Projected State-of-the-Art for Frequency Standards for the DSN in the 1982–1990 Time Frame

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A study has been made of frequency standards that are potentially useful to the DSN in the 1980s. A combination of several devices that have inherently good performance over different averaging time regimes is recommended. This combination consists of: a quartz oscillator for short-term, either a quartz oscillator or active hydrogen maser for medium-term, and a passive hydrogen maser or cesium standard for long-term stability.

I. Introduction

Progress in the development of frequency standards over the last three decades has been truly impressive. Over this time the performance has improved by five orders of magnitude from 10^{-9} in 1950 to 10^{-14} today in 1979. It was not easy to foresee this progress in 1950, just as it is not easy to foretell the changes that will occur in the next ten years. However, better knowledge of the physics of atoms, molecules, and crystals is now available, and techniques for utilization of frequency standards are better understood.

For the present and near future, atomic and molecular frequency standards provide the best overall performance. Quartz crystal oscillators and superconducting cavities or a combination of both may be a cost effective means to achieve the required stability over short to medium averaging times.

The purpose of this article is to present an elementary discussion of the physical bases for various kinds of frequency standards.

II. Physical Basis for Modern Frequency Standards

Two recent publications (Refs. 1 and 2) on frequency standards written by H. Hellwig, who was chief of the Time and Frequency Division, NBS, provide excellent summaries of the present state of the art.

Here the similarities and differences between different standards will be explained in a qualitative way so that the nonspecialist can, with the help of Hellwig's publications, become acquainted with the rationale for various devices and techniques.

A. Electromechanical Oscillators

Historically, the quartz crystal oscillator was the first precision oscillator used as a frequency standard. The piezoelectric properties of quartz are used in various ways to sustain stable oscillations. The frequency range is from a few kilohertz to several tens of megahertz and Qs of the order of 10^6 are readily achieved. A great advantage of the crystal oscillator is the relatively high power level at which it oscillates; this provides the high signal-to-noise ratio needed to obtain stability at short averaging times. The disadvantage of this type of oscillator is its long term drift, which is attributed to aging phenomena in the crystal.

However, recent studies have shown that the aging process can be reduced by operating newly designed crystals at low power levels. Thus, it is possible to use a high-power crystal for good short-term stability, and a low-power crystal for good medium-term stability.

A new kind of electromechanical oscillator has recently been developed that uses the fundamental longitudinal mode of vibration in large single-crystal cylinders of sapphire or silicon. These crystals are not piezoelectric, but are readily excited by electric fields from capacitor plates located near the ends of the cylinder. By cooling the crystal cylinder to cryogenic temperatures (1.8 K), Qs of the order of 8×10^9 have been achieved for resonators at 20 kilohertz (Ref. 3). These resonators were developed for gravity wave detection and have not yet been used in frequency standards. The high Q obtainable is impressive, but unfortunately cannot be achieved at higher frequencies since Q is proportional to the ratio of the length of the cylinder to the surface finish of the end faces, i.e., to the parallelness of the two ends.

B. Superconducting Cavity Stabilized Oscillators

Electromagnetic resonators with high Q can be obtained by the use of superconducting cavities at microwave frequencies. Recent advances in fabrication techniques have resulted in Qs of the order of 10^{10} at X-band and temperatures of 1 to 1.2 K. By using a high-Q cavity as a frequency discriminator, it is possible to phase lock a crystal oscillator to the line center of the cavity. Stabilities of the order of $< 10^{-15}$ have been achieved for averaging times of the order of minutes. They have been measured by JPL on a superconducting cavity stabilized oscillator built by Stanford University. For this kind of fractional frequency stability, a 3-cm-diameter (D) cavity (X-band) must be held to $\Delta D = 3 \times 10^{-15}$ cm. This is two orders of magnitude smaller than the classical electron radius! Such dimensional stabilities require temperature control to within a few micro-Kelvin of the operating temperature. Equally important would be the control of vibration and of the VSWR of all transmission lines connected to the cavity. These challenging problems must all be solved before the superconducting cavity stabilized oscillator can be regarded as more than a laboratory curiosity, except for very short averaging times ($\tau < 300$ sec).

C. Atomic Frequency Standards

1. Devices employing the hyperfine transitions. All the currently available atomic frequency standards employ the hyperfine atomic transitions. Hydrogen, rubidium, and cesium have nonvanishing nuclear moments that give rise to magnetic moments. Each of the atoms has a single valence electron exposed to the weak but precise nuclear magnetic field. The spinning electron in conjunction with the nuclear spin gives rise to energy levels as shown in Fig. 1. Although the energy levels look different for the three atoms, it is noted that they all have in common a pair of levels that, for small external fields, is independent of the field. Transitions between these levels are called sigma transitions and the others are called pi transitions.

It is a simple matter to select the sigma transition over the field dependent pi transitions by a proper orientation of the RF magnetic field relative to a weak reference dc magnetic field.

For high magnetic fields, all energy states are strongly dependent on the magnitude of the fields. This dependence may be used to separate those with positive slopes from those with negative slopes.

In principle, all three may be operated as active standards (masers) or as passive devices. So far, only hydrogen and rubidium have been used in the two modes; cesium has been used only in the passive mode.

Table 1 summarizes the frequencies and line-widths in typical hydrogen masers, cesium standards, and rubidium standards.

In all these standards, neutral atoms in the ground state (the state in which the orbital angular momentum of the valence electron is zero) are employed. This makes it easier to approach the ideal condition for spectroscopic observation of an atom: one which is isolated in space and free from all perturbations. However, because the magnetic moments due to nuclei are weak, the hyperfine transition frequencies are in the lower microwave range as shown in Table 1. It turns out that higher Qs are achievable in atomic transitions for higher energies or higher frequencies. This can be realized, for example, by employing fine structure transitions in atoms as discussed later.

It is important to point out the differences among the standards employing hyperfine transitions. In the hydrogen maser, the transitions are used directly to produce oscillations at 1420 MHz. In the rubidium standard, an optical transition that is coupled to the hyperfine transition is used as a mechanism in an optical frequency discriminator.

Finally, in the cesium standard, a particle detector discriminates between atoms that have made transitions from those that have not.

Active standards are desirable when good short-term stability is necessary. In the hydrogen maser, a flux produces the high signal-to-noise ratio needed for short-term stability at the expense of a lowered Q. However, a high Q is desirable for long-term stability. The recent interest in passive hydrogen standards is due to the higher Q that may be realized by the use of a low hydrogen flux. The National Bureau of Standards employs a cesium standard of several meters in length to achieve a high Q in its standard.

The cesium standard is regarded as a primary standard because the atoms are observed spectroscopically in free flight in a vacuum chamber. Thus, any number of standards could be expected to have the same line center frequency. This is different than the case of the hydrogen maser. In the hydrogen maser, the atoms are stored in a teflon-coated quartz bulb for approximately one second during the emission of microwave energy. Since each storage bulb will affect the atoms in a slightly different way, it will produce a small and different frequency shift (wall shift) in the line center frequency. This is why the hydrogen maser is regarded as a secondary standard.

Similarly, the atoms in a rubidium standard are contained in a cell with a buffer gas, such as argon, when spectroscopic measurements are made to determine the center frequency. Again, no two cells are expected to have identical characteristics, and the rubidium standard is referred to as a secondary standard.

2. Active versus passive frequency standards employing the hyperfine transitions. Many parameters determine the usefulness of a particular atomic species in a frequency standard, not the least important of which is the vapor pressure of the substance at room temperature. It is the differing vapor pressures in the alkali atoms (H, Rb, and Cs) that led to the different configurations in frequency standards. Hydrogen and rubidium have been employed both in masers and in passive standards. To date, cesium has been operated only in the passive mode because of its low vapor pressure.

The passive hydrogen maser shows promise as a frequency standard with good long-term stability. The passive hydrogen maser operates as a frequency discriminator to phase lock a crystal oscillator to the hydrogen resonance at 1420 MHz. The flux of atoms entering the maser cavity is reduced below the level at which oscillation occurs. The device then operates as a frequency discriminator and standard techniques are then used to stabilize a crystal oscillator.

The principal advantage of the passive standard is that reducing the flux reduces the width of the hydrogen line significantly since collision (spin-spin exchange) broadening is reduced. The atomic line Q is thus increased and the cavity pulling effect reduced correspondingly. Since the principal cause for long-term instability is due to cavity-pulling, the long-term stability is improved.

A serious disadvantage of the passive hydrogen standard is the poor performance for short averaging times since the signal-to-noise ratio is reduced appreciably below that in the active maser. The only change made in the maser was a reduction in the atomic flux; hence, the maser still operates as a negative temperature device. However, the noise generated is proportional to the magnitude of the negative temperature, and this may be quite large when the maser stops oscillating. However, the crystal oscillator that is locked to the maser determines the short-term stability that may be made very good by proper design.

The passive hydrogen standard differs from an absorption cell in a subtle way. Since no change except beam intensity was made, the atoms are still emitting microwave power. The emission, however, is far below the level required to overcome cavity losses, and the device may appear to operate like an absorption cell. Figure 2 shows the actual amplitude and phase characteristics of the passive standard as compared with an absorption cell, and demonstrates that the term "passive hydrogen maser" is not a misnomer.

The Q of the cavity may be reduced to reduce the cavity pulling effect even more in the passive maser. A small-sized frequency standard has been made in which a dielectrically loaded cavity is fabricated such that the inner wall of the cavity, when coated with teflon, forms the storage bulb. The practical problem here is to be able to find a low-loss dielectric with the desired dielectric constant. Alumina, fused quartz, and sapphire are being evaluated.

In the hydrogen maser, a fractional frequency stability of the order of 10^{-15} requires that the cavity dimensions be held constant to a fraction of an Angstrom, which is 10^{-10} meter or roughly the diameter of a hydrogen atom. The passive maser seeks to relax this requirement by an order of magnitude or more.

3. Standards employing atomic fine-structure transitions. Historically, the fine structure in atomic spectra was observed long before hyperfine transitions. The observation was that optical radiation from atoms often consisted of a multiplicity of regularly-spaced spectral lines. Quantum mechanics explained the spectra in terms of the magnetic moment of the electron due to its orbital motion interacting with the magnetic moment due to electron spin. Since magnetic moments of electrons and protons are inversely proportional to the mass of the respective particles, the magnetic moment for electrons is roughly 1800 times stronger than for protons. Thus the fine structure splitting of spectral lines is in the submillimeter range, and high Qs are achievable.

A working standard employing the fine structure has yet to be realized for several reasons:

1. The atom selected must have no nuclear magnetic moment lest the sharp resonance line be smeared by hyperfine transitions.
2. The orbitally excited state must be sustained during the spectroscopic observation to realize the benefits of the high Q.
3. An atomic beam type of device is difficult to implement at the high frequencies involved because the waveguides and cavities are extremely small and necessitate quasi-optical techniques.
4. The orbitally excited state must have a sufficiently long lifetime so as to appear to be in a stationary state during the spectroscopic measurement. Such metastable states in atoms are found only through difficult laboratory investigations. Magnesium and calcium are being studied for this application.

4. **Trapped ions.** As mentioned in the discussion of hyperfine transitions, the resonant frequencies are in the microwave region due to the weak nuclear magnetic moments of the light nuclei in which nuclear spins cancel in pairs, and it is necessary to find atoms with an odd number of nuclei so that one unit of spin will be uncancelled. As the nucleus gets heavier, however, it is possible for more than one unit of spin to remain uncancelled if such a configuration turns out to have a lower energy. Such an atom with a single valence electron would behave like hydrogen, rubidium, and cesium, and might give a good atomic frequency standard because of the high Q.

The trapped ion technique creates an atom to meet these requirements. To illustrate with a specific example, mercury (Hg 199) has two valence electrons with a ground state of spin zero. If one of the electrons is removed, there results an ion with a single valence electron and a nucleus with spin 1/2; it has the hyperfine characteristics of atomic hydrogen, except that the zero-field splitting is 40 GHz rather than 1.4 GHz. An electrostatic field of the proper size and shape is used to trap the ion in a microwave spectroscope. The trapping of an ion is difficult and considerable effort will be required before a frequency standard can be realized (Ref. 4).

III. Conclusion

From the preceding, one may determine that within the next five years short-term stability will be most readily achieved with a quartz oscillator; medium-term by a rubidium vapor passive standard, a quartz oscillator, or a hydrogen maser; and long-term stability by a passive hydrogen maser, or a cesium standard. There are, of course, unknowns in this evaluation. An active hydrogen maser at high flux still out-performs in short term the best quartz oscillator; it may, in its cryogenic form, be better in the long term than the passive hydrogen maser.

The cryogenic systems (i.e., the superconducting cavity oscillator, the cryogenic hydrogen maser) are as yet unproved, untested, and uncertain. The known best short-term stability is available from the superconducting cavity stabilized oscillator, the hydrogen maser, and the quartz oscillator. Medium-term stability, in most oscillator systems, is at best a compromise between long- and short-term optimized oscillators. The most likely candidates at the moment appear to be the hydrogen maser and (with some uncertainty) the quartz oscillator and the superconducting cavity.

Long-term stability is an ephemeral, difficult achievement reached by selection of oscillating systems with very little aging and environmental influences and careful engineering to isolate them from the outside world. Because of the times required to test and develop such standards, very little can be forecast about future performance. The best presently available unit is the cesium standard; the most promising candidate among units being developed is the passive hydrogen maser; a possible future candidate may be the cryogenic hydrogen maser.

Combining several oscillators with different regimes of optimum performance is a straightforward systems problem. One example, which would produce the best possible frequency standard system using presently available standards, would combine a superconducting cavity in the $\tau < 300$-sec area, an active hydrogen maser for the $300 < \tau < 30000$-sec regime, and a cesium standard for the $\tau > 30000$-sec regime. Such a system is shown in Fig. 3a. The performance (hypothetical) for the three standards in Fig. 3b is combined in this system to produce the heavy curve, the best of all possible frequency standards, for the nonce.

References

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3. McGuigan, D. F., and D. H. Douglass, "Clocks Based Upon High Mechanical Q Single Crystals," in *Proc. 31st Annual Symposium on Frequency Control,* 1977, pp. 616-619.
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Table 1. Characteristics of hydrogen, cesium, and rubidium atomic frequency standards[a]

Element	Nuclear spin	Electron spin	Hyperfine separation resonance frequency, Hz	Second-order magnetic-field dependence, Hz, where H is in oersteds	Typical Qs in frequency standards
Hydrogen 1	1/2	1/2	1,420,405,751.768	2750 H^2	10^9
Rubidium 87	3/2	1/2	6,834,682,605	574 H^2	10^7
Cesium 133	7/2	1/2	9,192,631,770	427 H^2	10^7 to 3×10^{8}[b]

[a] Data was extracted from references (2) and (5).

[b] The Q for cesium standards is for portable devices (10^7) and large laboratory (e.g., NBS, standards (3×10^8)).

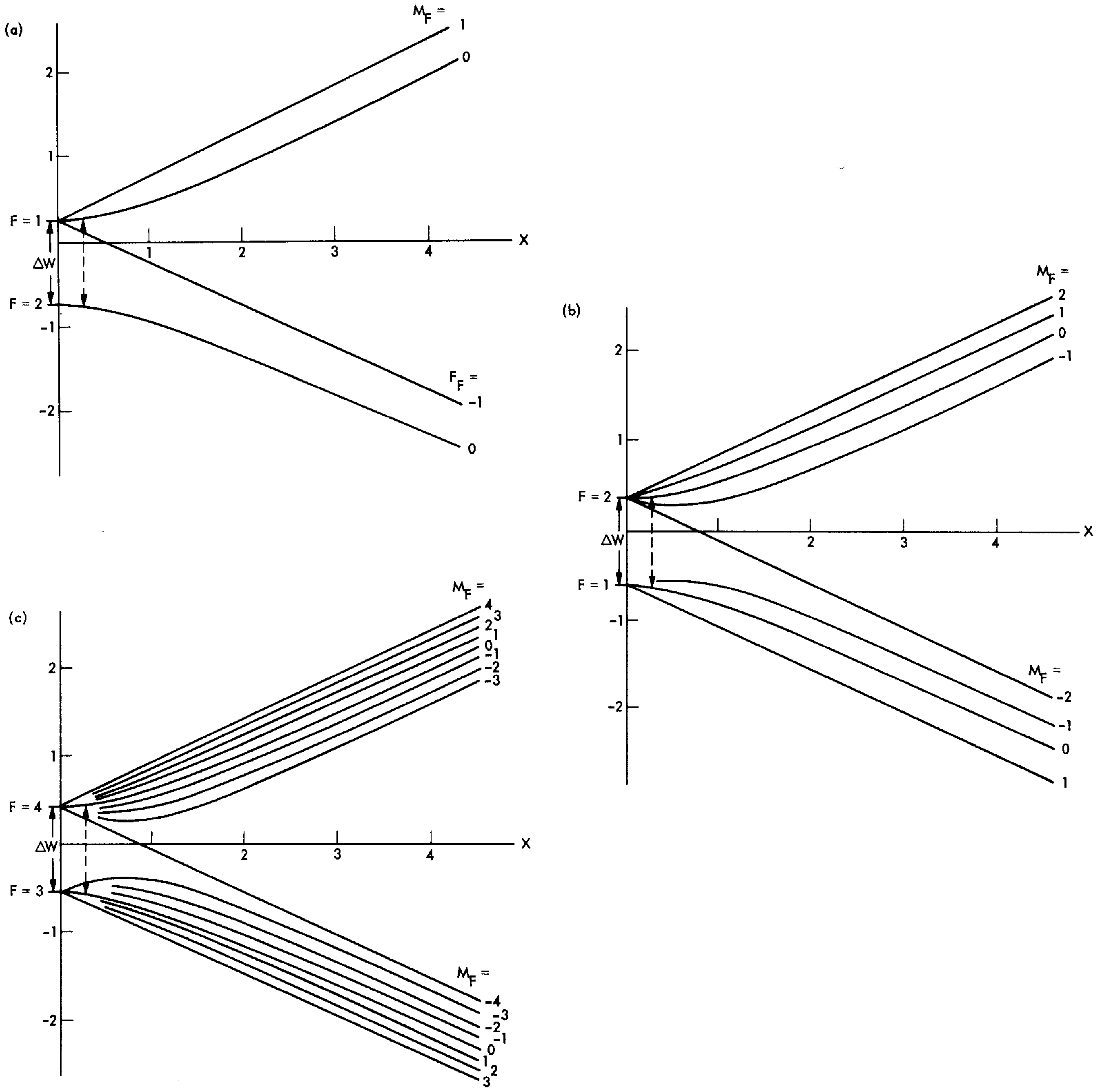

Fig. 1. Hyperfine structure: (a) atomic hydrogen, with nuclear spin $I = 1/2$, $\nu_0 = \Delta W/h$ = 1,420,405,751 Hz; (b) ^{87}Rb, with nuclear spin $I = 3/2$, $\nu_0 = \Delta W/h$ = 6,834,682,605 Hz; (c) ^{133}Cs, with nuclear spin $I = 7/2$, $\nu_0 = \Delta W/h$ = 9,192, 631, 770 Hz

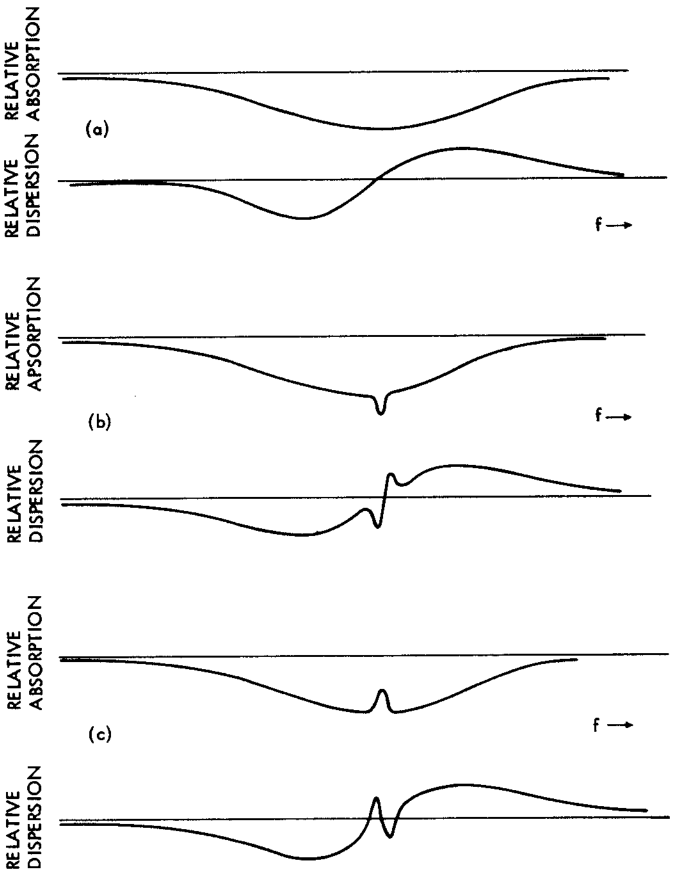

Fig. 2. Absorption and dispersion: (a) cavity only; (b) cavity with absorbing atoms; (c) cavity with emitting atoms

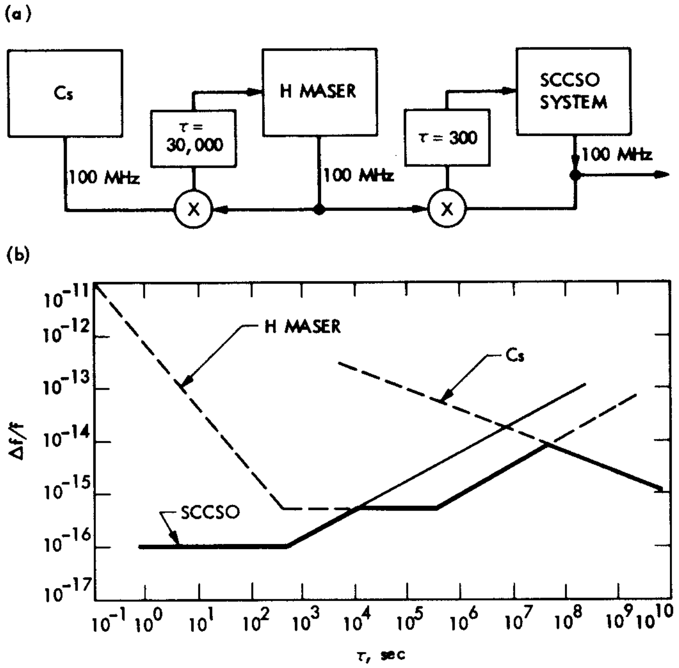

Fig. 3. Combining system for frequency standards: (a) block diagram; (b) performance of individual standards and of combining system