N90-19972

A REVIEW OF ATOMIC CLOCK TECHNOLOGY, THE PERFORMANCE CAPABILITY OF PRESENT SPACEBORNE AND TERRESTRIAL ATOMIC CLOCKS, AND A LOOK TOWARD THE FUTURE

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I. INTRODUCTION — A REVIEW OF ATOMIC CLOCK TECHNOLOGY

Clocks have played a strong role in the development of general relativity. The concept of the "proper clock" is presently best realized by atomic clocks, whose development as precision instruments has evolved very rapidly in the last decades. To put a historical prospective on this progress since the year AD 1000, Figure 1 shows the time stability of various clocks expressed in terms of seconds of time error over one day of operation. This stability of operation must not be confused with accuracy. Stability refers to the constancy of a clock operation as compared to that of some other clocks that serve as time references. Accuracy, on the other hand, is the ability to reproduce a previously defined frequency.

Table 1 outlines the issues that must be considered when we talk about accuracy and stability of clocks and oscillators. The late I. I. Rabi and J. R. Zacharias, in their work with atomic and molecular beams, were the first to realize that atoms were capable of being used as clocks, and N. F. Ramsey's invention of separated oscillatory fields made possible the first practical cesium clocks. In general, the most widely used resonances result from the hyperfine interaction of the nuclear magnetic dipole moment and that of the outermost electron, which is characteristic of hydrogen and the alkali atoms. During the past decade hyperfine resonances of ions have also been used, as will be seen later. Figure 2 shows, as an example, the hyperfine structure of ^{87}Rb with nuclear spin $I = 3/2$, $\nu_0 = \Delta W/h = 6.834$GHz. Here $\Delta W = h\nu_0$ is the hyperfine separation energy and h is Planck's constant. The principal reason for both the accuracy and the stability of atomic clocks is the ability of obtaining very narrow hyperfine transition resonances by isolating the atom in some way so that only the applied stimulating microwave magnetic field is a significant source of perturbation. It is also important to make resonance transitions among hyperfine magnetic sublevels where separation is independent, at least to first order, of the magnetic field. In the case of ^{87}Rb, shown in Figure 2, this transition is between the $F = 2$, $m_F = 0$ and $F = 1$, and $m_F = 0$ hyperfine levels. In the case of ions stored in traps operating at high magnetic fields, one selects the trapping field to be consistent with a field-independent transition of the trapped atoms.

a) Detecting Atomic Transitions

Several techniques are used to detect the transitions in the hyperfine levels of atoms (or ions) so that information can be obtained to control the frequency of signal applied to the atoms or ions. The original technique is based on molecular beam apparatus where the linewidth of the atom was narrowed by extending the distance over which the microwave field is applied. The presence or absence of transitions is determined by the change in the effective dipole moment of atoms, which is observed by changes in the trajectory of atoms when they travel through highly inhomogeneous magnetic fields.

TABLE 1

CONCEPTS OF ACCURACY AND STABILITY

ACCURACY	STABILITY
• DEPENDS ON CONTROL AND UNDERSTANDING OF SYSTEMATICS	• A STATISTICAL CONCEPT allan variance <-----> SPECTRA
• VERY NARROW LINEWIDTHS	• A QUESTION OF NOISE/SIGNAL RATIO
• HIGH TRANSITION FREQUENCY	$\sigma(\tau) \propto \frac{1}{Q_{line}} \frac{\text{NOISE POWER}}{\text{SIGNAL POWER}}$
• WELL DETERMINED OFFSETS	$\sigma(\tau) \propto K\,\tau^{-1/2}$
• LOW LEVEL PERTURBATION FROM AMBIENT EFFECTS	• WE MUST NOT IGNORE NOISE OUTSIDE THE ATOMIC SYSTEM (e.g., receivers)

• ACCURACY CAPABILITY IS LIMITED BY THE STATISTICAL COMBINATIONS OF ALL UNCERTAINTIES

OBVIOUSLY - TO REALIZE *ACCURACY* CAPABILITY WE MUST ALLOW ENOUGH AVERAGING TIME TO DEVELOP *STABILITY*, AND THIS TIME PERIOD MUST BE COMPATIBLE WITH THE EXPECTED TIME VARIATION OF SYSTEMATIC PERTURBATIONS.

In the case of masers and lasers we observe the microwave signal or the light that is coherently generated by an aggregate of stored atoms (or ions) undergoing self-stimulated transitions from regeneration or reflection of energy in a cavity (or between mirrors in the case of lasers). In the case of hydrogen masers, the signal is the familiar 21cm line of radio astronomy. This very low per signal (-100dBm) at 1,420,405,751.768Hz, is amplified and is used with synthesizers to control the phase of a 100MHz voltage-controlled, crystal oscillator.

In the past decade, with the advent of lasers that can be tuned to optical transitions involved in these "clock-like" ions and atoms, it has been possible to change the distribution of the population in the hyperfine levels by selectively emptying the unwanted hyperfine ground state levels of atoms (or ions) by "pumping" these atoms to higher energy states. This technique, which was pioneered by Kastler and Dehmelt in the 1950's, also allows several useful possibilities for very sensitive detection of hyperfine transitions made by the application of microwave signals.

In summary then, we presently use three methods to detect the transitions: 1) we can observe the energy of transition; 2) we can observe a change in atomic dipole moment; and 3) we can observe, by optical methods, whether or not atoms have made transitions by exciting optical transitions from the selected ground state hyperfine levels to higher states and observing this process by monitoring either the absorption of the exciting light or the fluorescence of the atoms making spontaneous transitions from the upper state back down to a lower energy state.

b) The Quest for Narrow Resonances

Resonance linewidths of transitions depend on the length of time we can observe the atoms or ions in a relatively unperturbed manner. This essential feature of all atomic clocks has been a major focus of attention in the development of atomic clocks. Historically, the development began with atomic beams and cesium beam devices that have been in production commercially since the 1950's. The success of the cesium clocks led, in 1967, to the adoption of the hyperfine transition to Cesium 133 as the basis for the definition of the second. The second was defined as 9,192,641,770 periods of oscillation of the ground state hyperfine transition of ^{133}Cs. In 1983, the meter was defined in terms of the velocity of light as the distance light travels in 1/299,792,453 of a second. This makes possible a permanent value for ε_o, the permittivity of free space in the SI system, where the velocity of light is given as $c = (\mu_o\varepsilon_o)^{-1/2}$. (The SI value of μ_o has always been exactly $4\pi \times 10^{-7}$.)

Atomic beam devices depend on the time of flight atoms across the microwave interaction region. Even when low velocity atoms in the beam are selected, this type of apparatus in the primary standards laboratories is generally a few meters in length. Commercially available cesium beam devices are much shorter but still some 25cm in length. Figure 3 is a schematic sketch of a cesium beam tube resonator.

In the mid-1950's Dicke, Bender, and Carver found that alkali atoms could be immobilized in a glass cell filled with gas to buffer the atoms' thermal motion. Combinations of nitrogen and various inert gases can be chosen to reduce the temperature coefficient of the hyperfine resonance line of atoms when they are subject to collisions with buffer gases. This line-narrowing technique, in combination with optical pumping, led to the development in the late 1950's of commercially available rubidium gas cell devices and has since led to a very high level of production of rubidium gas cell standards with performance much superior to crystal controlled oscillators and very well suited to hostile vibration environments. These are small, lightweight, and frugal in their power requirements.

In 1960, Kleppner, Goldenberg, and Ramsey invented a storage technique that would work with atomic hydrogen, which led to their invention of the hydrogen maser. The heart of the maser is a quartz, Teflon-lined storage bottle, located in the uniform magnetic field region of a cavity resonator. Atoms enter, at thermal velocities of about 2×10^5 cm/sec, through a small hole, rattle about inside the bottle, and randomly emerge through the same hole. A storage time of about 5 seconds can be achieved with spherical bulbs having a volume of about 3 liters before oscillation is inhibited by wall collision effects that recombine the atoms or dephase the oscillating hyperfine interaction of the atoms. The dephasing effect is also accompanied by an average phase retardation per collision, which produces a wall collision frequency shift in the output signal. This frequency shift depends on the collision rate of atoms with the wall surface, and hence on the surface texture, which, though stable over time, varies from bulb to bulb depending on how it is coated. In our experience, the variability can be as large as 5 parts in 10^{13}. This lack of reproducibility limits the usefulness of the hydrogen maser as a primary standard.

The variability of the wall shift and the nature of hydrogen interactions with surfaces of various materials is the subject of ongoing study at SAO.

Another method of storage involves the use of ions in two forms of electromagnetic traps. The Penning trap uses a strong, static, magnetic field and an electrode configuration as shown in Figure 4. The residual motion of the ions have two basic frequencies. One is associated with the cyclotron motion of the ion in the magnetic field, the other with the electrostatic fields generated by the electrodes. The Paul traps, shown in Figure 5, works with a superposition of static and oscillating electric fields. This trap has been successfully used in a frequency standard of extraordinary long-term stability, which will be described later.

With the advent of tuneable lasers, it has become possible to use the momentum of absorbed optical photons as a means of slowing down a beam of atoms. The scheme is shown in Figure 6, where atoms (or ions) are shown entering from the left and a laser beam is shining on the atoms from the right. By tuning the light from the laser to be lower in frequency than the optical transition frequency of the atoms (or ions) by an amount equal to the Doppler shift owing to their motion, they will absorb the photons, and in so doing, undergo a change in the momentum of their motion. They reradiate the absorbed energy in random direction and later can reabsorb further energy from the directed beam of photons and, again radiate it; the process continuing many thousands of times for each atom. The result is to slow the atoms (or ions) down to the velocity of recoil of its randomly emitted photons. In the case shown in Figure 6 for magnesium 25, the atoms are slowed down, or cooled, to a kinetic temperature of 0.05K. It is possible to go even further with this process and to stop atoms or even to reverse their direction! Figure 7 describes a technique for slowing atoms, where the resonance frequency of the atoms is progressively Zeeman-shifted along the beam by the applications of a spatially varying magnetic field, which shifts the energy levels of the moving atoms to keep their resonance in tune with the laser beam and thus continue to absorb energy. Another method that has worked with *both* atoms and ions is to modulate the laser frequency so that groups of atoms, which have Doppler frequencies that follow the modulation, are retarded.

II. THE CURRENT STATUS OF ATOMIC CLOCKS - FREQUENCY STABILITY (1987-1988)

In the past 3 decades there has been an actively continuing program of atomic clock development, and it is, therefore, a bit risky to give an accurate portrayal of the situation at any point in time. Figure 8 is the writer's latest effort at putting together a picture of the frequency stability of a number of clocks (or oscillators) in terms of the Allan variance. The Allan variance, $\sigma(\tau)$, is a measure of the one-sigma value of the fractional frequency departure between pairs of adjacent frequency measurements, each of duration τ. The behavior of $\sigma(\tau)$ with τ depends on the spectral distribution of the frequency (or of the phase) fluctuations in the signal from the clock.

At the upper right of the figure is the Allan variance representation of a celestial clock — the millisecond pulsar. The variance data are made from the residuals of the frequency measurements after removing a linear drift rate of 9.07 parts in 10^{15}. As more and more data accumulate, and as more of these clock-like objects are discovered, I become increasingly sure that a very powerful timing resource for testing general relativity and for studying cosmology will become available.

Below the pulsar line is a line representing the specification for spaceborne clocks used in the United States Global Positioning System (GPS), which is used for worldwide navigation and time transfer. to the left of the GPS specification are the specifications used to define the performance of small commercially available rubidium gas cell standards and commercially available cesium beam standards. Near to this line is performance observed from recently developed cesium beam clocks qualified for spaceborne use that have been developed and built by Kernco, Inc., Danvers, Massachusetts.

The performance of two newly developed clocks, that have been developed with the intention of eventual use in space, is shown below the GPS specification. Of these, upper trace is the Allan variance of the EG&G (Salem, Massachusetts) rubidium gas cell frequency standard with, and without, removal of its frequency drift. Slightly below the EG&G, rubidium gas cell data are data made from a small hydrogen maser developed by the Hughes Research Laboratory in Malibu, California. This maser operates with a very small storage volume located within a capacitively loaded resonator of small dimensions. In order for this system to oscillate, the quality factor, Q, of the resonator is enhanced by external amplification and feedback.

To the right of, and slightly below these new space clocks, is an estimate of the day-to-day to month-to-month variation of the international atomic time scale, TAI, at an Allan variance level slightly below 1 part in 10^{14}.

Below the TAI line is a very long plot that describes the behavior of the relative stability of two ^{199}Hg trapped-ion clocks, developed by Hewlett Packard by Cutler and his associates. These are located at the U.S. Naval Observatory in Washington, D.C. These clocks use the 40.5 GHz transition in the ground state of singly ionized mercury 199 atoms in a Paul trap. The residual motion of the cloud of trapped ions is cooled by collisions with helium gas admitted into the trap at pressure of about 15^{-5}Torr. This cools the atoms from a kinetic temperature of about 6000K to about 300K. The undisturbed lifetime of the atoms in the trap is about 40 minutes. The magnitude of the second-order Doppler frequency shifts, owing to the residual motion shown in Figure 4, is about 2 parts in 10^{12}; predictable to about 2 parts in 10^{13}. This is presently thought to be the major source of inaccuracy of these remarkably stable clocks.

The lowest trace shows the behavior of hydrogen masers (in this case the VLG series masers built by SAO), of the 23 which have built; 21 are in operation in observatories and tracking stations worldwide. A spaceborne version of this maser was developed and flown in the 1976 redshift test, and the design of this maser is presently being revised for long-terms (70 year operation in space. This maser's stability reaches a best value of about 4 parts in 10^{16} at about 10^3 seconds. For longer periods, the stability is degraded chiefly by systematic variations caused by thermal perturbations and by a very slow monotonic increase in the cavity resonance frequency.

Figure 9 shows a cross-section of the redeveloped SAO hydrogen maser for spaceborne use. This maser, since it has the same design parameters as the VLG masers, is expected to have comparable stability.

The dimensions, weights, and power requirements for these spaceborne clocks are summarized in Table 2.

TABLE 2

SIZE, WEIGHT AND POWER CONSUMPTION OF SPACEBORNE CLOCKS

	DIMENSIONS	WEIGHT	POWER
EG&G Rubidium Gas Cell Standard	11.3 x 21.2 x 17.5	4.5	13
Kernco Cesium Beam GPS Standard	20.3 x 3.3 x 38	12.2	27
Hughes Hydrogen Maser under Development	32.8 x 22.6 x 58.9	23	50
SAO Hydrogen Maser under Development	421cm. dia x 85.3	44	50

III. TRENDS OF DEVELOPMENT FOR FUTURE CLOCKS

The advent of tuneable lasers and the application of modern, low-temperature techniques have provided the stimulus for a number of fundamental changes in clock technology. It is now possible to change the states of atoms selectively and make more efficient use of atomic beam techniques. For example, in the cesium beam frequency standard shown schematically in Figure 3, only one of the 16 hyperfine magnetic sublevels is used to operate the clock. The others are scavenged away by cesium "Getters." Furthermore, the magnetic state selecting system will only deflect a narrow range of velocities. The resulting efficiency in the use of atoms is very small: only a few percent. The first magnet can be replaced by laser-induced transitions that pump nearly all the atoms into the desired $F = 4$, $m_F = 0$ transition. While the microwave interaction region can remain the same, the detection of the presence (or absence) of microwave transitions again can be done using the laser to pump atoms that have made "clock" transitions to the $F = 3$, $m_F = 0$ to an upper energy state. The presence (or absence) of such atoms is detected by observing the optical fluorescence of transitions back to the ground state. Besides improving the efficiency of flux usage and so improving the signal-to-noise ratio in cesium beam standards, and hence their stability, these laser techniques also make possible a substantial improvement in their accuracy. The second-order Doppler frequency correction is difficult to determine in the distribution of velocities of the beam in the present magnetically state selected primary frequency standards and this causes the principal source of uncertainty in the error budget that defines accuracy capability. Using laser techniques, there is very little disturbance in the easily predicted velocity distribution of the beam and the Doppler correction is far more accurately determined.

Better state selection techniques, using permanent magnets, are also available for atomic hydrogen masers. Normally the maser is operated with a single hexapole (or other multipole) magnet which focuses both the $F = 1$, $m_F = 0$ and $+1$ hyperfine sublevels of ground state atomic hydrogen into the storage bulb of the maser. The inclusion of the unwanted $F = 1$, $m_F = +1$ state essentially doubles the population of atoms, the interatomic collision rate and, consequently, the rate of spin-exchange quenching of the oscillation. Not only is the storage lifetime adversely affected, systematic frequency shifts will result if collisions occur among atoms that are not symmetrically distributed among the $F = 1$, $m_F = +1$ and -1 states. Changes in the population of these states can result from changes in the magnetic field seen by the beam as it travels from the magnet to the storage bulb and, in practice, this sensitivity to ambient magnetic fields is far more serious than the residual second-order magnetic field shifts in the $F = 1$, $m_F = 0 \rightarrow F = 0$, $m_F = 0$ transition that are very well attenuated by magnetic shields surrounding the maser cavity-interaction space.

It is possible to eliminate the unwanted $F = 1$, $m_F = +1$ state by using adiabatic fast passage (AFP) technique to the population in the $F = 1$ manifold as shown in Figure 10. The beam is then refocussed into the maser bulb by a second magnet twice the length of the first. The inversion is performed by a combination of r.f. and d.c. fields applied to the beam as it passes through the "AFP region" shown in the figure. We are using this new state selection system in a new design of SAO maser.

Another program underway at SAO is research with an atomic hydrogen maser operating at temperatures below 1K using superfluid liquid helium to coat the surfaces of the hydrogen storage volume. So far, three groups of researchers have operated such masers: at MIT, at the University of British Columbia, and at Harvard/SAO. The maser technique allows extremely high precision measurements to be made of low-temperature, hydrogen-hydrogen, hydrogen-helium interactions both in the gas and in the storage vessel and on the surfaces of the storage vessel. From the viewpoint of clock technology, there appears to be an excellent possibility of producing signals with stability in the 10^{-18} region because of the combined benefits of the following low-temperature effects:

(1) The intrinsic storage time is hours in duration;

(2) Thermal noise, kT, per unit bandwidth is reduced;

(3) Both the collision cross-section and the velocity of the hydrogen atoms are smaller (the effective collision rate is reduced by a factor of about 500 so higher power can be obtained in the master output);

(4) Magnetic problems can be very effectively reduced using superconducting shields; and

(5) The stability of components is much better at low temperatures.

Figure 11 shows the stability expected from the SAO AFP maser and the cryogenically cooled maser.

In the fields of trapped ion standards using laser technology, the projected improvements expected by the Time and Frequency Research laboratory at the Jet Propulsion Laboratory is shown in Figure 12. The improvements shown are for Mercury 199. Work on a trapped ion system using Mercury 201 is in progress at the National Bureau of Standards and the expected stability of this device is shown by the dashed line.

The use of superconducting cavity resonators makes possible superb "fly wheel" oscillators to replace the presently used crystal-controlled oscillators. The combined stability of such an oscillator, locked to a mercury ion resonator with a lock loop time constant of about 1 hour, is shown in the heavy bottom line of Figure 12.

IV. CONCLUSION

One way to assess the potential usefulness of clocks in tests of relativity and gravitation is to express their performance in terms of the limits of their performance on measurements of velocity, distance, and angle. The stability of present (1988) hydrogen masers is shown as the plot labelled $\sigma_y(\tau)$ in Figure 13. Beneath it is another plot labelled $\sigma_{\Delta\tau}(\tau) = \tau\sigma_y(\tau)$, which is the one-sigma expectation of the time error in the next (figure) adjacent time interval, also of duration τ. The inner, right hand, vertical axis measures $\sigma_{\Delta\tau}(\tau)$.

In the case where we use electromagnetic signals to measure distance, the time error $\sigma_{\Delta\tau}(\tau)$ is readily converted to distance error by multiplying by the velocity of light. The right hand outer scale is such a measure of distance error. For example, if we continuously track a space vehicle, the clock-induced error in position expected between tracks made of 10^3 second duration, is about 3×10^2cm (or 0.3mm) with existing hydrogen masers. The one-sigma precision of range-rate measurements made during adjacent measurements of 10^4 second duration is about 1.8×10^{-5}cm/sec.

Angular resolution depends on the capability of time correlating the arrival of signals at both ends of a baseline of known length L (which can also be measured using time signals). The one-sigma resolution of angular measurements made τ seconds apart, is given by

$$\sigma_{\Delta\theta}(L,\tau\theta) = \frac{C\sigma_{\Delta\tau}(\tau)}{L_{\sin\theta}} ,$$

where θ is the angle between the baseline and direction of the signal. For $\theta = \pi$, and a 3,000km baseline (intercontinental distances), $\sigma_{\delta\theta}$ (L, $\tau,\theta) = 6 \times 10^{-14}$ radians. (This, of course, is not realized in terrestrial Very Long Baseline Interferometry owing to tropospheric and other systematic effects.) It is clear that, to realize this precision of measurement, the signal transmission paths both within the tracking station, and beyond its antenna must be free of phase perturbation. A measure of earth's tropospheric and 2 GHz ionospheric perturbation is shown in Figure 14 in terms of the Allan variance. The Ionospheric and tropospheric noise is shown by black dots labelled (a). These data were made during the 1976 SAO/NASA GP-A redshift experiment, using the 4-stage Scout Rocket system with a near-vertical trajectory going to 10,000 Km. altitude.

The ionospheric and tropospheric noise was removed by a 3-link Doppler cancelling system. The frequency residual after removing the predicted gravitational and relativistic effects for the entire 2-hour mission are shown in plot (b). The solid line in plot (b) is the Allan variance of the two ground-based masers used in the experiment. It is clear that the stability comparisons between the space and earth clocks are nearly the same and that the Doppler cancelling system is very effective at removing the combined propagation effects of the atmosphere, ionosphere, and rapidly ongoing path distance.

Future systems will best be operated from spaceborne terminals or space stations and will not be subject to earth's environment. Spaceborne clocks, with cryogenically operated masers or superconducting cavity oscillators, will make possible measurements one to two orders of magnitude more precisely than are shown in Figure 14. The present progress in spaceborne cryogenics is very encouraging. I believe that the most challenging future applications of ultra-high stability oscillators will be in cryogenically-cooled spaceborne systems involved in measuring relativistic and gravitational effects.

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Vanier, J., and Audoin, C., *Quantum Physics of Atomic Frequency Standards*, I.O.P. Publishing Limited, Adam Hilger, London, In press.

DISCUSSION

MALEKI: Let me comment on the mercury 199 clock. The HP clock has the dimensions Bob mentioned -- this is an effort to develop a mercury ion standard at JPL, and we expect our device would have dimensions of 50 cm x 50 cm x 50 cm when fully developed.

SHAPIRO: For the Hg 199 clock made by Hewlett-Packard, what are its physical dimensions and its present cost for an R&D model?

VESSOT: Two 6' racks. $600K +. I talked to Dr. G. M. R. Winkler of the USNO and his comment was: Present state does not allow uninterrupted operation for more than 6 months. No useful short term stability--only useful for 1-10 days of averaging. Used as prototype with an H maser as flywheel for day to day usefulness. "We must have a 10 day stable flywheel" for this system to be useful.

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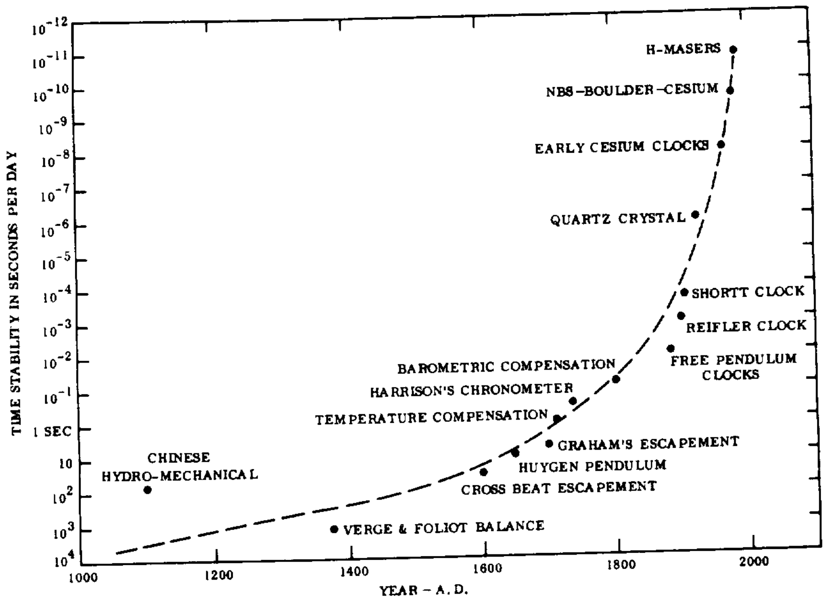
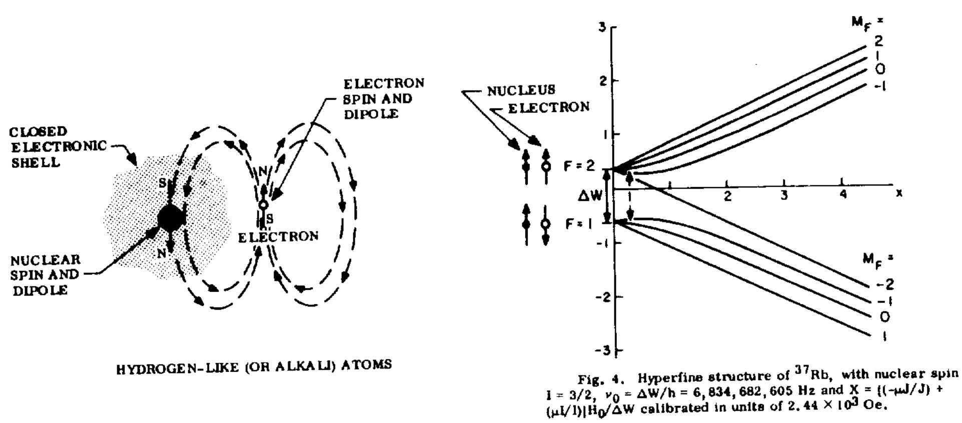


FIG. 1.—Performance of various clocks since 1000 AD



HEISENBERG'S UNCERTAINTY PRINCIPLE

FROM $\Delta E\,\Delta t \simeq h\nu$ AND $E = h\nu$, LONG STORAGE TIME

WE HAVE $\Delta\nu\,\Delta\tau \simeq 1$ AND $\Delta\nu = \frac{1}{\Delta t}$

SMALL FREQUENCY UNCERTAINTY

FIG. 2.—The hyperfine st ructure of a typical alkali atom

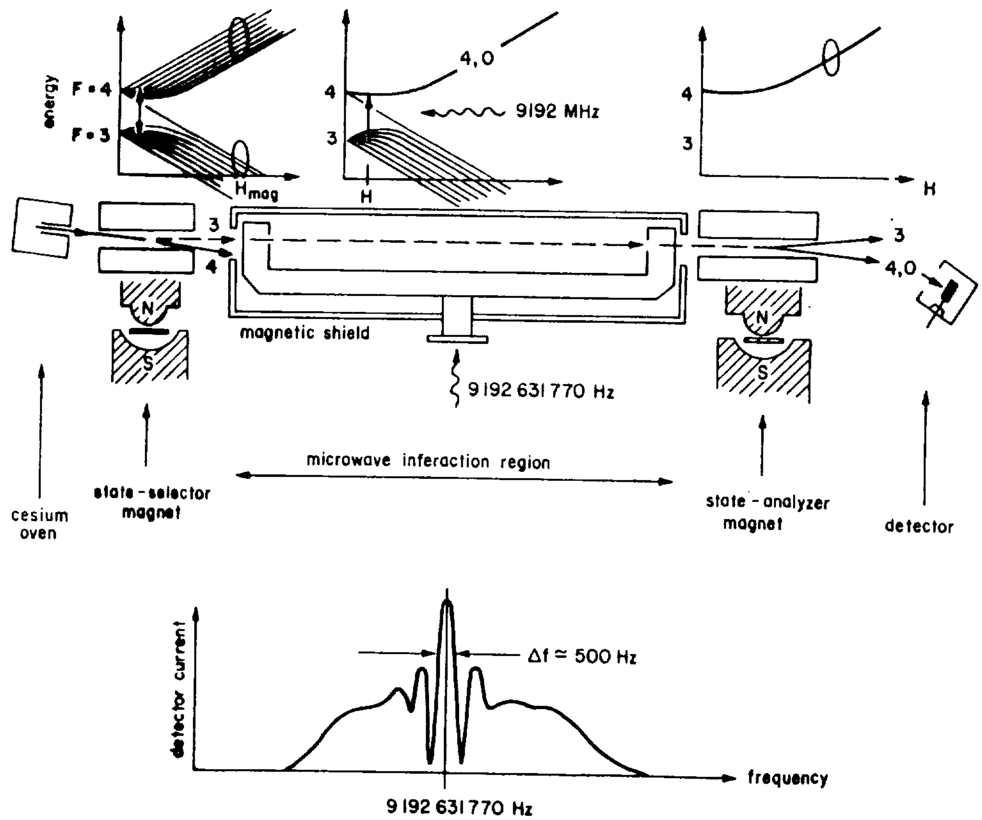


FIG. 3.—Schematic sketch of a cesium beam tube and the hyperfine structure of Cesium 133

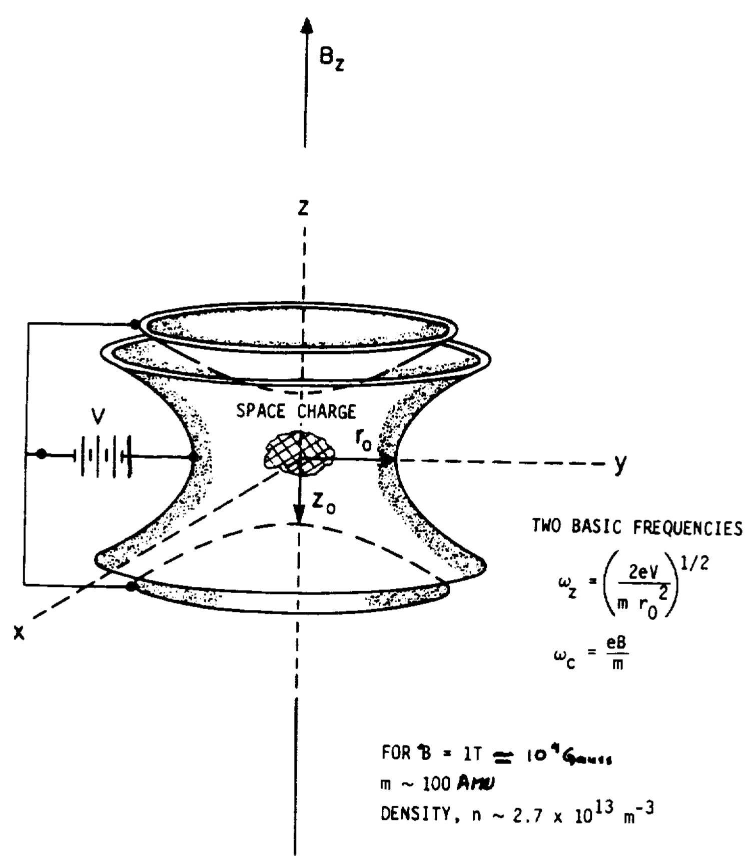
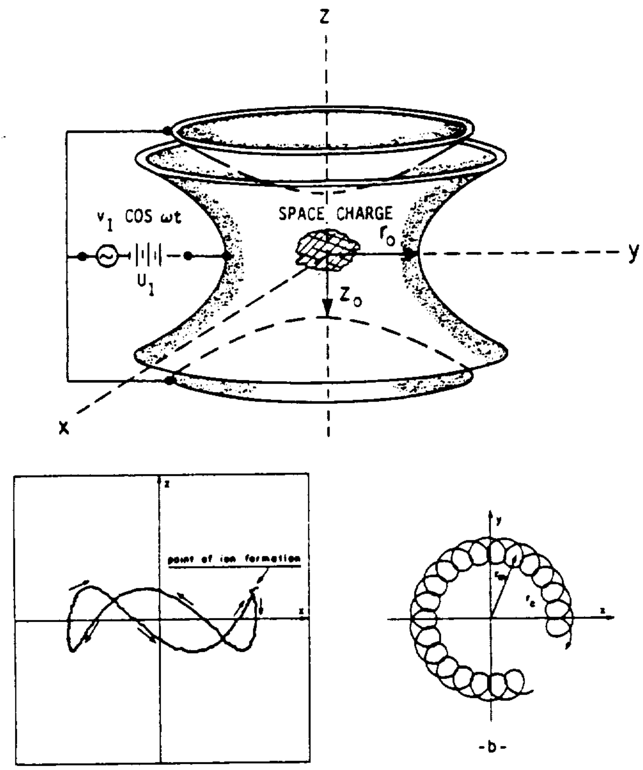


FIG. 4.—The Penning trap



EXAMPLE FOR $^{199}Hg^+$ IONS: POTENTIAL WELL DEPTH ~ 10-30 eV
UNCOOLED SECOND-ORDER DOPPLER $\Delta f/f \sim 5.4 \times 10^{-13}\ (eV)^{-1}$
TYPICALLY, KINETIC ENERGY IS 10% OF WELL DEPTH

FIG. 5.—The Paul trap

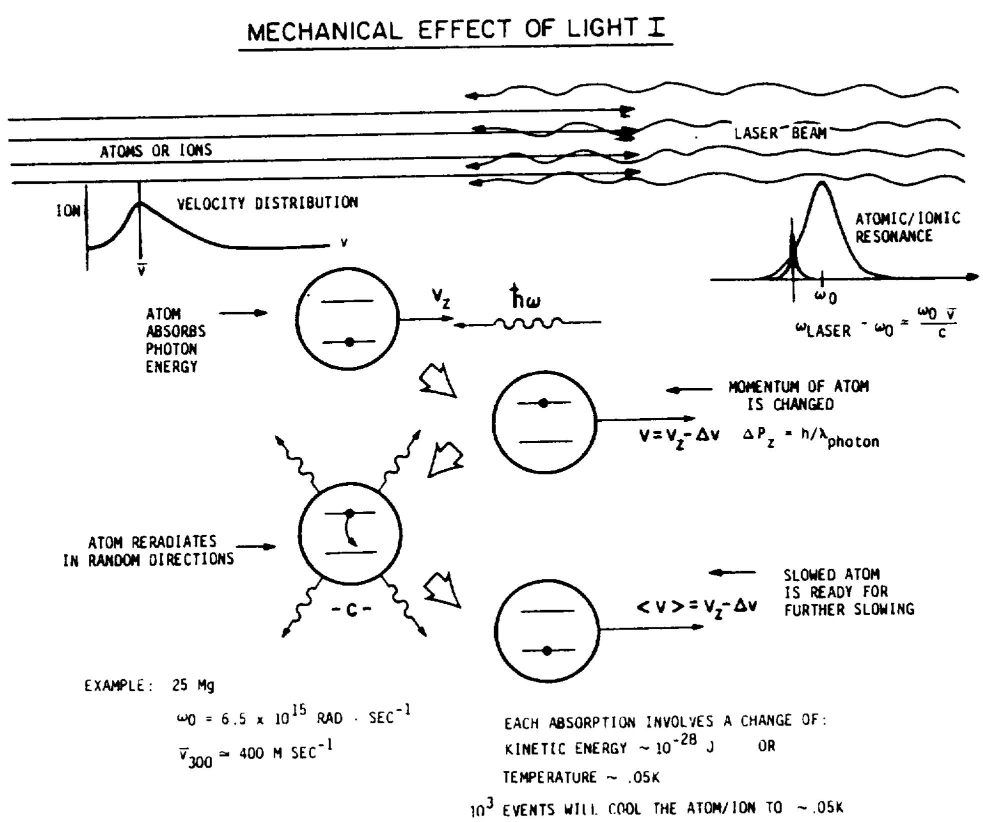


FIG. 6.—Slowing of atoms or ions by absorption of resonant radiation from a beam of light emitted by a laser.

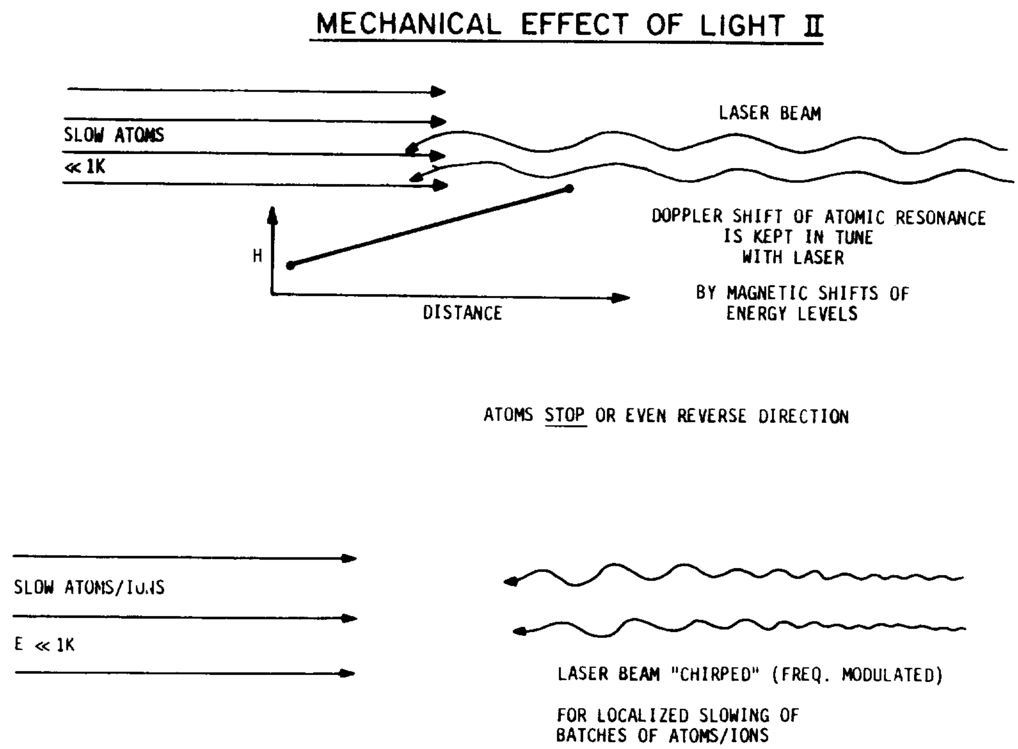


FIG. 7.—Two methods for slowing already very slow atoms

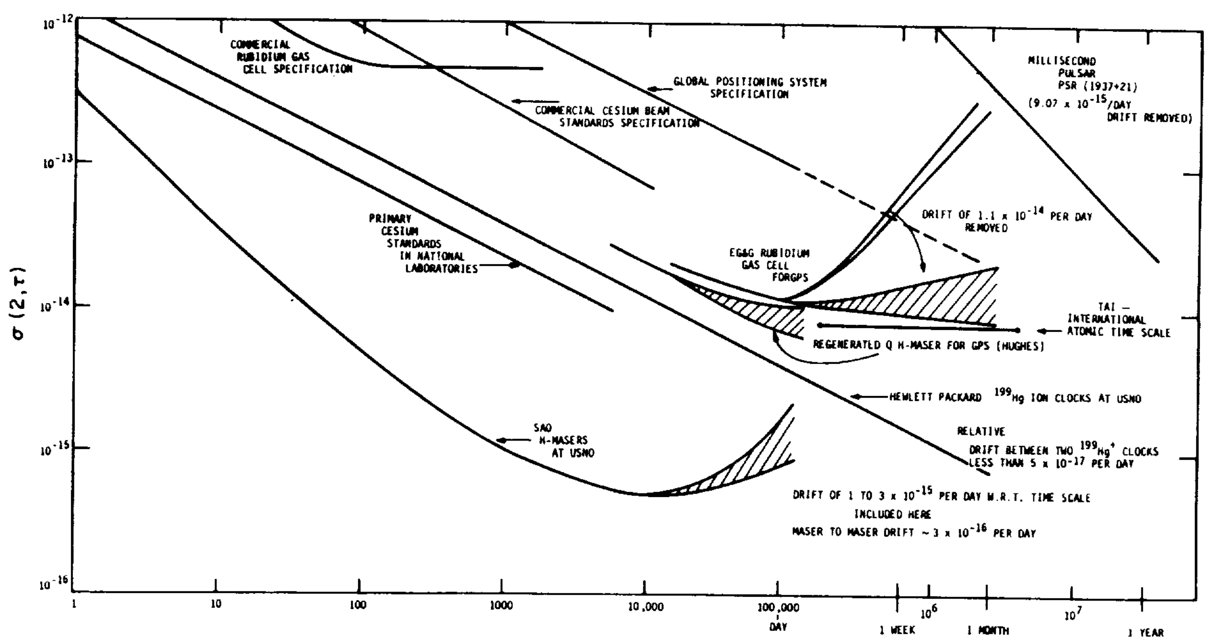


FIG. 8. – An estimate of the 1987-1988 status of the stability of working frequency standards.

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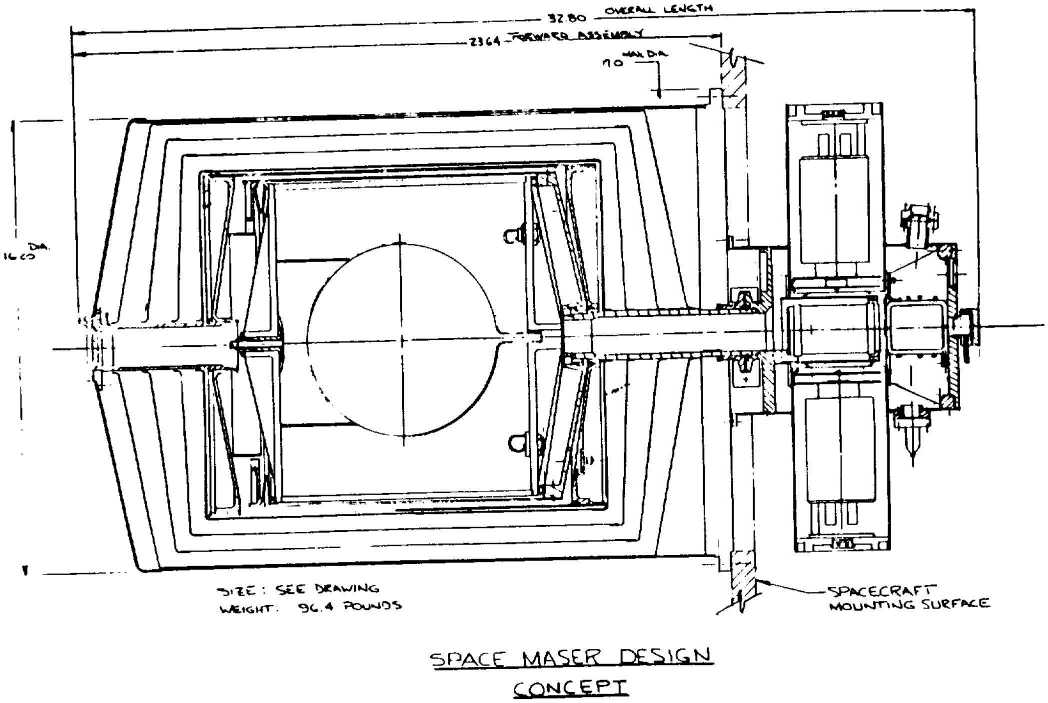

FIG. 9. – Cross sectional view of the SAO space maser. Weight 44 kg., Power 50 watts

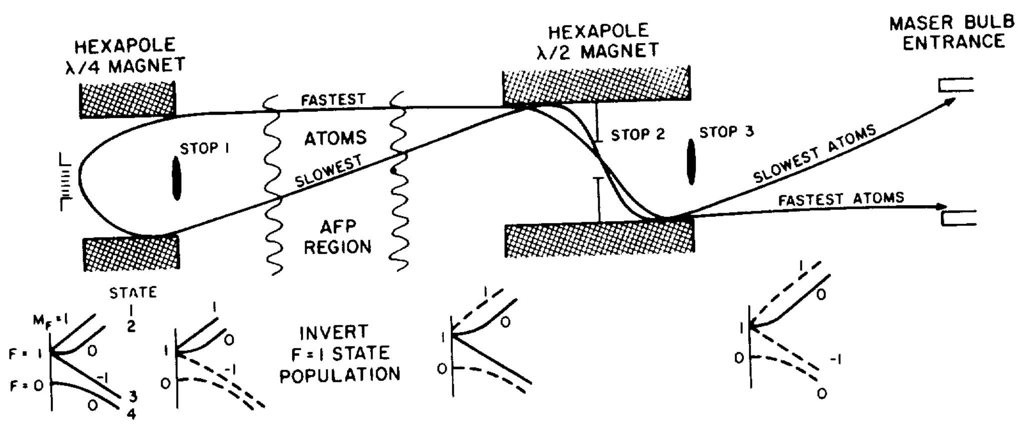

FIG. 10. – Schematic diagram of a state selection scheme to obtain a beam of hydrogen atoms only in the F = 1, $m_F = 0$ hyperfine state.

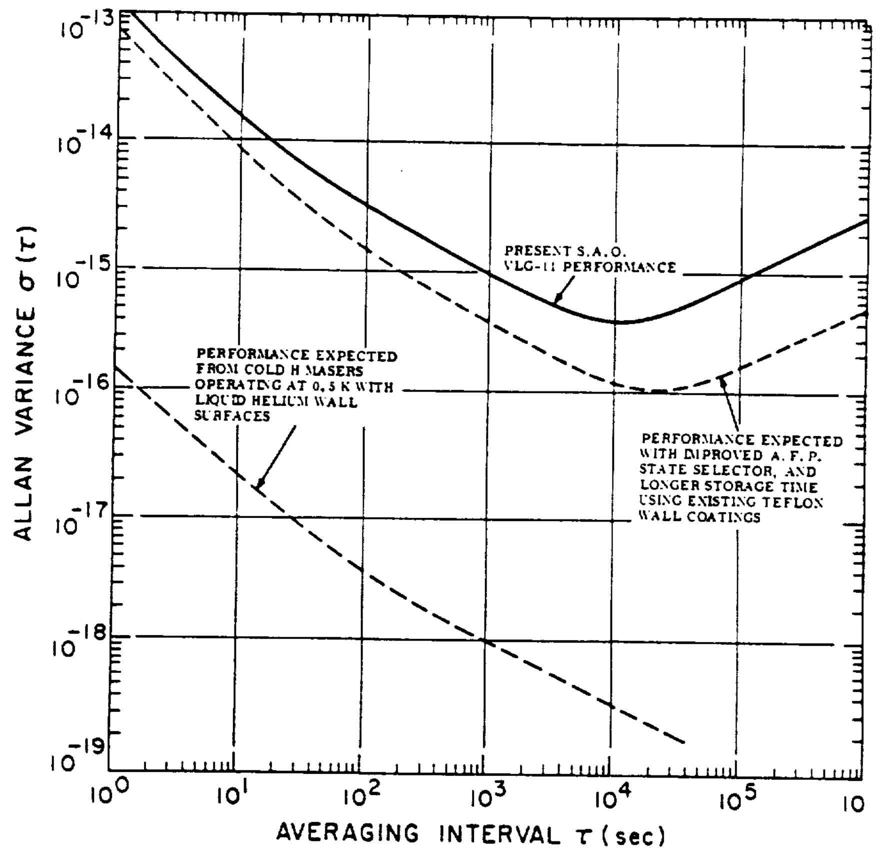

FIG. 11. – Stability expected from the SAO room temperature AFP maser with liquid helium storage container surfaces.

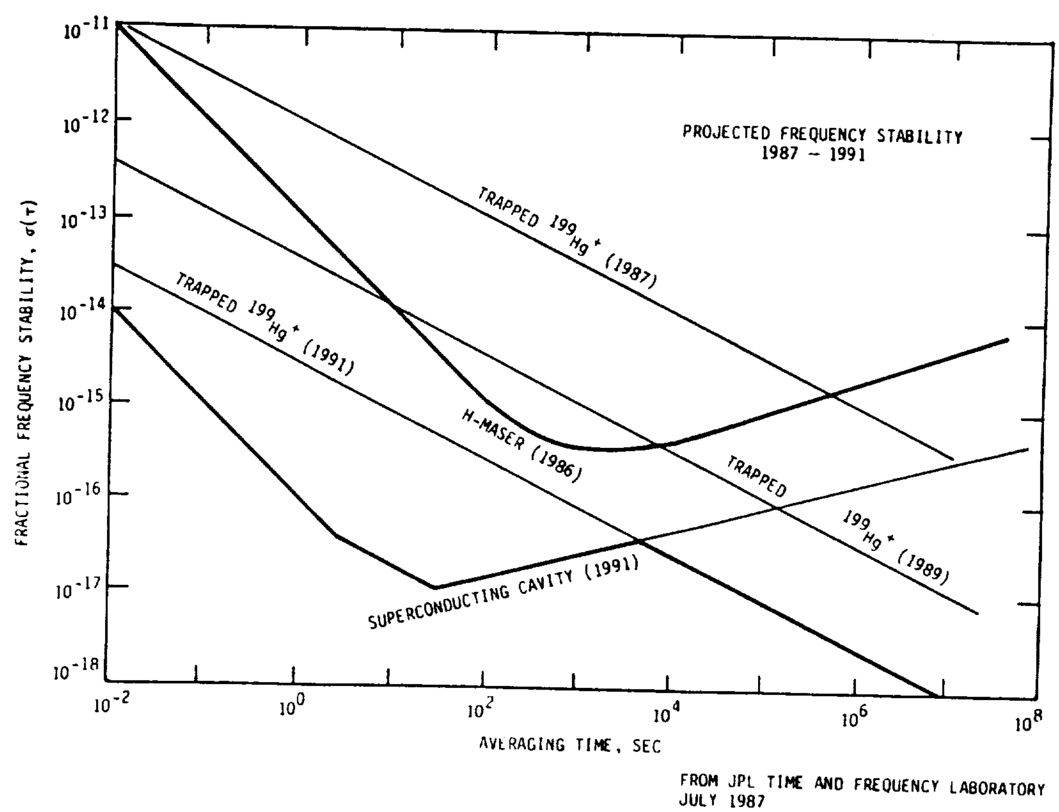

FIG. 12. – Frequency stability projections for trapped ion frequency standards and superconducting cavity stabilized oscillators.

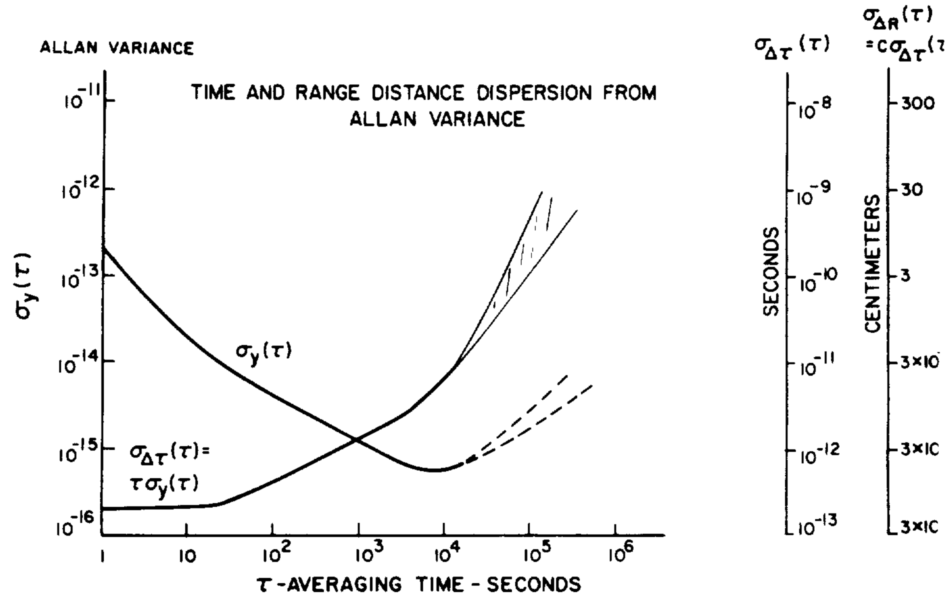

FIG. 13. – Atomic clock range and time error contributions to measurements made using electromagnetic signals.

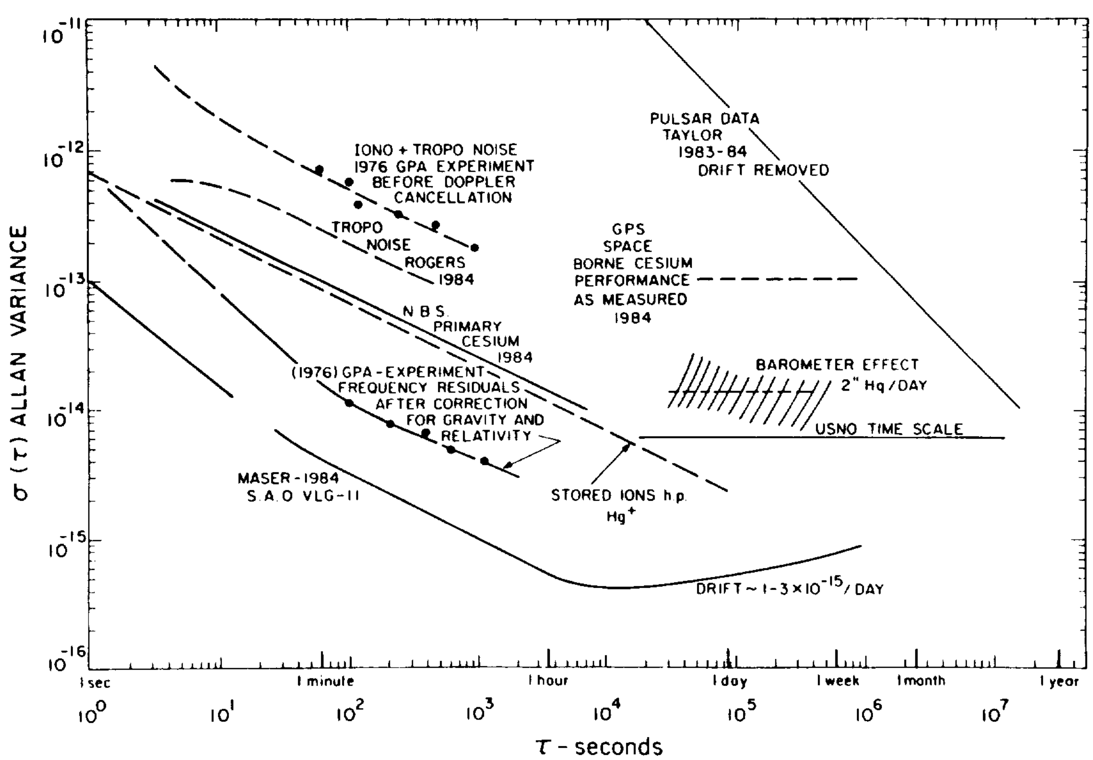

FIG. 14. – The effects of ionospheric and tropospheric fluctuations in earth-to-space signals at 2.2 GHz compared to hydrogen maser stability.