A PASSIVE HYDROGEN MASER FREQUENCY STANDARD

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Abstract

Basic principles, circuit details, and measurements on a passive hydrogen maser frequency standard are presented. The perturbations to the output frequency are discussed and it is shown that the temperature coefficient of the microwave cavity is negligible in this system. Thus the fractional change in the output frequency is about 10^{-13}/K determined by the second order Doppler shift and the wall shift (10^{-14}/K is possible). A temperature stability of only .1 K is required in order to maintain a frequency stability of 1×10^{-14}. Long term stability and reproducability are expected to be improved over other designs because of this greatly reduced sensitivity to changes in temperature and temperature gradients. Measurements indicate a frequency stability of $\sigma_y(\tau) = 2\times10^{-12}\tau^{-1/2}$ for $10s<\tau<4\times10^5 s$. Frequency stability at several days is the best ever reported for a single device. The design of a small passive hydrogen maser using a dielectrically loaded cavity is described. Similar frequency stability is expected for the small maser.

Introduction

The basic design, circuit details, and measurements on a passively operating hydrogen maser frequency standard are presented. The various perturbations affecting the output frequency of such a standard are discussed in detail. It is shown that the temperature dependence of the microwave cavity is negligible in this design, leaving the second order Doppler and the wall shift as the major effects determining the temperature coefficient of the frequency determining element.

As a result, the net temperature coefficient of the output frequency is fractionally equal to 1.3×10^{-13}/K. Calculations indicate that the use of a storage bulb of approximately 17 cm diameter coated with FEP 120 teflon should yield a net temperature coefficient of less than 1×10^{-14}/K near 313 K. With a temperature dependence of 10^{-13}/K, the temperature stability required in order to achieve a long term frequency stability of 10^{-14} is only 0.1 K. This temperature sensitivity is several orders of magnitude less than conventionally oscillating masers, consequently the long term stability and reproducability of this passive hydrogen maser is expected to be much superior to that of present oscillating maser designs. This expectation has been born out for measurement times at least as long as four days. Measurements against an ensemble of nine cesium atomic standards indicate a frequency stability of better than $\sigma_y(\tau) = 2 \times 10^{-12}\tau^{-1/2}$; $10s<\tau<4\times10^5$ s. Measured frequency stability is $2.5 \pm 2 \times 10^{-15}$ at a measurement time of four days. For timekeeping applications, this single standard is predicted to outperform ensembles of tens to thousands of presently available cesium standards. An additional improvement of a factor of 7 in frequency stability is expected.

A small passive maser design based on an alumina loaded TE_{011} cavity will be briefly described. This copper coated dielectrically loaded cavity is approximately 15 cm in diameter and 20 cm in height. Loaded Qs are about 5000. The inside is coated with teflon and serves as the storage bulb, and the cavity also serves as the vacuum chamber. This greatly increases the ruggedness and reduces the weight of the cavity over conventional designs. Using this cavity design with the passive electronics developed for the full sized maser, it is possible to achieve overall dimensions for the frequency standard of about 23 cm diameter and 50 cm long. The frequency stability is expected to be of order $2 \times 10^{-12}\ \tau^{-1/2}$ for measurement times out to at least 10 days.

Concept of the Passive Hydrogen Maser

The passive hydrogen maser is based on the well known magnetic hyperfine separation in atomic hydrogen of 1420405751.77 Hz shown in Fig. 1.[1,2] Atomic hydrogen is produced in an rf discharge, state selected with a hexapole magnet and stored in a teflon coated quartz storage bulb contained within a microwave cavity resonant at the hydrogen frequency. The source, state selector, storage bulb and microwave cavity are nearly identical with those used in conventional oscillating masers.[1,2] The basic concept of the passive design is illustrated in Fig. 2.[3] A probe source is phase modulated at two different frequencies; f_1 corresponding to the nominal half-width of the microwave cavity, and f_2 corresponding to the nominal half-width of the hydrogen resonance. This phase modulated probe signal is then coupled to the microwave cavity containing atomic hydrogen which has been appropriately state selected. The FM spectrum of the probe signal is schematically shown in Fig. 3, where it is seen that the f_2 sidebands primarily interact with the narrow hydrogen line while the f_1 sidebands primarily interact with the broad cavity resonance. The signal transmitted from the cavity is amplitude modulated at frequencies f_1 and f_2. The size and the sign of the amplitude modulation at f_2 relative to the impressed phase modulation is proportional to the frequency offset between the probe oscillator and the center of the hydrogen line. The microwave signal is envelope detected in order to recover the f_2 amplitude modulation which is then processed in a synchronous or phase sensitive detector referenced to the f_2 phase modulation. The resulting error signal is used to correct the probe oscillator so that it is precisely centered on the hydrogen line.

In a similar manner, the f_1 phase modulation simultaneously probes the cavity resonance causing amplitude modulation of the transmitted microwave signal at f_1 which is proportional to the detuning of the microwave cavity from the center of the probe frequency. By processing the amplitude modulation at f_1 in a synchronous detector referenced to the f_1 phase modulation, an error signal is derived which is used to electronically tune the microwave cavity frequency to the probe frequency. The correction time of this cavity servo loop is about 10 s. Measurements indicate that the accuracy of the cavity servo loop is better than 1 Hz and that the stability over a week is better than .1 Hz. This is approximately equal to stabilizing the equivalent electrical dimensions of the 28 cm diameter cavity to 0.3 Å. To our knowledge long term mechanical stability of this precision has never been achieved in a room temperature apparatus, e.g., see reference 4.

Hydrogen Maser Frequency Perturbations

The various effects and their temperature coefficients which can cause perturbations in the output frequency of the passive hydrogen maser are shown in Table 1. The most serious frequency pulling effect in all hydrogen masers is due to cavity mistuning. This effect scales as the ratio of cavity quality factor, Q_c to the hydrogen line quality factor, Q_H, multiplied by the fractional mistuning of the cavity. As we have discussed above, this effect can be virtually eliminated with the cavity servo design used with the passive hydrogen maser.

Assuming $Q_H = 10^9$ and $Q_c = 3x10^3$, one would expect in the absence of the cavity control to observe a frequency change of about 2×10^{-11}/K from the approximately 1 kHz/K change in cavity frequency due to dielectric changes of the quartz storage bulb with temperature. With the new teflon storage bulbs the temperature coefficient of the cavity pulling would be smaller.[5,6] Our measurements described below indicate a closed loop temperature coefficient due to pulling of 10^{-14}/K or less.

The second order Doppler effect causes a shift proportional to temperature with a value of 4.3096 x 10^{-11} at 313 K and a temperature coefficient of 1.3769 x 10^{-13}/K, where the temperature is the average temperature of the atoms which is assumed to be identical to the average temperature of the wall coating. This assumption has been verified to the 10^{-14} level.[7]

The wall shift causes an offset which is of order 0-5 x 10^{-11}, depending on the area to volume of the storage bulb and the type of teflon used. From the literature[8] one calculates a temperature coefficient for this effect of +1-5 x 10^{-13}/K, again depending on the type of coating and the area to volume ratio.

The magnetic field of 10^{-8}T (100 μg) used to separate the various magnetic hyperfine sublevels causes a shift of 2.75 x 10^{-14}. The temperature dependence of this effect is assumed to be zero.

Spin exchange collisions between hydrogen atoms causes a frequency shift due to direct interaction which amounts to a few x 10^{-13} for the passive maser. The small value for this effect is due to the low density of hydrogen atoms in the storage bulb. From the literature one would estimate a temperature variation of about 2 x 10^{-15}/K.[9] The frequency shift due to the finite duration of the spin exchange collision causes an additional shift of order 10^{-15} in the passive maser, again due to the low density of hydrogen. The temperature coefficient of this efect is expected to be smaller than 10^{-16}/K at 313 K.[10]

Magnetic field inhomogeneities also can cause frequency offsets. The best guess of the frequency offset due to this effect is approximately 1-5 x 10^{-13} with a temperature dependence which should be less than 10^{-16}/K. The frequency shift can be easily reduced by about a factor of 100 by mixing the three upper magnetic hyperfine levels before the atoms enter the storage bulb.[11] Tests on the several recent hydrogen maser designs reveal that their magnetic field sensitivity is dominated by their sensitivity to gradients.[12,13] Mixing these upper hyperfine states reduces the signal by 33 percent and hence the short term stability by 17 percent. Since the long term stability of hydrogen masers--indeed all frequency standards--is limited by systematic effects, the 17 percent decrease in short term frequency stability seems a small price to pay for virtually eliminating the very troublesome shifts due to magnetic field inhomogeneities.

Upon reviewing the above efects one finds that once the offset and the temperature coefficient for cavity pulling are eliminated, the most serious temperature effects are the second order Doppler effect and the wall effect. By coincidence they are of an opposite sign and by choosing FEP teflon for the coating material and the proper size storage bulb, the net temperature coefficient can be made less than 10^{-14}/K. The size of the storage bulb in order to obtain this cancellation is approximately 17.6 cm in diameter. For example, compare the data of references 8, 9, and 14. Since the temperature dependence of the wall effect is not strictly linear with temperature, slight adjustments in the effective temperature coefficient can be made by changing the bulb temperature. Both the wall effect and the second order Doppler effect depend on the average temperature of the wall coating, therefore, one would expect this compensation scheme to work very well. Using this type of compensation a passive maser would require only 0.1 K temperature resetability and stability in order to show long term stability and reproducibility of 10^{-15}. The most likely limitation in the reproducibility would be changes in the wall shift with time from contamination or structure changes within the teflon. All other effects can probably be kept to parts in 10^{15}.

Hydrogen Maser Electronics

The block diagram of the electronics used to realize the cavity servo scheme is shown in Fig. 4.

A 5 MHz oscillator is distributed through several low noise, high isolation amplifiers,[15] phase modulated at 12 kHz--the nominal half width of the microwave cavity, and at .4 Hz--the nominal half width of the hydrogen resonance, and multiplied to 1440 MHz where it is mixed with a synthesizer to produce the nominal hydrogen frequency of 1420405751.7 Hz. The output microwave signal from the cavity is amplified through broad band low noise amplifiers, heterodyned to 20 MHz, and amplitude (envelope) detected. The recovered amplitude modulation at .4 Hz and 12 kHz is then processed in separate synchronous detectors referenced to the impressed phase modulation. In order for the servo systems to operate without devastating biases, it is essential that the amplitude modulation and the second harmonic of the desired phase modulation present on the carrier as it enters the cavity be less than -100 dB relative to the phase modulation at both .4 Hz and at 12 kHz.[16] In order to achieve these performance levels, careful attention must be paid to circuit design and gain flatness in the phase modulator, the multiplier chain, the microwave amplifiers, the 20 MHz amplifier, envelope and synchronous detectors. For example, the reference signals for the phase modulator are derived by dividing down the 5 MHz signal with the last stage being a divide by two circuit. This precision square wave signal is then filtered to remove the odd harmonics. This technique easily produces a sinewave signal with the second harmonic surpressed by 100 dB. The phase modulator is a low Q (~2) series tuned LC circuit with C being a varactor diode with signal levels stabilized using AGC on the input isolation amplifier.[15]

Several multiplier chains have been tried. The first used conventional class-C type multiplier stages from 5 MHz to 240 MHz followed by a step recovery diode to reach 1.4 GHz. The second multiplier chain used emitter-coupled-pair current switches to multiply from 5 MHz to 45 MHz followed by cascaded doublers to reach 1.4 GHz.[16] This second multiplier chain is much easier to align, has lower noise, and greatly surpresses any amplitude modulation present in the input. Output power is stable to within .2 percent over months without any temperature control or compensation. The microwave amplifiers and associated circuitry has a minimum bandwidth of 1 GHz and therefore caused very little frequency dispersion over the frequency modulation range of ± 12 kHz. The 20 MHz amplifier and envelope detector used to recover the 12 kHz amplitude modulation had a bandwidth of about 20 MHz, while the .4 Hz channel had a bandwidth of about 1 kHz. The phase detectors were of the FET bridge type driven by a square wave reference derived from the appropriate phase modulation signal. Circuit diagrams for all the electronics shown in Fig. 4 are available from the authors upon request.

Experimental Measurements on Full Sized Passive Hydrogen Maser

Fig. 5 shows the output frequency variation of the full sized passive hydrogen maser during a .7 K change in microwave cavity temperature. Without the cavity servo system one would have expected to see a fractional frequency change of about 2×10^{-11}/K, however, the observed change is only 1.3×10^{-13}/K.

Using the average values for TFE type teflon given by reference 8 and the dimension of the storage bulb, we calculate a temperature coefficient of $+2.7 \times 10^{-13}$/K due to the wall effect, a coefficient of -1.38×10^{-13}/K from the second order Doppler for a net coefficient of $+1.32 \times 10^{-13}$/K. The excellent agreement between the calculated results and the observed temperature variations of the output frequency verify that the cavity servo eliminates variations in cavity frequency to a very high degree. If type FEP 120 instead of type TFE teflon had been used, the temperature coefficient would have been less than 3×10^{-14}/K.

The spin exchange shift is quite small in the passive hydrogen maser due to the low hydrogen density. Measurements showed that a 30 percent increase in hydrogen density changed the output frequency by $6 \pm 4 \times 10^{-14}$, indicating a total spin exchange frequency shift of less than 3×10^{-13}. Variations in microwave power also have little effect on output frequency. A change of 2 dB caused a frequency shift of $8 \pm 4 \times 10^{-14}$. These measurements demonstrate that both the spin exchange frequency shift and the microwave power shift are so small that one would expect to achieve fractional frequency stabilities of 10^{-15} for very extended periods of time.

Curve (a) of Fig. 6 shows the measured fractional frequency stability of the full sized passive hydrogen maser as measured against NBS-6, one of our primary cesium standards, and UTC (NBS) generated from an ensemble of 9 cesium standards, including NBS-6. The measurements were made at 5 MHz with a beat period of 1941.6 s. Since the cesium standards and the passive hydrogen maser are based on entirely different atoms with different apparatuses and situated in separate rooms, it is extremely unlikely that the frequencies could have moved in unison under the influence of environmental conditions like temperature or pressure, or that they could have inadvertently been phase locked together. Since the temperature varied by about ± 2 K and the pressure varied with atmospheric conditions during the measurements, these data provide strong evidence that the passive hydrogen maser is relatively free from these types of environmental influences.

The measurements of Fig. 6 show a combined frequency stability for the passive hydrogen maser and NBS-6-UTC(NBS) of $\sigma_y(\tau) = 2 \times 10^{-12}\tau^{-1/2}$ for measurement times from 10 s to 4 days. This is the best frequency stability ever measured for a single device at measurement times greater than two days. Moreover, it should be noted that these measurements provide only a worst case estimate of the actual frequency stability of the passive hydrogen maser since the contribution of the cesium standards were not subtracted. From linewidth and signal-to-noise considerations, it is expected that a frequency stability of $3 \times 10^{-13} \tau^{-1/2}$ can ultimately be achieved, primarily limited by the short term noise in the crystal oscillator used to drive the passive maser. This is shown as curve b in Fig. 6.

Fig. 7 compares the minimum time dispersion obtainable from the space qualified cesium clock flown on the Navy Research Laboratory NTS-2 satellite, a commercial "high performance" cesium clock, and a passive maser having the frequency stability shown in curve a of Fig. 6. Note that for timekeeping accuracies beyond 1 day, a single passive hydrogen maser outperforms the best average of 10 to thousands of presently available cesium clocks. The expected time dispersion is less than 2 ns/10 days for the passive hydrogen maser. If expected improvements in frequency stability are achieved, the time dispersion could well be less than 1.0 ns per month.

Small Passive Maser Design

There is considerable interest in a small, ruggedized passive maser design that would be suitable for field use. A new small cavity design is under development at NBS which has the virtue of not only small size and weight but also simplicity. The cavity cylinder of low loss Al_2O_3, is plated with about 10,000 Å of copper via a dc sputtering technique and then electroplated with about .0015 cm of copper. The top and bottom endcaps are of solid aluminum. The ceramic has a dielectric constant of 9.3, thus making possible a cavity 15 cm in diameter and 15 cm in height for the TE_{011} mode. The measured Q is about 5000. The inside of the cavity will be coated with teflon and used for the storage bulb. The volume is ∿1 ℓ. We intend to try both conventional coatings as well as manufactured teflon sheets bonded to the inside of the cavity with epoxy. The microwave coupling to the cavity uses links which penetrate about 3 mm into the outer wall of the $A\ell_2O_3$ cylinder.

The TE_{011} mode has no longitudinal electric currents that flow along the copper jacket. Nearby unwanted modes, on the other hand, contain longitudinal electric components, particularly at the endcap-cylinder interfaces. We have introduced a gap at this point so that the unwanted modes must sustain displacement currents. Microwave absorbent material with a loss tangent of about 1.1 is wrapped around the outside of the cylinder and covers the gaps to absorb any fringing fields. This technique greatly reduces and separates the unwanted modes which previously were very close to the desired TE_{011} mode. A two layer 1 turn per cm solenoid provides the C field. The pitch changes sign from the inner to the outer layer of the solenoid so that it can be driven from a coax line with virtually no extra end or pitch effects. Measurements show that the C-field is uniform to 5×10^{-10} T (5 μG) at a magnetic field of about 10^{-8} T (100 μG). A two turn Zeeman coil is wound outside the C field coil.

The magnetic shields are fabricated in two halves joined together at the center with a 5 cm wide overlap joint. This arrangement allows the endcaps of the magnetic shields to be permanently spotwelded to the end of each cylinder. This should allow assembly and disassembly of the shields without degradation of the shielding performance due to work hardening of the end joints as is usually encountered.

The electronics developed for the full sized hydrogen maser will be used on the small cavity design. The frequency stability is expected to be about $2 \times 10^{-13}\tau^{-1/2}$ for measurement times from 10 S to 10 days.

Conclusion

We have described a passive hydrogen maser frequency standard having a fractional frequency stability of $\sigma y(\tau) = 2 \times 10^{-12}\ \tau^{-1/2}$ for $10s<\tau< 4\times10^5 s$. The frequency stability of this device for measurement times from two days to at least one week is unexcelled by any other single frequency standard. Additional improvements of up to a factor of 7 in frequency stability appear feasible. For timekeeping applications this single standard is predicted to outperform ensembles of tens to thousands of presently available cesium standards. In addition we have presented some of the details of a small dielectrically loaded microwave cavity with integral storage bulb and vacuum container. This new design is expected to make it possible to obtain a fractional frequency stability of order $2 \times 10^{-12}\ \tau^{-1/2}$ for measurement times from 10s to 10 days in a total package size of 23 cm diameter and 50 cm long.

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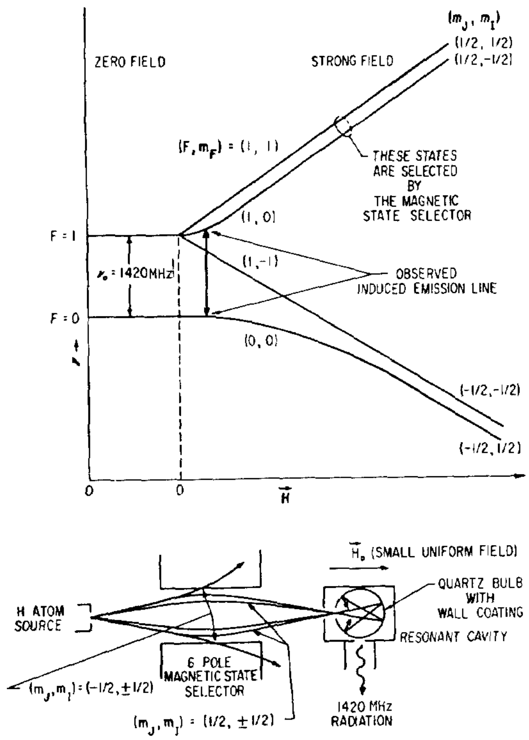

FIGURE 1.

PASSIVE HYDROGEN MASER

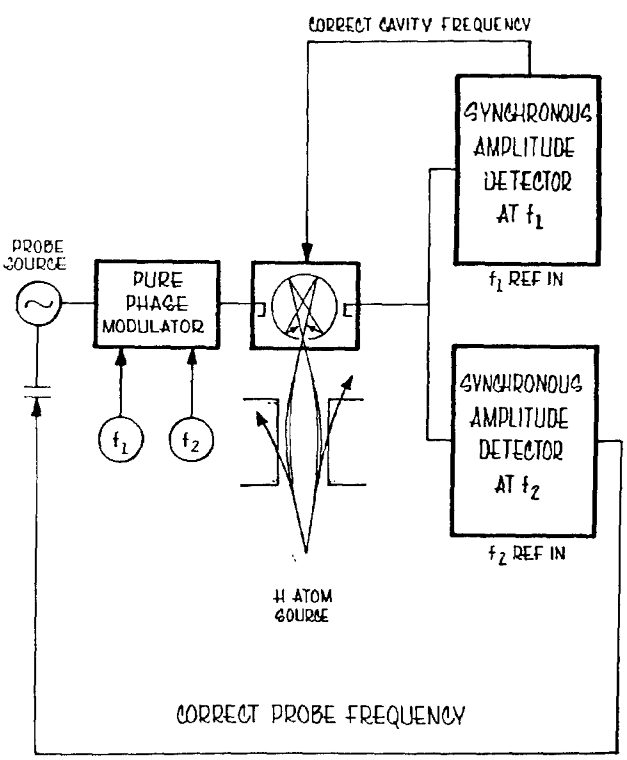

FIGURE 2.

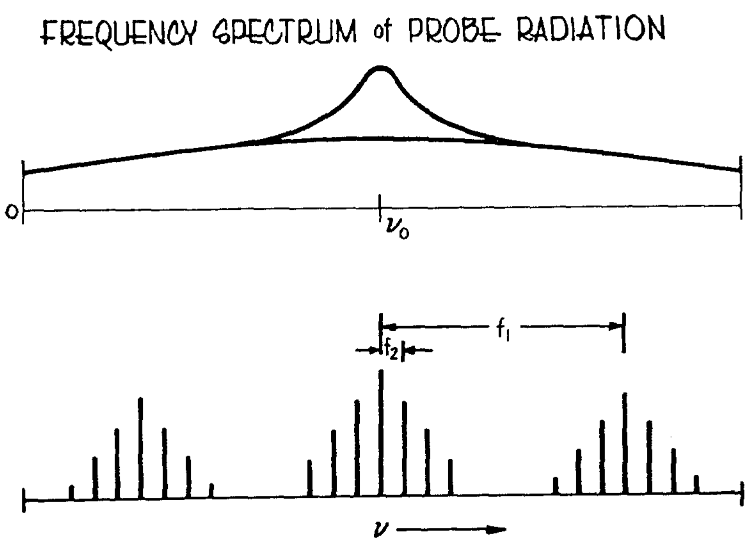

FIGURE 3.

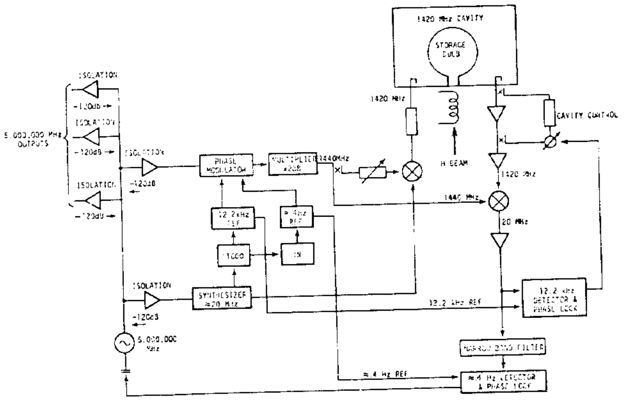

FIGURE 4.

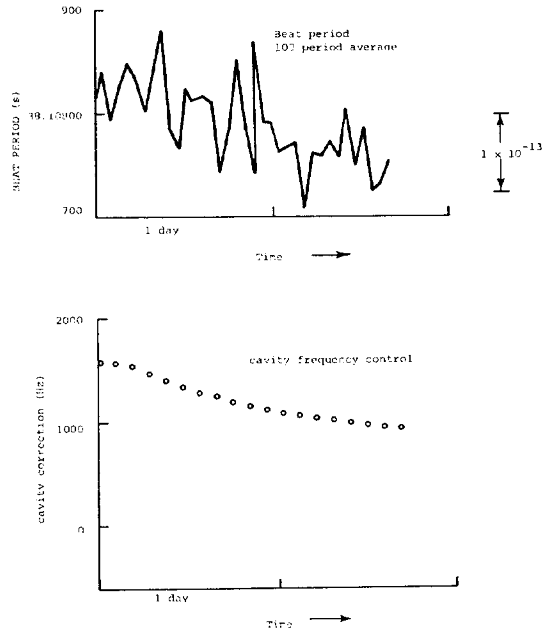

FIGURE 5.

H MASER FREQUENCY PERTURBATIONS

Effect	$\Delta\nu/\nu_0$	≈ Value	Temp. Coef.
Cavity Pulling	$\sim 1/2 \frac{Q_C}{Q_H} \frac{\nu_c - \nu_0}{\nu_0}$	$< 10^{-14}$	$\approx 2 \times 10^{-11}$/K open loop $10^{-14} - 10^{-15}$/K closed loop
2nd order Doppler	$-1.38 \times 10^{-13} T$	-4.3096×10^{-11}	-1.3769×10^{-13}/K
Wall Shift	$\frac{-K \text{ Area}}{\nu_0 \text{ Volume}} [1-\alpha(T-313)]$	$0-5 \times 10^{-11}$	$+(1-5) \times 10^{-13}$/K
Magnetic Field	$2.75 \times 10^{11} H^2(T)$	2.75×10^{-14}	0
Spin Exchange	$-\frac{\lambda n_a \bar{V}_r}{8\pi\nu_0} (\rho_{1,0} - \rho_{0,0})$	few $\times 10^{-13}$	$\approx 3 \times 10^{-15}$/K
Spin Exchange	$\frac{e_H n_a \bar{V}_r \sigma}{2\pi\nu_0}$	$\sim 10^{-15}$	$< 10^{-16}$/K
Magnetic Field Inhomogeneity	$[K'(\rho_{1,1} - \rho_{1,-1})]$ $\left\langle \frac{H_r^{rf}}{H_Z^{rf}} H_r^{dc} \right\rangle_{\text{bulb}}$	few $\times 10^{-13}$ ↓ few 10^{-15}	$< 10^{-16}$/K

TABLE 1.

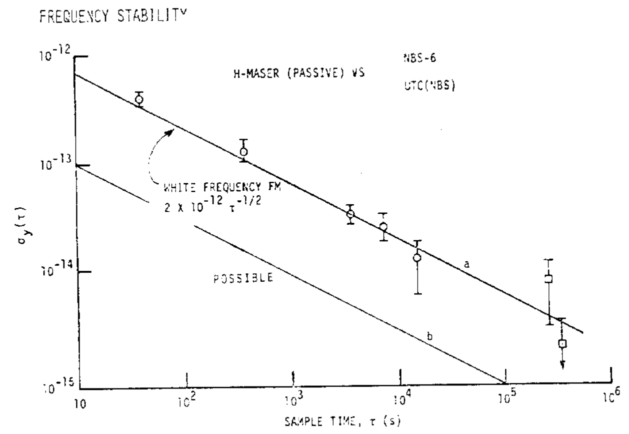

FIGURE 6.

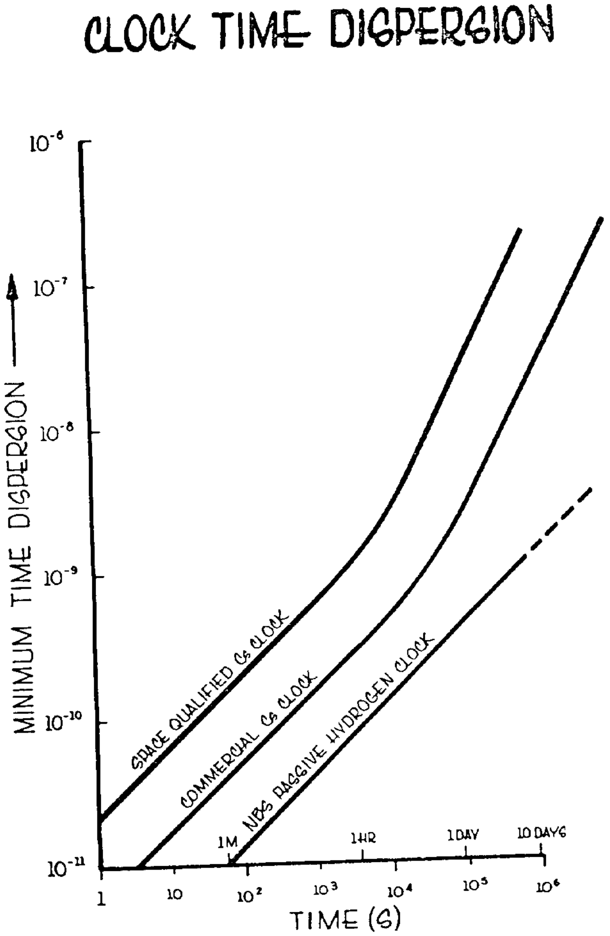

FIGURE 7.

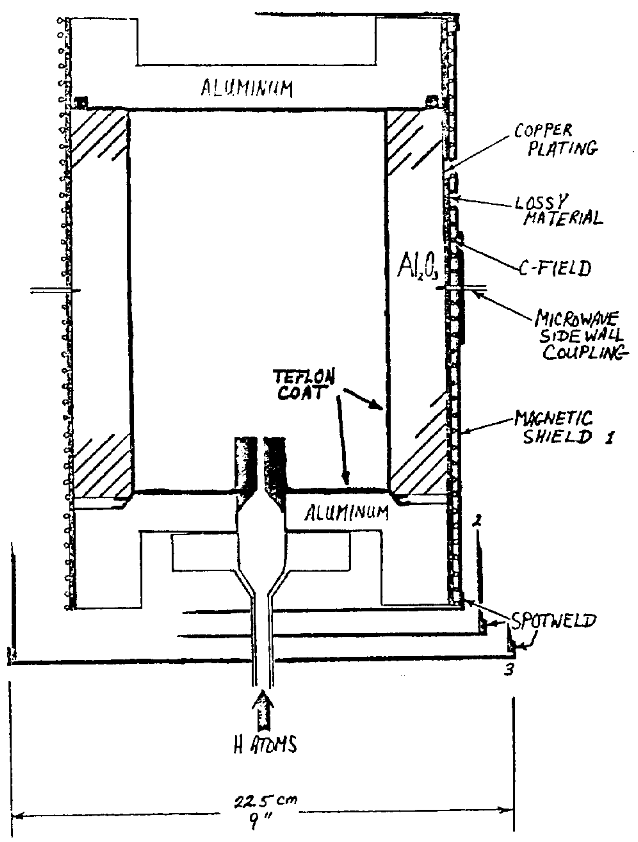

FIGURE 8.