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HYDROGEN MASERS WITH CAVITY FREQUENCY SWITCHING SERVOS

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Abstract

The stability of the free-running hydrogen maser is limited by pulling of the unperturbed hydrogen transition frequency due to instability of the cavity resonance frequency. Two automatic approaches to cavity stabilization have been used successfully in field operable atomic hydrogen masers in the past. One method is based upon the "spin-exchange" tuning procedure and was used in masers constructed at NASA's Goddard Space Flight Center.^[1, 2] The other method is the cavity frequency switching servo used on Sigma Tau Standards Corporation (STSC) hydrogen masers.^[3, 4, 5]

While automatic spin-exchange tuning is in principle the more basic and accurate method, the required beam intensity switching and the long servo time constant result in reduced stability for measuring intervals up to 10^6 seconds. More importantly, the spin-exchange tuning method requires a second stable frequency source as a reference, ideally a second hydrogen maser, to get the best results.

The cavity frequency switching servo, on the other hand, has very little effect on the maser short term stability, and is fast enough to correct for cavity drift while maintaining the cavity at the spin-exchange tuned offset required to minimize instability due to beam intensity fluctuations. Not only does the cavity frequency switching servo not require a second stable frequency source, but the frequency reference is the atomic hydrogen radiated beam signal, so that no extra RF connections need be made to the cavity, and externally generated signals that would perturb the hydrogen atom need not be transmitted through the cavity.

In this paper we will discuss the operation of the cavity frequency switching stabilization method and will illustrate the transient response of the servo and certain other aspects of the technique that have potential for achieving improved basic accuracy. We also will give stability results obtained between masers at STSC and long term stability data obtained with STSC hydrogen masers at the United States Naval Observatory.

INTRODUCTION

The stability of the hydrogen maser for measuring intervals beyond 1000 seconds is primarily limited by cavity pulling. For very long term stability and for long term intrinsic reproducibility and accuracy, variation in the wall shift is also of serious concern. (Accuracy as defined by first, a realistic error budget and second, substantiation of the accuracy factors by reproducible measurements between standards.)

Cavity pulling can be reduced to a minimum by carefully spin-exchange tuning the cavity^[6] and then stabilizing the cavity at the spin-exchange tuned frequency by use of the cavity frequency switching

servo. Results given in this paper illustrate the performance obtained at present using this technique. Further development of the cavity frequency switching technique at STSC indicates substantial improvements in stability can still be made, and further that use of this cavity stabilization method will provide the means to achieve improved accuracy.

The determination of the wall shift requires the operation of hydrogen masers with different size storage bulbs that are coated with chemically identical materials and processed with carefully controlled procedures. The accuracy previously achieved has been in the 1 or 2 parts in 10^{12} region.^[6] We believe this may be reduced by an order of magnitude or more by use of improved techniques, particularly the use of the cavity frequency switching servo, as well as improved wall coating materials and computer instrumentation techniques.

THE CAVITY FREQUENCY SWITCHING SERVO

The operation of the cavity automatic frequency tuning system (the "cavity servo") is based upon switching the cavity resonance frequency between two frequencies approximately equally spaced about the maser oscillation frequency. The two frequencies are about one half the cavity resonance width apart and are switched at a rate that is slow compared to the cavity field decay time constant but fast in comparison with the atomic relaxation rate.

The modulation (switching) rate and the relative duration of the high and low frequencies are controlled by a digital circuit called the Modulation Period Generator (MPG). The voltage on a varactor diode coupled to the cavity is switched between two precisely controlled voltages by the MPG, thereby changing the cavity frequency.

When the maser frequency is located at the crossover point of the two cavity resonances, there is no amplitude modulation on the maser signal coupled from the cavity; but when the signal is not at this point, there is an amplitude modulation, and this is detected on the receiver IF signal. The modulation envelope is processed in a phase sensitive "Synchronous Detector" circuit that sends up or down correction commands to a "Cavity Register." The cavity register integrates the up or down signals and produces a voltage which corrects the cavity average frequency. Two ways of controlling the cavity average frequency have been used successfully.

In early STSC masers the register voltage changed the temperature of the cavity by applying a bias to the temperature control circuit. Since the STSC masers have metal cavities with quite linear frequency variation with temperature, this method results in a well controlled servo, but the response is relatively slow due to the large thermal mass of the cavity assembly.

In the most recently constructed STSC masers the cavity frequency is controlled by applying the register voltage to a second varactor diode coupled to the cavity. The servo time constant is then not limited by the cavity thermal response. The varactor control method has the capability of compensating very quickly for systematic cavity disturbances, while the temperature variation method has the advantage of maintaining the cavity assembly, coupling components and storage bulb at a constant temperature.

For future experimental work the masers can be changed rather quickly between either the temperature control or the varactor control method. This can prove very valuable in measurements to establish temperature coefficients of systematic variables, oscillation parameters, or fundamental temperature dependencies such as the second order Doppler shift or wall shift.

SPIN-EXCHANGE TUNING USING THE CAVITY FREQUENCY SWITCHING SERVO

One of the unique features of the cavity frequency switching servo is the method used to establish and maintain the maser cavity at the spin-exchange tuned frequency. Cavity pulling and atom-atom spin exchange pulling of the maser output frequency both depend in a nearly linear, monotonic fashion upon the density of atoms within the storage bulb. There is a unique cavity offset from the unperturbed transition frequency where the maser frequency is independent of beam intensity. This is the basic concept in all spin-exchange tuning methods.

In the usual method of spin-exchange tuning, the output frequency of the maser to be tuned is compared with another stable reference source, optimally another hydrogen maser. Curves of output frequency versus cavity frequency are plotted at different beam intensities (source pressure settings) and the point at which the curves cross establishes the proper cavity setting.

With the cavity frequency switching servo, the cavity is automatically held at the cross-over point of the two resonances. This is a stable point, but not necessarily the cavity average frequency (if the cavity Q's and coupling factors are exactly equal the tuned cavity position would be the average of the two cavity resonances).

However, with the cavity switching continuously between two frequencies, the average pulling effect experienced by the radiating atoms is not just a function of the two frequencies (and the resonance shape at the two frequencies), but is also a function of the time spent at each frequency. So by controlling the relative time spent at the high frequency in relation to the low frequency, the time average cavity resonance frequency experienced by the radiating atoms can be varied, and a spin-exchange compensation point can be established in a manner very similar to the conventional method of establishing a fixed cavity offset frequency.

A full analysis of the physics of the hydrogen maser using the cavity frequency switching system will not be presented here, but the well behaved linear relationship between modulation periodicity and the effective cavity frequency is easily demonstrated experimentally.

The data presented in Figure 1 illustrates the spin-exchange cavity tuning of a STSC hydrogen maser. The maser being tuned is referenced to a second STSC maser and the ordinate in Figure 1 is the fractional frequency difference between the masers. The abscissa gives the number set in the modulation period generator (MPG), which has a maximum range of 0 to 99999 corresponding in this maser to a change of 16 kHz in cavity frequency. The MPG number range in Figure 1 is 50000 to 59000, which corresponds to a range in cavity frequency of 1.44 kHz.

The two curves in Figure 1 show the results obtained by varying the MPG number using two different values of the source pressure. The spin-exchange tuned position is the point at which the two curves cross. The frequency data were obtained with a precision of 2 to 3 parts in 10^{15} and the least significant digit of the MPG represents 0.16 Hz, which is equivalent to a maser frequency change for the low pressure curve of 1.60 parts in 10^{15} . The maser would be tuned to better than one part in 10^{14} by setting the MPG within 6 digits of the crossover point. To the extent of the stability of the cavity servo and maser oscillation parameters, the cavity will be tuned to this precision whenever the cavity tuner is on and stabilized.

CAVITY SERVO TRANSIENT RESPONSE

The transient response of the cavity servo following a step offset in the cavity register is shown in Figure 2. This curve illustrates the cavity response when the system uses a varactor diode as the frequency varying element. Here the full scale ordinate is $\pm 5 \times 10^{-13}$ and the abscissa is time in seconds.

The reference maser and the maser to be tested were initially stable, and then the cavity register of one maser was offset by an amount to change the output frequency in one direction by 3 parts in 10^{13} . The cavity servo returned the cavity to the tuned position during a transient period, after which the register was again offset, this time in the negative direction. After another transient period the maser had again returned to the tuned position within the frequency resolution of the test.

From Figure 2 the time constant of the cavity servo can be obtained and in the present case it is approximately 2,000 seconds. While Figure 2 shows the maser frequency transient response when the register voltage (cavity varactor voltage) is purposely offset, Figure 3 illustrates the servo response when a relatively large change in cavity temperature is purposely set in the thermal control system.

There is a tapped resistor array in the cavity temperature control system through which temperature changes to the cavity can be made from the maser control panel. In Figure 3a the maser was stable at the beginning, and then a cavity temperature change of approximately -0.05°C was made. This corresponds to a thermally induced offset in maser frequency of approximately 1.55×10^{-11} . The cavity servo responded at the maximum rate, and after approximately 11 hours reached equilibrium at the new temperature.

In Figure 3b the cavity temperature was raised by $+0.05^\circ\text{C}$, back to the original temperature, and the cavity servo again corrected for the change in a similar time period. At the end of Figure 3b the maser frequency was measured and was found to be within 5×10^{-15} of the original frequency. From the known cavity frequency response to temperature variation, this corresponds to returning to the original temperature to within approximately $1.6 \times 10^{-5}\text{C}$.

After the transient at the end of Figure 3a the maser did not quite reach the original frequency, the slope of the phase curve gives a frequency offset of $+3.4 \times 10^{-14}$ (the sign of the slope is reversed in this plot). This illustrates that there are temperature dependent factors other than cavity frequency that influence the output frequency.

The second order Doppler shift accounts for part of the difference, namely 0.7×10^{-14} . The temperature coefficient of wall shift is the wrong sign to account for the remainder, so we may assume there are thermal variations in the cavity parameters (Q_c , n' , coupling or filling factor for example) or electronic component temperature sensitivities. Cavity spin-exchange tuning was not checked during the test.

The corrections indicated on the cavity register after the transients shown in Figure 3 were approximately 1/2 of full scale. On the basis of current maser data, this is a relatively huge correction that would occur only after several years of operation, and the drift associated with this rate is typically less than 10^{-14} per year.

THE WALL SHIFT

Due to the use of automatic cavity tuners on all STSC hydrogen masers, we have a precise means of separating cavity drift from other frequency perturbing influences, including possible variation in the wall shift. It has been our experience that the frequencies of new hydrogen masers drift upward during the first few months of operation relative to masers that have been operating for much longer periods. The change is on the order of 1×10^{-14} per day at first, even though the cavity tuners are operating properly.

After extensive testing of electronic systems and searching for drift of cavity parameters or other systematic variables, the most plausible conclusion appears to be that the wall shift decreases with time when the bulb is first exposed to atomic hydrogen. By the time the masers have been fully tested and prepared for delivery (typically 2 to 3 months after first operation) the relative drift upward decreases to a few parts in 10^{15} per day, well within specifications. However, tests of six masers delivered to the United States Naval Observatory and one maser delivered to NIST indicate that there is a residual drift upward relative to international standards.

One plausible reason for the drift is that, upon exposure to the atomic hydrogen beam, the atoms interact with and remove contaminants on the Teflon surface. Atomic hydrogen is a free radical and very reactive. Many of the possible contaminants probably do not cause first order transitions, but introduce anomalous phase shifts which go away with time.

Another possible reason for the initial drift is that the Teflon surface may be in the process of stabilization of its physical phase. It is quite reasonable that this clean-up, or phase stabilization, is the reason that the older masers have very little relative drift in frequency — the material of the wall is no longer changing — which implies that the storage bulb surfaces are relatively pure, phase stable substances, namely Teflon.

While experimental errors in storage bulb geometrical factors such as the macroscopic surface to volume ratio or the microscopic smoothness of the coating introduce errors in wall shift determinations using traditional procedures^[6], properties such as the temperature coefficient of the phase shift per collision should be relatively reproducible if the wall material is a pure substance.

It is important to note here that the wall shift of Teflon FEP-120 goes to zero and reverses sign at a temperature near 100 °C.^[6] In view of this it is very possible that hydrogen masers, fitted with different size bulbs and operated at different temperatures for periods of time long enough to allow the bulb coatings to become clean and stable, could very likely provide a means for experimentally determining the temperature at which the wall shift becomes zero.

STSC hydrogen masers can be fitted with bulbs ranging from under 7 cm to over 16 cm. It is also possible to operate these masers over a wide range of precisely controlled temperatures. It is therefore possible to envision the continuous operation of field operable hydrogen masers under conditions such that the wall shift is negligible and other perturbations to the hydrogen atom have been accurately accounted for. This is one of the interesting experimental goals of Sigma Tau Standards Corporation.

SIGMA TAU MASER STABILITY

Figure 4 shows the relative stability of two STSC hydrogen masers as measured at the company. The masers were located in a laboratory environment with the temperature controlled within $\pm 1^\circ\text{C}$ by

the building air conditioner. These data are typical of the stability realized for the 21 masers of the current design for measuring intervals up to 100,000 seconds in a relatively well controlled laboratory environment.

All the STSC hydrogen masers constructed to date have been built for sale to various customers, so they have not been present at STSC for long enough periods to characterize the very long term stability. However, through the courtesy of the United States Naval Observatory, data has been provided showing the stability of NAV-2, one of the STSC masers located at the observatory, relative to the BIPM.

Data on the relative phase variation of the other NAV series masers (STSC masers) versus other Naval Observatory standards has also been obtained during the above period, and from this data we have calculated the relative stability of several of the six hydrogen masers STSC has delivered to the Observatory.

Figure 5 shows the frequency of four STSC masers over a period of 90 days. The frequency starting points on the vertical axis are synthesized and arbitrary. The important feature in Figure 5 is the excellent long term stability. All four of the masers are increasing smoothly in frequency relative to the BIPM at approximately 2 part in 10^{15} per day. The masers are typically varying amongst themselves by 1 part in 10^{15} per day or less.

CONCLUSION

While the present performance of STSC hydrogen masers is excellent, we feel that it can still be improved significantly. Research and development is continuing at STSC and new discoveries are being made continuously. One of the purposes of this paper is to illustrate that the state of the art in hydrogen maser technology has not reached a plateau.

The first maser using the cavity frequency switching servo was delivered only five years ago and the design has been changed very little in the 25 hydrogen masers of this type that have been produced since then. Tests done in the course of construction indicate that the cavity coupling, Q , and other oscillation parameters of these masers can be improved. We do not understand at present the source of a residual temperature coefficient of frequency that is typically about a part in 10^{14} per $^{\circ}\text{C}$ (ambient) and it is likely that further experimentation can show the way to improve upon this.

We have the ability at present to spin-exchange tune the masers very precisely at different cavity temperatures and should be able to characterize the frequency dependence on wall shift at different temperatures, using different bulb sizes and different wall coatings, and watch the relative frequencies over extended operating periods.

Using the state of the art in cavity tuning and spin-exchange tuning as well as the ability to determine precisely the frequency of masers fitted with different size storage bulbs with improved coatings as a function of temperature and time, we hope to be able to provide significant improvements in intrinsic reproducibility and fundamental accuracy in the future.

ACKNOWLEDGEMENTS

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NPL MASER OUTPUT FREQUENCY VS. MPG NUMBER

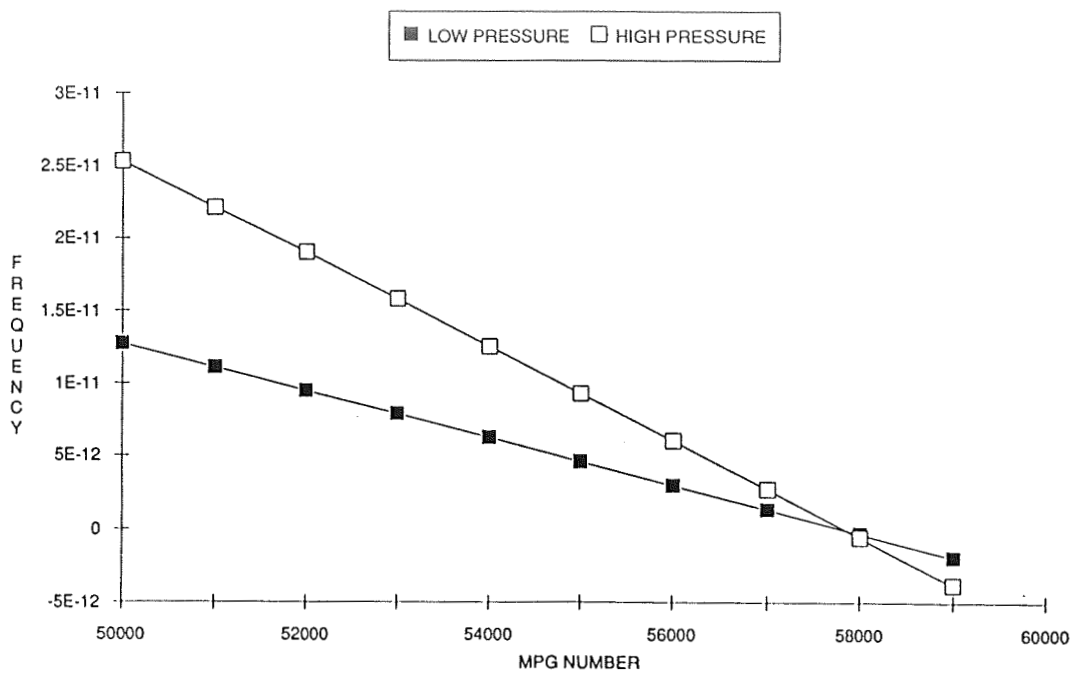


Figure 1. Spin-exchange tuning a STSC hydrogen maser equipped with a cavity frequency switching servo.

COMPARISON FREQ. = 100 MHz

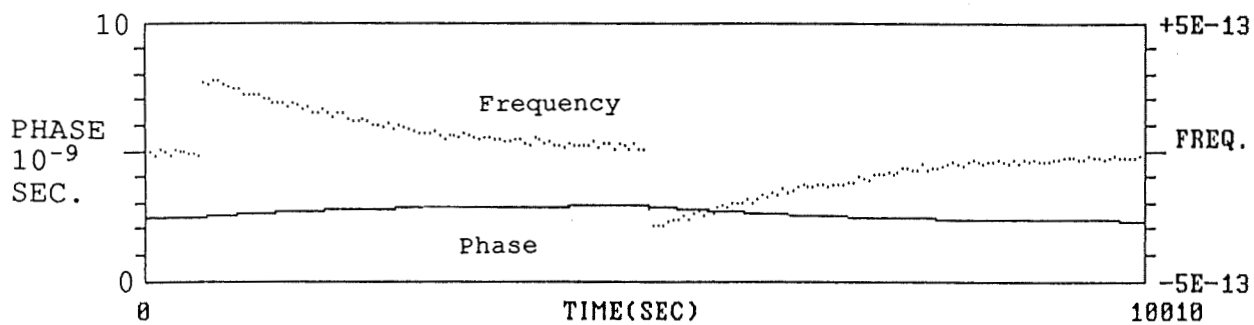


Figure 2. STSC cavity switching servo transient response.

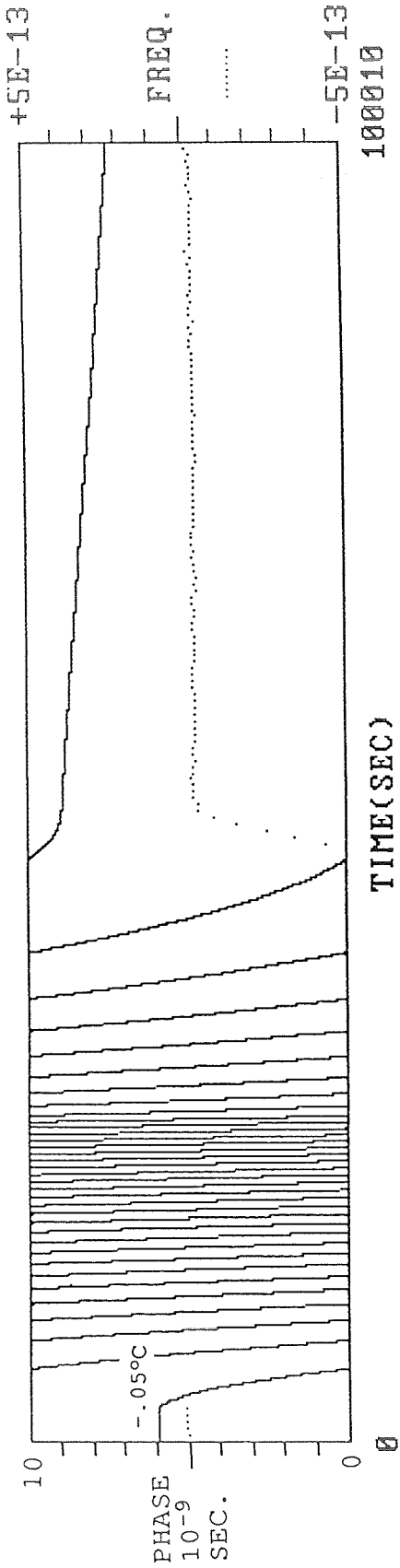


Figure 3a. Servo transient response to a decrease in the cavity thermal control set point using a varactor for the servo frequency control.

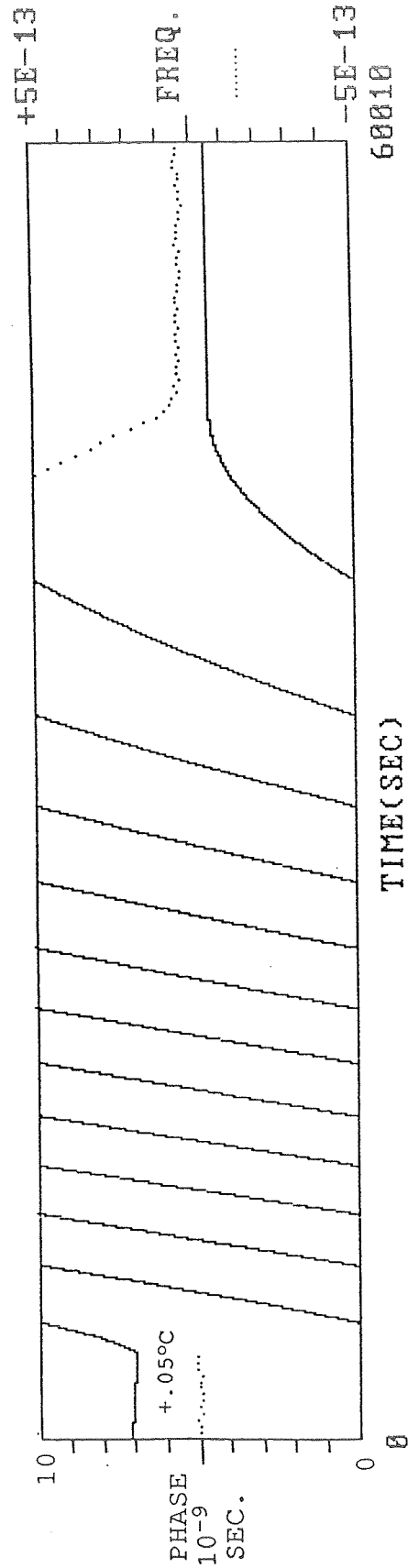


Figure 3b. Servo transient response to an increase in the cavity thermal control set point (resetting to the temperature at the beginning of Figure 3a.)

TAU= 400010

COMPARISON FREQ.= 100 MHz

ST1= 1.131462E-13 (29998)	ST500= 2.013706E-15 (59)
ST2= 6.224469E-14 (14999)	ST1000= 1.567694E-15 (400)
ST5= 2.944684E-14 (5999)	ST2000= 1.632116E-15 (200)
ST10= 1.765067E-14 (2999)	ST5000= 1.616498E-15 (80)
ST20= 1.06276E-14 (1499)	ST10000= 1.407244E-15 (40)
ST50= 6.369069E-15 (599)	ST20000= 1.187939E-15 (20)
ST100= 4.402457E-15 (299)	ST50000= 1.967648E-15 (8)
ST200= 2.65002E-15 (149)	ST100000= 1.717134E-15 (4)

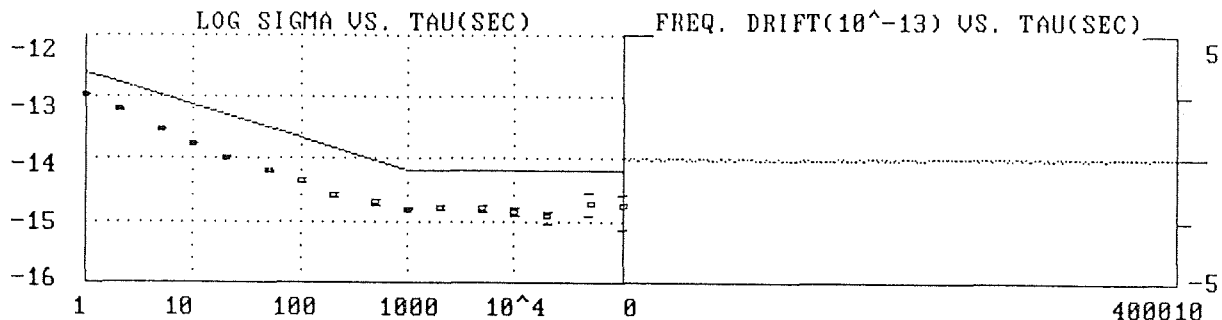


Figure 4. STSC measurement of maser stability.

NAVAL OBSERVATORY STSC HYDROGEN MASERS VS. BIPM

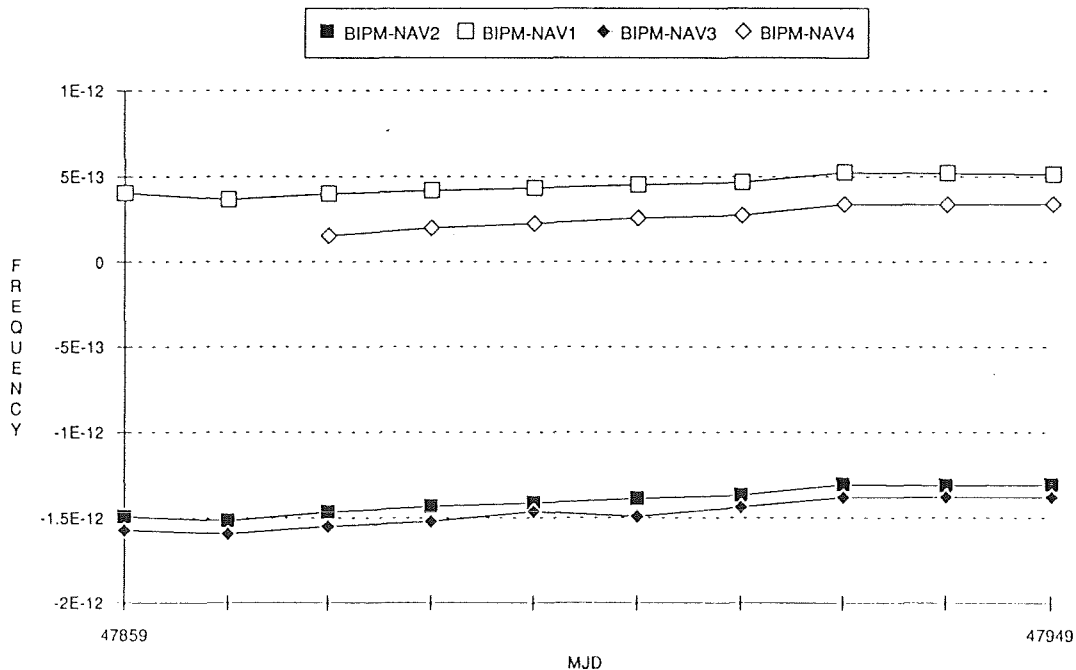


Figure 5. Long term stability of Nav-series hydrogen masers.