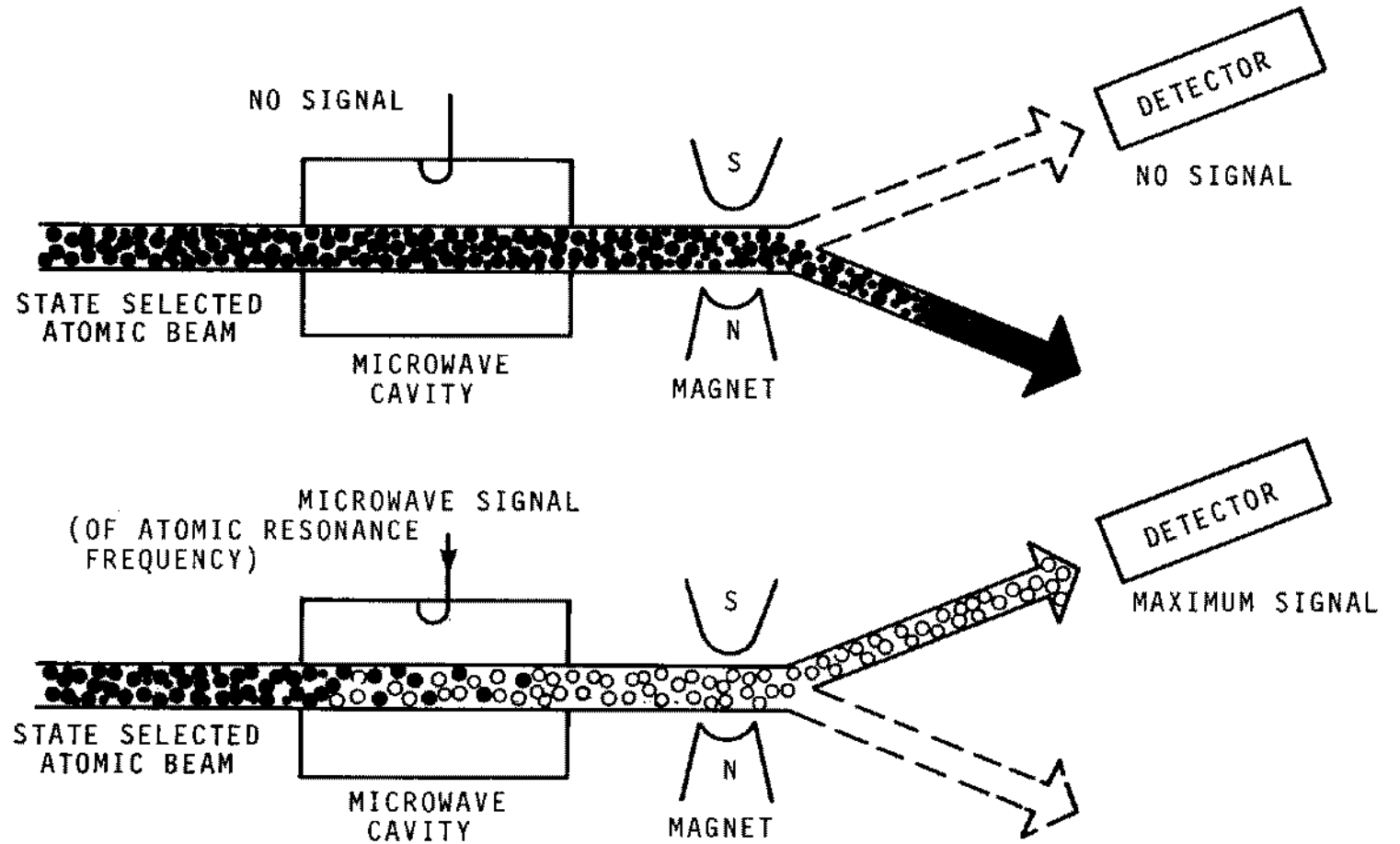


Fig. 16. Atom detection.

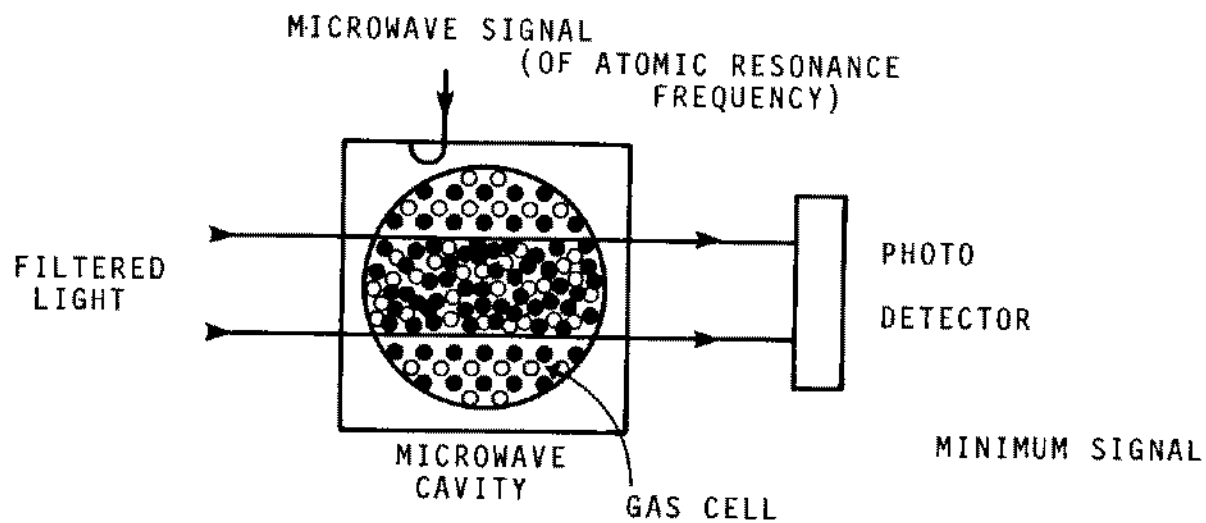
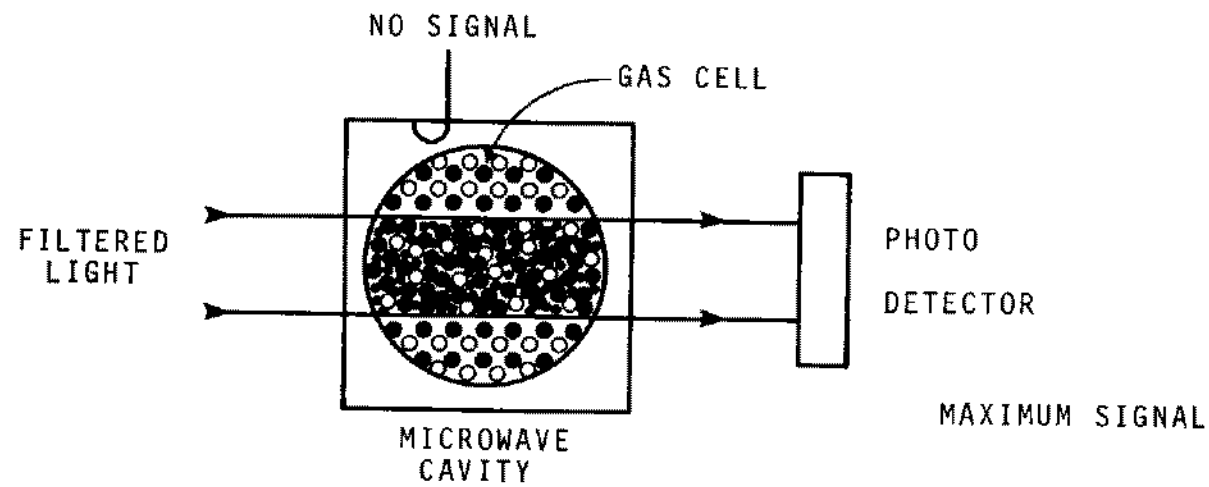


Fig. 17. Optical detection.

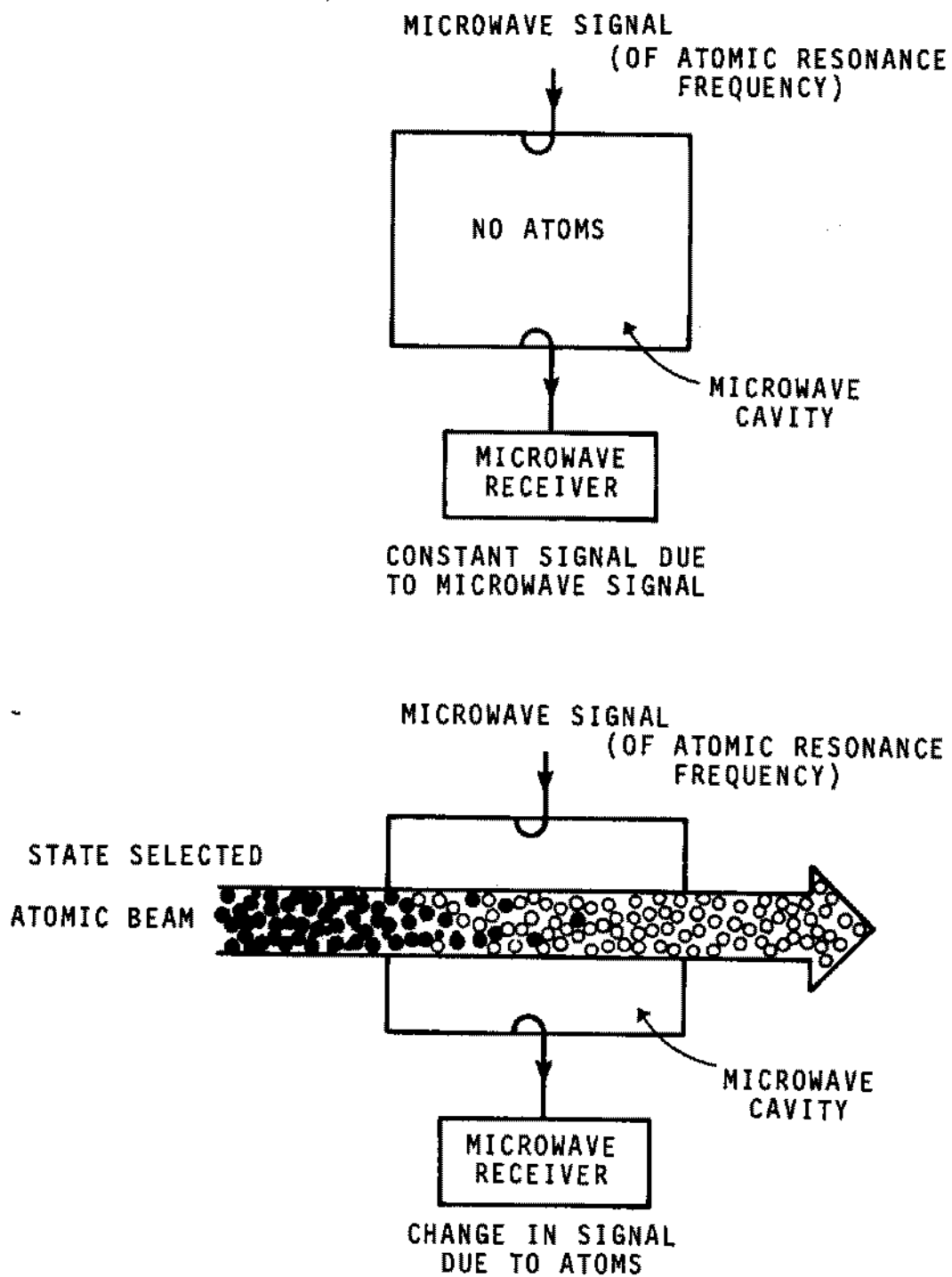


Fig. 18. Microwave detection.

(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.

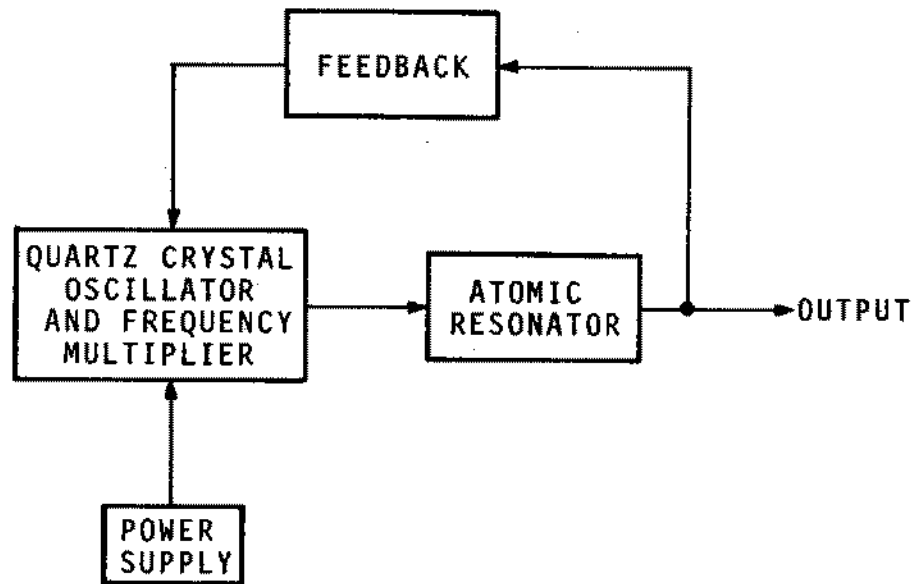


Fig. 19. Atomic frequency standard.

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

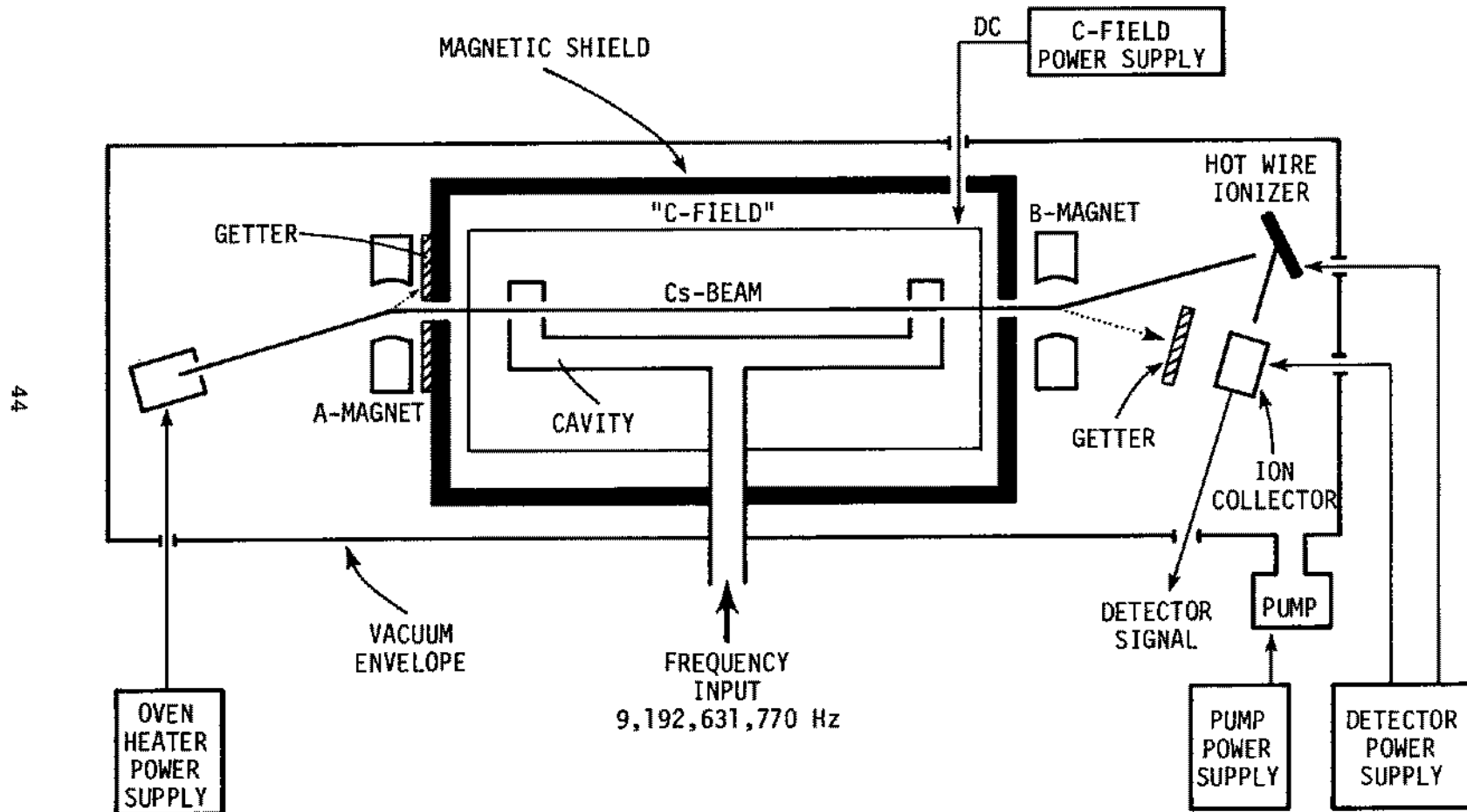


Fig. 20. Schematic of a cesium beam tube. Typically, a cavity with separated interrogation regions is used. This design offers certain advantages over a simple cavity of a length equivalent to the separation of the two regions. See Appendix II.

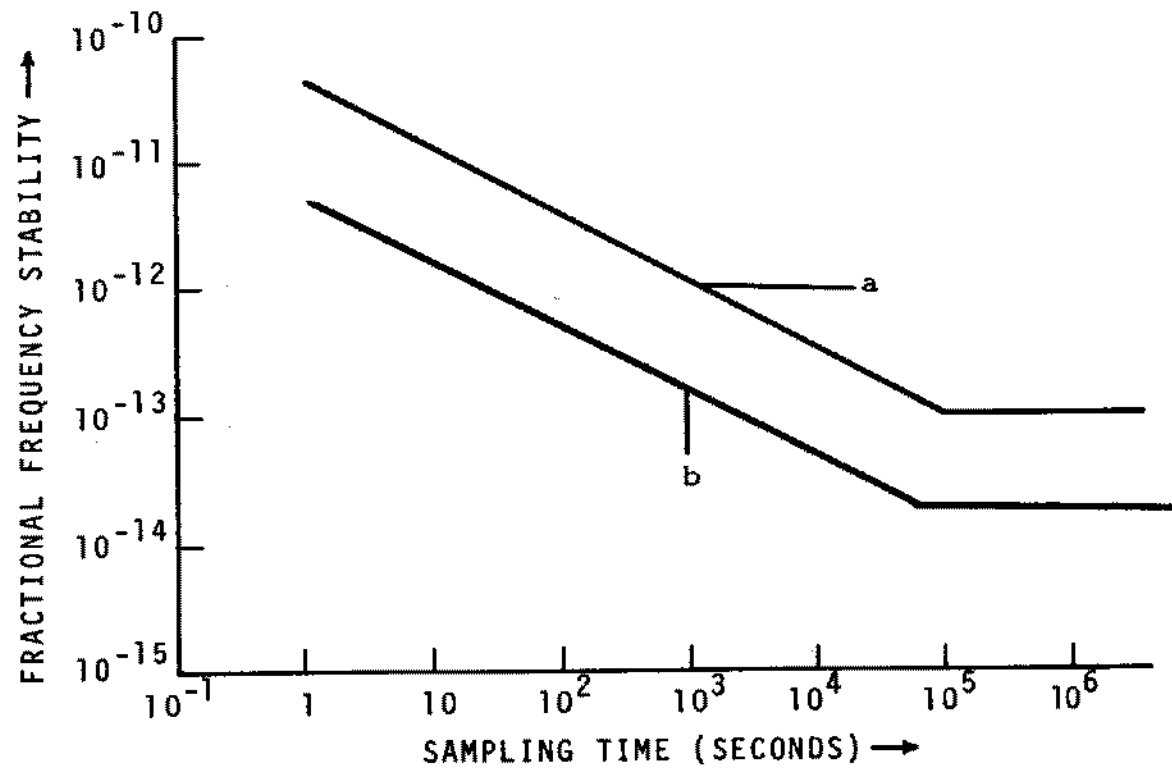


Fig. 21. Frequency stability of commercial cesium beam frequency standards.

a) typical performance

b) typical performance of high beam intensity tubes

Individual units may perform slightly worse or better than shown.

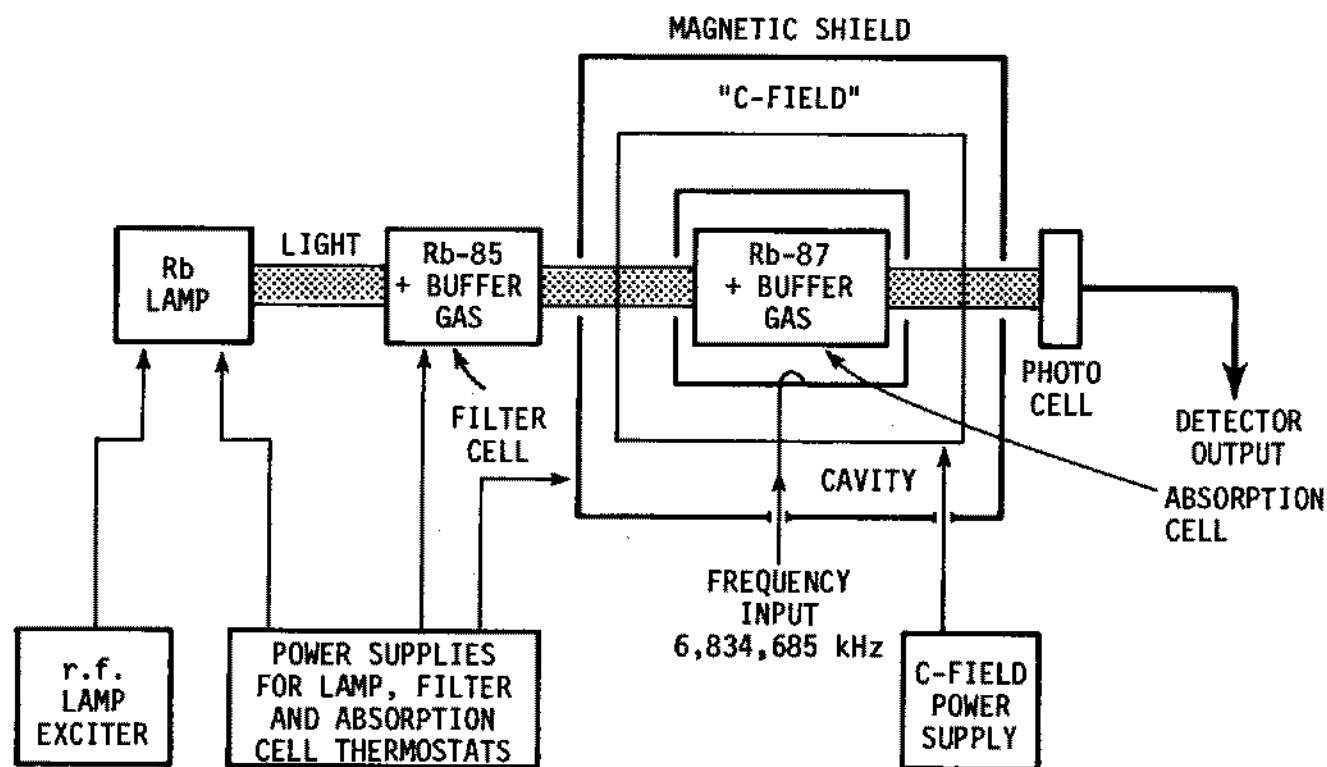
Modern laboratory standards perform still better.

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



47

Fig. 22. Schematic of a rubidium gas cell.

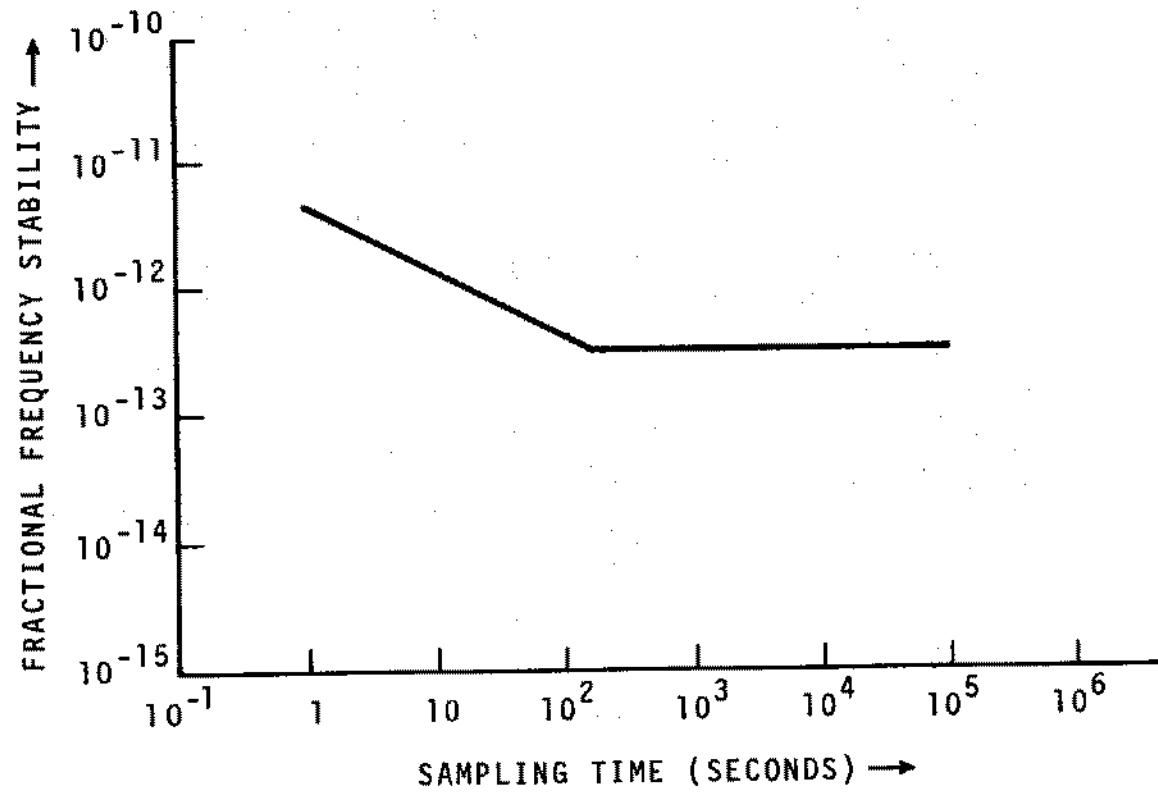


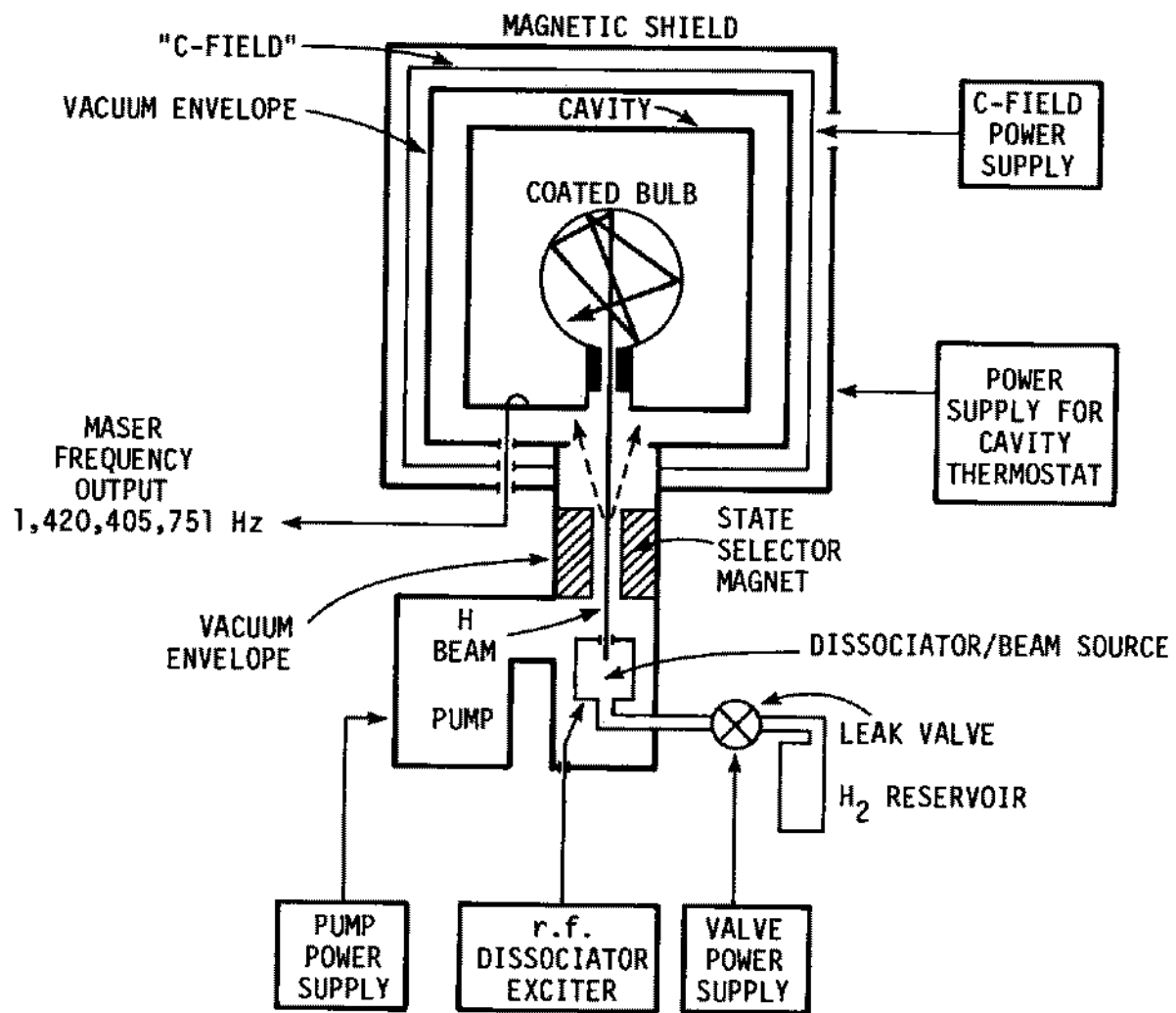
Fig. 23. Frequency stability of commercial rubidium gas cell frequency standards.

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

HYDROGEN MASER



50

Fig. 24. Schematic of a hydrogen maser oscillator.

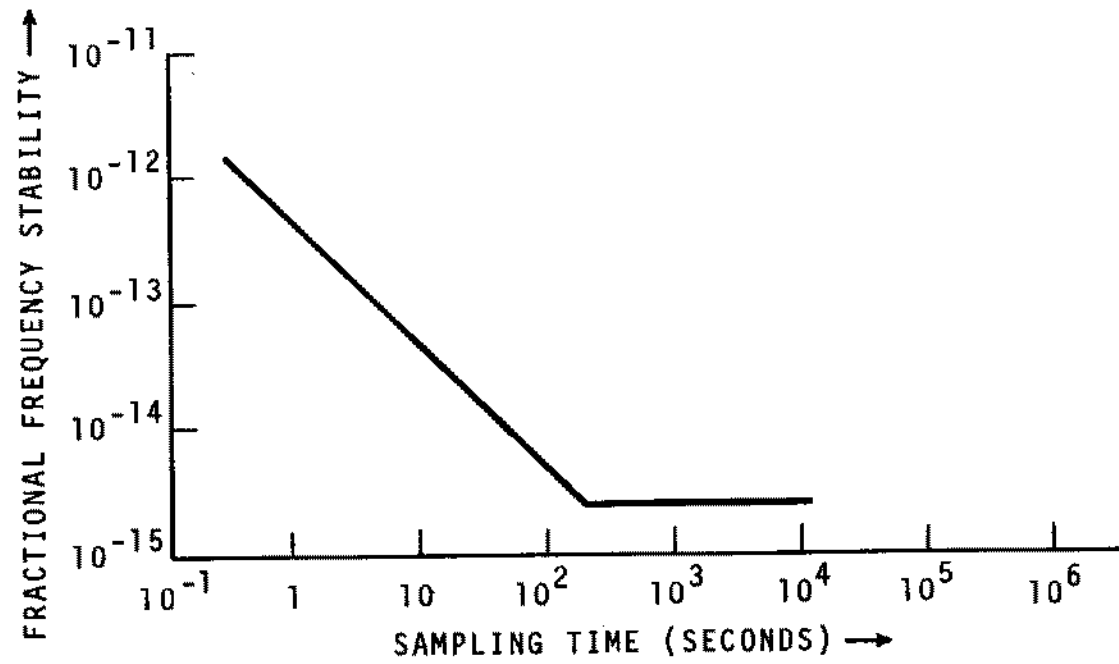


Fig. 25. Frequency stability of a hydrogen maser oscillator.

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	Manufactured throughout the kHz and MHz regions	10^5 to 10^6
	Oven controlled		
	High performance type (oven controlled)*	1 MHz to 10 MHz, typically	a few 10^6
Cesium Beam	Small commercial	9 192 631 770 Hz	10^7
	Typical commercial		a few 10^7
	High performance commercial		several 10^7
	Laboratory type		a few 10^8
Rubidium Gas Cell	Small commercial	6 834 682 608 Hz	a few 10^7
	Commercial		
Hydrogen Maser Oscillator	Laboratory type**	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
	(2×10^{-13}) 1×10^{-12}	(2×10^{-13}) 1×10^{-12}	(5×10^{-13}) 1×10^{-11}	(5×10^{-12}) 1×10^{-10}	several hours	one month
Aging of components, environmental effects; some units continue to improve in stability without apparent limitation	4×10^{-11}	7×10^{-13}	1×10^{-13}	1×10^{-13}	several days	one year
	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
	1×10^{-12}	2×10^{-14}	1×10^{-14}	1×10^{-14}	months	many years
Aging of light source, filter, and gas cell, environmental effects	1×10^{-11}	3×10^{-13}	1×10^{-12}	3×10^{-12}	few days	few months
	5×10^{-12}	3×10^{-13}	3×10^{-13}	3×10^{-12}		
Cavity pulling, environmental effects	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	5×10^{-11}	1×10^{-13}	
1×10^{-11} per month	5×10^{-11}	5×10^{-10}	Strong magnetic fields*, temperature changes, atmospheric pressure
None detected with resolution of 1×10^{-12} per year	5×10^{-13}	1×10^{-12}	Strong magnetic fields*, temperature changes

56

* 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
	Lifetime of the cesium resonator is 3 mo. - 3 yrs. (continuous operation) depending on particular devices.	700,000	1000	100	200
Warm-up in 10 - 30 minutes	Life of the rubidium resonator (optical pkg.) is at least 3 yrs. (cont. operation)	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 (internal) electric fields; relatively low Q. First "atomic" clock (1948), insensitive to external magnetic fields.
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. Storage principle & atom detection, or straight beam (as in cesium) & atom detection. Detection problems with this approach.
Ion storage	In the GHz to visible region depending on chosen ion	10^8 to 10^{15}	Storage in electric & magnetic fields (no walls!). Problems with storing a sufficient number of ions. Helium and mercury ions have been used.
Saturated molecular absorption	In the THz region* depending on chosen atom or molecule	10^9 to 10^{11}	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.
2-photon absorption	In the THz region* depending on chosen atom or molecule	10^9 - 10^{15}	Some promising results with hydrogen and alkali. Problems because of needed very high frequency (comp. saturated absorption).
Rubidium maser oscillator	6.8 GHz	a few 10^7	Similar to rubidium gas cell with similar limitations, but self-oscillations with microwave detection.
Cesium maser/gas cell	9.2 GHz	10^7	Performance and design similar to rubidium maser/gas cell (see above and main text).
Superconducting microwave cavity	In the GHz region	10^8 - 10^{11}	Technology problems. Very low accuracy but excellent stability demonstrated (parts in 10^{16}).

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

9. LITERATURE

The following references are a limited selection. They are intended as a guide for those who wish to penetrate the subject in greater depth.

A. Introduction

- (1) J. Kovalevsky, "Astronomical Time," *Metrologia* 1 (1965) 169.
- (2) H. M. Smith, "International Time and Frequency Coordination," *Proc. IEEE* 60 (1972) 479.
- (3) The American Ephemeris and Nautical Almanac, U.S. Government Printing Office, Washington, D. C.
- (4) S. L. Howe, "NBS Time and Frequency Dissemination Services," NBS Special Publication 432 (1976).

B. Basic Concepts

- (1) D. A. Howe, "Frequency Domain Stability Measurements: A Tutorial Introduction," NBS Tech. Note 679 (1976).
- (2) D. W. Allan, "The Measurement of Frequency and Frequency Stability of Precision Oscillators," NBS Tech Note 669 (1975).
- (3) J. A. Barnes et al, "Characterization of Frequency Stability," *IEEE Trans. on Instr. and Meas.* IM-20 (1971) 105.
- (4) L. S. Cutler and C. L. Searles, "Some Aspects of the Theory and Measurement of Frequency Fluctuations in Frequency Standards," *Proc. IEEE* 54 (1966) 136.
- (5) D. W. Allan, H. Hellwig, D. J. Glaze, "An Accuracy Algorithm for an Atomic Time Scale," *Metrologia* 11 (1975) 133.
- (6) H. Hellwig, D. W. Allan, and F. L. Walls, "Time and Frequency," *Proc. of the 7th International Conference on Atomic Masses and Fundamental Constants*, Paris, France (1975), p. 305.

C. Frequency Standards, General Aspects

- (1) Most general physics textbooks.
- (2) A. E. Siegmann, "An Introduction to Lasers and Masers," Chapter 2, McGraw-Hill 1971.

D. Quartz Crystal Devices

- (1) E. A. Gerber and R. A. Sykes, "State of the Art - Quartz Crystal Units and Oscillators," *Proc. IEEE* 54 (1966) 103
- (2) E. A. Gerber and R. A. Sykes, "A Quarter Century of Progress in the Theory and Development of Crystals for Frequency Control and Selection," *Proc. 25th Annual Symp. on Frequency Control*, Ft. Monmouth, NJ (1971) 1 (available from Electronic Industries Assoc., Washington, DC).
- (3) R. A. Heising, "Quartz Crystals for Electrical Circuits," Van Nostrand, 1946.

E. Atomic Resonance Devices

- (1) N. F. Ramsey, "History of Atomic and Molecular Control of Frequency and Time," Proc. 25th Annual Symp. on Frequency Control, Ft. Monmouth, NJ (1971) 46 (available from Electronic Industries Assoc., Washington, DC).
- (2) N. F. Ramsey, "Molecular Beams," Oxford, 1956.
- (3) A. E. Siegmann, "An Introduction to Lasers and Masers," McGraw-Hill, 1971
- (4) H. Hellwig, "Design Principles and Characteristics of Frequency and Time Standards," IEEE Trans. on Nuclear Science NS-23 (1976) 1629.

F. Available Atomic Frequency Standards

- (1) A. O. McCoubrey, "A Survey of Atomic Frequency Standards," Proc. IEEE 54 (1966) 116.
- (2) D. 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. 138 (1965) A972.
- (3) R. E. Beehler, R. C. Mockler, and J.M. Richardson, "Cesium Beam Atomic Time and Frequency Standards," Metrologia 1 (1965) 114.
- (4) P. Davidovits and R. Norvick, "The Optically Pumped Rubidium Maser," Proc. IEEE 54 (1966) 155.
- (5) H. Hellwig, "Atomic Frequency Standards: A Survey," Proc. of the IEEE 63 (1975) 212.
- (6) C. Audoin and J. Vanier, "Atomic Frequency Standards and Clocks," Jnl. Phys. E: Scientific Instruments 9 (1976) 697.

G. Trends

- (1) H. Hellwig, "Areas of Promise for the Development of Primary Frequency Standards," Metrologia 6 (1970) 118.
- (2) H. S. Boyne, "Laser Frequency Stabilization Techniques and Applications," IEEE Trans. on Instr. and Meas. IM-20 (1971) 19.
- (3) H. Hellwig, "Clocks and Measurements of Time and Frequency," WESCON Technical Papers, Session 32 (1976).

H. General Scientific Overview

- (1) Byron E. Blair, Editor, "Time and Frequency: Theory and Fundamentals," National Bureau of Standards Monograph 140, 460 pages (January 1974). Available from: Superintendent of Documents, U. S. Govt. Printing Office, Washington, DC 20402 (SD Catalog No. C13.44:140)

ACKNOWLEDGMENTS

The author owes much to his colleagues within and outside of the National Bureau of Standards for many suggestions and contributions.

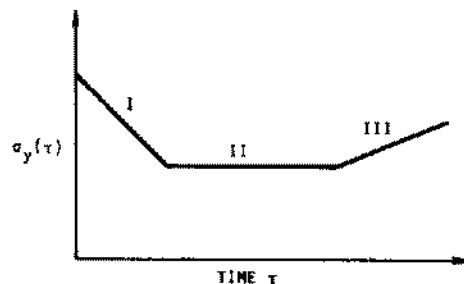
SPECIFYING AN OSCILLATOR IN THE TIME-DOMAIN

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