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Final Technical Report, STNR-F1

ADVANCED DESIGN ATOMIC HYDROGEN MASER RESEARCH AND DEVELOPMENT

Sigma Tau Standards Corporation

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Research and development of a new design of atomic hydrogen maser frequency standard incorporating advanced features such as automatic cavity stabilzation, reduced size and weight, and improved stability was completed and two devices exhibiting the anticipated features were delivered to NRL for evaluation. Several publications referenced in the report document the results.

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SUMMARY

A. OBJECTIVES OF THE CONTRACT

The objectives of this contract were to develop atomic hydrogen masers based upon novel concepts of cavity stabilization and new designs of the maser physics unit to provide improved stability and environmental isolation as well as a reduction in size, weight, cost and power consumption. A further objective was to construct, test and deliver two operational devices to NRL for further tests and evaluations.

B. TECHNICAL PROBLEM

The utility of the atomic hydrogen maser for use as an operational standard of frequency and time has been limited in the past by the large size and weight resulting from the required large cavity structure; by the limited lifetime of the vacuum pumps required by past physical concepts of atomic state selection and beam trajectory configuration; and by the realized instability due to drift in frequency of the resonant cavity. As discussed in the referenced documents, means for overcoming these difficulties were conceived at Sigma Tau Standards Corporation and the present contract was undertaken to develop and deliver improved masers.

C. GENERAL METHODOLOGY

First, new maser designs were developed which implemented electronic cavity frequency stabilization using the cavity frequency switching technique previously conceived at Sigma Tau Standards Corporation[1]. These new designs also incorporated a novel cavity assembly which is smaller than that used in past masers[2] and new quadrupole state selectors[3] based upon concepts described in the cited references. Then two representative hydrogen masers were constructed and tested and experiments were performed to optimize the electronic systems. The maser stability and other performance criteria were tested and evaluated at Sigma Tau and the masers were then delivered to NRL for further tests.

D. TECHNICAL RESULTS

The design of the new hydrogen masers resulting from this contract and the results of tests at both NRL and Sigm Tau were presented in a paper at the 17th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting held December 3-5, 1985[1]. A copy of the paper is attached to this report. In summary, the contract goals have been successfully achieved. The cavity stabilization system has resulted in greatly improved long term stability, the masers are much more efficient in the use of hydrogen, the environmental isolation is very good, and the masers are smaller, lighter and less expensive than past designs.

E. CONCLUSIONS

The improved hydrogen masers delivered under this program demonstrate performance which will enhance the frequency stability, reproducibility, and reliability of time and frequency organizations and also provide a basis for improved experimental results in space tracking, navigation, geodesy, and radio astronomy.

I INTRODUCTION

The Sigma Tau Standards Corporation Model MHM hydrogen maser frequncy standard is an active oscillator with a natural output frequency of 1,420,405,751.xxx,xxx Hz which is derived from quantum transitions between "hyperfine" energy levels in the ground state of atomic hydrogen. The hydrogen maser proper and the supporting electronics systems are uncomplicated and easily understood. Molecular hydrogen is supplied from a small storage bottle and passes via an electronic pressure control servo to an RF source discharge bulb where the molecules are separated into atoms of hydrogen. Atoms emerge from the source through a small elongated hole, the "source collimator," and then pass through a magnetic "state selector" which directs a beam of atoms in the correct quantum state to a teflon coated quartz storage bulb. The bulb is located within a microwave cavity which is resonant at the hydrogen transition frequency and CW emission from the atoms is produced by maser action. Power is coupled from the cavity by a small coupling loop and is transmitted to the receiver-synthesizer system through a coaxial cable. A high resolution frequency synthesizer system is used with a phase locked loop to maintain a voltage controlled crystal oscillator at a precise submultiple of the maser frequency, and integral dividers, multipliers and buffer amplifiers driven from the crystal produce standard output frequencies for user equipment.

To provide the proper environment for maser action to occur and to minimize systematic perturbations of the maser output frequency, the maser is maintained under high vacuum and the cavity is surrounded by a set of magnetic shields and isolated by a multilevel thermal control system. An axial magnetic field coil provides for control of the internal magnetic field, and a single turn coil placed transversely about the cavity provides a means for measurement of the field by the "Zeeman frequency" method.

One of the unique and important features of the MHM maser is the incorporation of an automatic control system to maintain the maser cavity at a constant frequency. This system and many other features of the maser are described in the attachments and references.

Figure 1 is a drawing illustrating the external appearance of the maser. The maser is mounted on an uninterruptable auxiliary power module in this figure; if desired, this module may be separated from the maser and located remotely.

Figure 2 is a drawing illustrating the internal configuration of the maser physical structures as well as placement of some of the electronics modules.

HYDROGEN MASER EXTERIOR

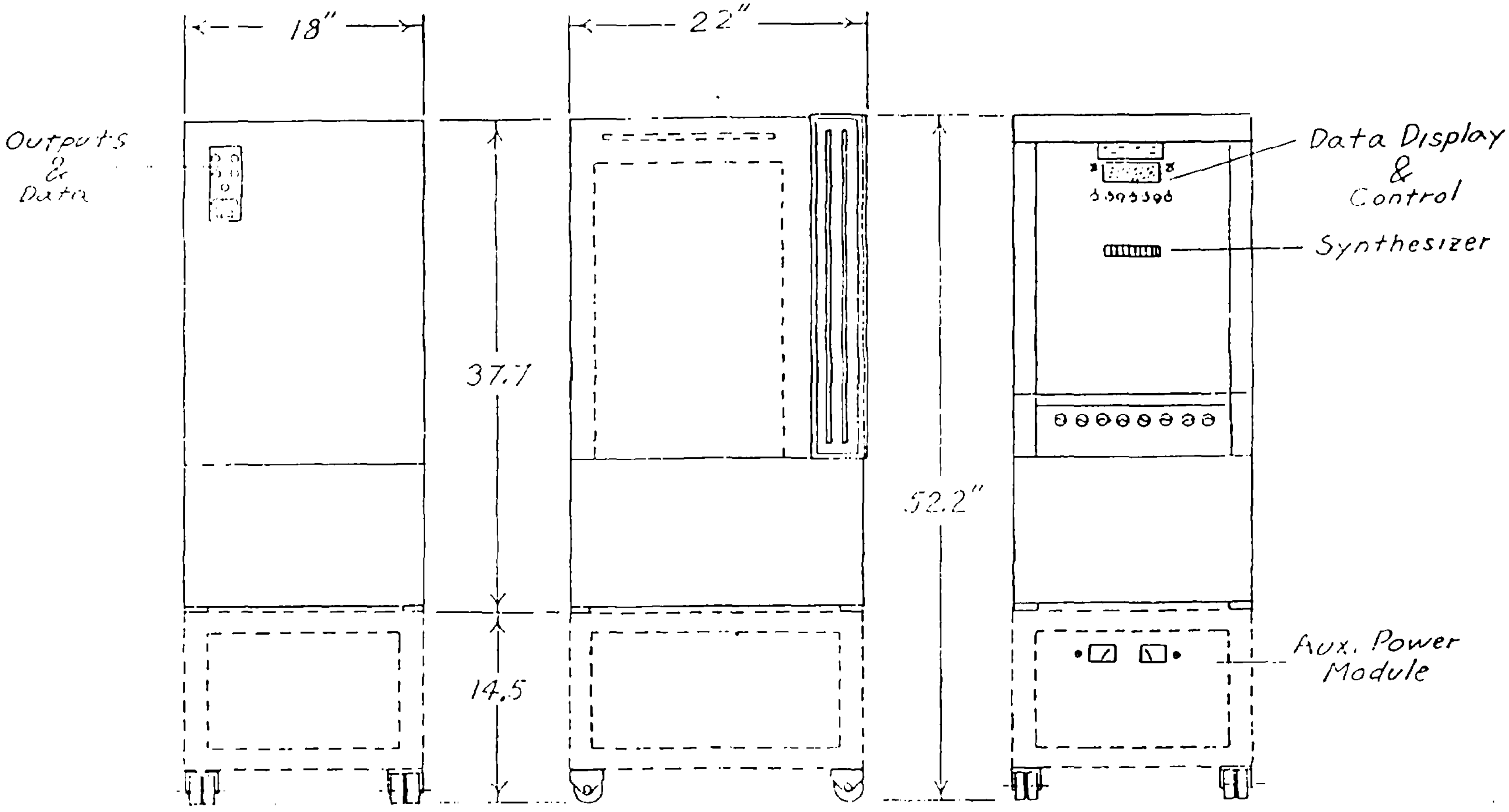

Figure 1

HYDROGEN MASER GENERAL CONFIGURATION

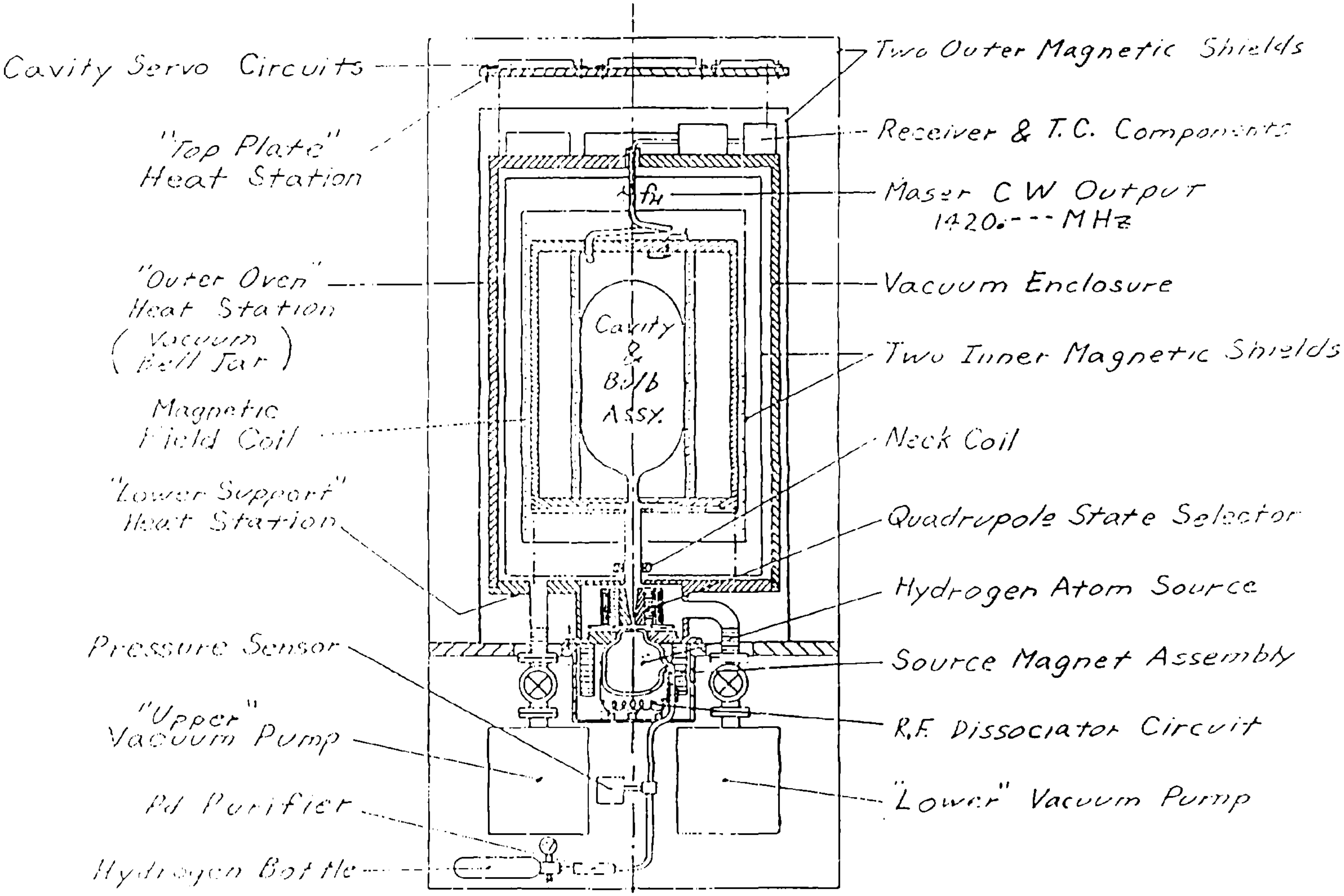

Figure 2

II SPECIFICATIONS

1. Stability, Time Domain: Specified as the maximum instability with a one Hz measurement bandwidth, the two sample "Allan Variance" with no dead time, for measurement intervals between one second and 50 seconds, is given as 5 x 10-13/Tau. For measurement intervals between 50 seconds and 30 days the stability is specified to be better than 1x10-14. The stability specification assumes that no drift or higher order terms are removed from the data, that the maser standard outputs at 5 MHz, 10 MHz or 100 MHz are used to drive the measurement system and that the standard is fully operational, including the cavity stabilization servo, during the course of the measurement. For periods longer than 30 days it appears that the nominal stability will be characterized by systematic effects which are at present outside the range of detectability in relation to world standards. The nominal stability performance will be approximately two to five times better than the specification, depending upon environmental perturbations or other variables.

2. Stability, Frequency Domain: The stability in the frequency domain is characterized by the stability of the crystal oscillator used in the phase locked loop, which has a loop bandwidth of 5 Hz. A Piezo Systems Model 2810007-2 10 MHz unit is used which has a Phase Noise in a 1 Hz bandwidth specified by the manufacturer as follows:

Phase Noise	Offset
-90dBc	1 Hz
-120dBc	10 Hz
-140dBc	100 Hz
-157dBc	1,000 Hz
-160dBc	10 KHz

3. Drift: Included in the stability specification.

4. Settability: The output frequencies are adjustable without phase discontinuity using front panel digital switches which give a resolution of 4.66 x 10-17 and a maximum continuous adjustment range which is limited by the control range of the voltage controlled crystal oscillator to approximately 1x10-7. The crystal frequency coarse adjustment may be used if a greater frequency offset is desired.

5. Reproducibility: Included as the maximum range of stability and environmental specifications.

6. Magnetic Field Sensitivity: The shielding factor for 1.5 Gauss ambient change is over 100,000. If the maser field is set to 250 microgauss (a typical operating value) the resulting frequency change would be less than 1 x 10-14. In general, for ambient field changes of .1 gauss or less and the internal field set to 1 milligauss or less, the maser output frequency will change by less than 1 x 10-14.

II SPECIFICATIONS

7. Temperature Sensitivity: The output frequency will vary less than ± 1 x 10-14 for ambient temperature changes of ± 1 °C in a normal laboratory environment.

8. Barometric Pressure Sensitivity: For a change in atmospheric pressure from 15"Hg to 35"Hg, the output frequency will change by no more than ± 1x10-14.

9. Power Supply Sensitivity: For ± 10% AC line voltage change or change to standby batteries, the frequency will change by no more than ± 1x10-14.

10. Operating Life and Mean Time Between Failure: The hydrogen supply is adequate for 200 years of normal operation. At nominal beam flux the ion pumps are expected to have approximately 20 years of operating life and may be changed relatively quickly by valving them off and restarting with a trapped fore pump. All of the electronics are solid state, so the most probable failure mode is random component failure with an extremely long mean time before failure.

11. Power Supply Requirement: AC power, 115V ± 10%, 50-60Hz, 100 Watts nominal, 150 Watts maximum with automatic crossover to standby batteries. On batteries the nominal current is 2.5 Amperes.

12. Standby Power Operation: A separate 40 A-H battery module with lead-acid maintenance free batteries and AC charging and back up supply is included. The nominal battery life is 15 hours when fully charged. If the AC power is interrupted, the load will be transferred to the AC back up, and if all AC power fails, the load will be transferred to the batteries. The battery module is on casters and can be located remotely, or the maser may be mounted on top of the battery module if desired.

13. Instrumentation: Thirty-two channels of analog data are multiplexed and selectable with binary coded switches or external TTL digital signals. The selected parameter is displayed on a 4½ digit panel meter and a buffered analog voltage is supplied for external monitoring.

14. Automatic Cavity Tuner: An automatic cavity tuner which requires no external frequency reference is installed. The tuner continuously maintains the maser cavity at the proper frequency by reference to the hydrogen maser emission line.

15. Size: Height 37.5 inches, Width 18.4 inches, Depth 22.2 inches. Add 14.5 inches when mounted on the battery module.

16. Weight: Approximately 300 lb; With battery module add 85 lb.

II SPECIFICATIONS

17. Standard Output Signals: There are two 5 MHz outputs, two 10 MHz outputs and one 100 MHz output. The signal levels are typically 1 volt RMS .3 v with a load of 50 ohms. The signal output impedance is 50 ohms (resistive).

18. Nominal Maser Parameters & Calibration Factors.

a. Cavity loaded Q: 45,000

b. Operating line Q: 2 x 10+9

c. Line frequency/Cavity frequency ratio: 2.25 x 10-5

d. Approximate pressure shift ratio at initial Hi/Low pressure settings: 5/1

e. Synthesizer factor (f2 - f1)/f = 4.6580715 x 10-17 (N2 - N1)

f. Initial MPG setting: M = 47334

g. Modulation Period Generator (MPG) factor (approximately):

[M2 -M1] = 2.6 x 10+15 x (Pressure Shift), where "Pressure Shift" = fractional change in maser frequency upon change of pressure from P2 to P1. [Abs. Value]

h. Cavity thermal mass (approximately): 5,000 W-S/ C

i. Cavity temperature: 47 C

j. Other oven temperatures: 46 C

K. Maser frequency correction factors:

Effect	Offset - Hz
2nd order Doppler @ 47 c	-.062,58
Wall Shift	--.038,64
Magnetic Field (.700 mg)	+.001,35

l. Assumed fo = 1,420,405,751.775,28

m. Nominal oscillation frequency: 1,420,405,751.675,41

n. Corresponding synthesizer setting, N = 86,931,192,000

III DETAILED DESCRIPTIONS AND OPERATING INSTRUCTIONS

A more detailed description of the hydrogen masers developed and delivered under this contract is contained in the operation and instruction manuals which were delivered with the masers. The manuals also include design drawings and circuit diagrams, operating instructions and installation and maintenance istructions. Attachments 1 and 2 are papers published in the course of this work which further describe features of the maser designs as well as some of the theoretical considerations and test results obtained at Sigma Tau Standards Corporation and at the Naval Research Laboratory.

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1. G. A. Gifford, J. D. White and H. E. Peters, "Hydrogen Maser Research and Development at Sigma Tau Standards Corporation and Tests of Sigma Tau masers at the Naval Research Laboratory," Proceedings, 17th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, December 3-5, 1985 (Attachment 1.)

2. H. E. Peters and P. J. Washburn, "Atomic Hydrogen Maser Active Oscillator Cavity and Bulb Design Optimization, "Proceedings, 16th Annual PTTI Meeting, 1984 (Attachment 2.)

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ATTACHMENT 1

Hydrogen Maser Research and Development at Sigma Tau Standards and Tests of Sigma Tau Masers at the Naval Research Laboratory

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INTRODUCTION

Two hydrogen masers of the active oscillator type using automatic cavity stabilization, but without active feedback gain, were designed, built and tested by Sigma Tau Standards for the Naval Research Laboratory (NRL). The masers were tested at Sigma Tau Standards prior to shipment and again at the NRL for a period of ten weeks following delivery. In addition, Sigma Tau has modified a Small Hydrogen Maser previously built to operate with cavity feedback to become an oscillating maser without feedback.

MASER DESIGN

The primary purpose of NRL's purchase of the two Sigma Tau Masers was to evaluate the long term stability of a hydrogen maser using the modulated cavity servo system developed by Sigma Tau. The design has been previously described [1,2] and will only be summarized here. The masers use a high-Q cavity with a thin quartz tube to provide dielectric loading and thus some reduction in cavity size as compared with previous oscillating hydrogen masers. Four magnetic shields are used. The state selector is a quadrupole assembly developed and manufactured by Sigma Tau. Both masers are designed to operate on either 115 VAC or 28 VDC and came equipped with a battery backup and an automatic charging system.

The cavity control circuit uses modulation of the cavity frequency about the nominal center tuning point to determine any cavity mistuning. The frequency of the cavity is alternately stepped between two tuning points which are equally and oppositely spaced about the center. The maser output signal amplitude is then synchronously detected with the modulating signal to determine the magnitude and direction of the mistuning. When the cavity is perfectly aligned, the amplitude modulation of the output signal is nulled. As will be shown in the phase noise measurements, the effect on the output signal at 5 MHz is 100 db below the carrier.

TESTING

The goal of the testing program at NRL was to measure the normal operating performance of the clocks, with particular attention being given to the long term drift. Measurements were made of short term stability, phase noise, IF signal level, ion pump loading and frequency drift with respect to the U.S. Naval Observatory (USNO). All tests were performed at NRL in a laboratory environment. These results were compared with the data that were taken at Sigma Tau prior to shipment. No drift was removed in any subsequent calculation.

The masers were delivered to NRL by the manufacturer under power for ion pump operation only. No problems were noted in delivery. Warm up time for the masers to achieve temperature stability and oscillation was 1 day for maser serial number N1 and about three days for maser number N2. The difference in warm up is due to a deliberate design difference in the thermal control systems of the two units. Both were operated on unconditioned 117 VAC power in a laboratory environment. Temperature control was on the order of two degrees C peak to peak. There was one air conditioning failure during the test period.

Short-term stability tests were performed using the 100 MHz outputs into a single mixer with one maser offset by approximately 1 Hz. The masers were measured against each other and also against NRL's house standard VLG-11 hydrogen maser (serial number P12). For measurements with averaging times greater than 1000 seconds, NRL's long-term data system was used. The long term system uses multichannel dual-mixer technology and allows measurements of up to 48 clocks simultaneously [3]. Data were taken at Sigma Tau using a single mixer prior to shipment and the results are shown in Fig. 1. This analysis assumes equality of the two clocks under test and thus includes division by the square root of two. Figures 2, 3 and 4 show the results of the NRL tests. The NRL computations do not assume equality.

The measured performance of the three clock pairs was very close for measurement times from 1 second through 1000 seconds. The measurements taken for averages of 2000 and 4000 seconds using maser N2 show a marked increase in noise as compared with the data taken with the single mixer system at 1000 seconds. This is apparently a measurement artifact due to the nature of the measurement system and the operating frequency of the cavity control servo system of the maser. The cavity modulation frequency of maser N2 is 20 Hz and, as will be seen in the following discussion on phase noise, there are sidebands at that frequency. The offset frequency used in the dual-mixer measurement system is 10 Hz. Thus, the N2 maser has a spurious output in the dual mixer system at the nominal beat frequency of the measurement. A subsequent repeat of the single-mixer test confirmed that the data shown in Fig. 1 and 2 for maser N2 had not degraded.

PHASE NOISE

Phase noise measurements were made using the 5 MHz outputs. For this measurement, the maser synthesizers were adjusted to provide essentially zero offset for the period of the measurement. No phase-lock techniques were used. Figure 5 shows the close-in phase noise for maser N1 vs N2. The peak at about 3 Hz offset from the carrier is due to the loop bandwidth of the maser crystal control loops. The peaks at 20 and 25 Hz are due to the cavity control modulation for N2 and N1 respectively. The 60 and 75 Hz responses are the third harmonics of the square wave modulation.

Figure 6 is a plot of the phase noise of the same clocks covering the frequency range out to 100 kHz. The largest discrete noise source is due to IF feedthrough in maser N2 at 5.751 kHz and its odd harmonics. The remaining peaks seem to be related to power supply switching frequencies leaking through to the RF outputs. As a way of identifying which of the two masers was responsible for the spurious outputs, the same tests were run using the VLG-11 maser as a reference. Figures 7 and 8 are for maser N1 and Figs. 9 and 10 show N2. Using these three points of comparison, the conclusion is that IF feedthrough and power supply noise are primarily in maser N2. It should be noted that the phase noise of the early VLG-11 masers, including P12, is quite poor within 100 Hz of the carrier due to the crystal oscillator. The power supply leakage at about 16 kHz is in maser P12.

FREQUENCY DRIFT

One of the major factors limiting the use of active hydrogen masers as clocks for long-term timekeeping has been frequency drift. NRL's experience with VLG-10 and VLG-11 masers has shown drift rates of just less than 1×10^{-14} per day. Since the Sigma

Tau masers included a continously operating cavity frequency control servo, a measurement of such drift is very significant. In order to determine the drift, several measurement techniques were used. Each Sigma Tau clock was measured on the long-term dual-mixer system over a period of about 6 weeks against each other, the VLG-11 and NRL's house cesium clock (HP 5061/004). Measurements were also made against the U.S. Naval Observatory (USNO) Master Clock. Relative time measurements were made against USNO using the carrier of television station WTTG as a common phase reference [4,5]. GPS common-view measurements were made using a single-frequency time-transfer receiver and the data published by USNO to verify the television method.

Figure 11 shows the phase of the Sigma Tau masers relative to each other. For the span shown, the drift rate between the two is just less than 1 x 10^{-14} per day. To determine the source of the drift, each maser was referenced to the cesium standard, Fig. 12. This showed a possible drift in maser N2 and an apparent frequency jump in either N1 or the cesium. Figure 13 plots the frequency offset of each clock with P12 as a reference, confirming that the frequency jump in the previous figure must have been in the cesium and not in the maser N1. Figures 14 and 15 show the phase comparisons to USNO for masers N1 and N2 respectively. Figure 16 verifies the TV comparison method, showing NRL's cesium with respect to USNO by both methods. The television time comparison with USNO clearly shows that significant drift is present in maser N2. There is no clearly discernible drift in the N1 data, and a linear fit to the frequency showed less than 1 x 10^{-15} per day drift. A fit of the N2 data indicates an average drift rate of about -7 x 10^{-15} per day for the period.

Readings of the analog monitors of various maser operating parameters were taken several times during the test period. The available monitors include oven voltages, servo loop parameters, power supply voltages, and pump currents. Only a few showed significant changes over the period of the test. Of these, the maser output power as shown by the signal level in the receiver IF, Fig. 17, and the cavity tuning register in Fig. 18 show correlation to the frequency drift for maser N2. Ion pump currents in both masers were stable for the entire test period with currents no more than 50 microamps. There were no indications of any other abnormalities in the maser physics units.

OPERATION

Another major concern in the use of hydrogen masers is the difficulty of operation in terms of special requirements for sites, maintenance, and reliability. As described earlier, these masers have been operated in a normal laboratory space. Their size and weight are sufficiently small so as to allow movement within the laboratory easily.

For the period covered by this report, there were no observed failures. There was one change in performance. Maser N1 experienced a large jump in the crystal oscillator control voltage 3 weeks into the test, as shown in Fig. 19. The offset and stability of N1 were not affected. Based on subsequent measurements, it was determined that this large change was due to a change in the crystal oscillator oven temperature which occurred over a period considerably longer than the maser loop time constant. Although there was no deterioration in laboratory performance, the oscillator will be replaced.

In order to be able to measure maser N2 accurately on the long term data system, the cavity servo modulation frequency will be changed slightly to avoid the spurious 10 Hz beat note. No other maintenance has been required.

SMALL HYDROGEN MASER

During the past year at Sigma Tau Standards the analysis of maser cavity structures has been extended to establish the smallest practical active oscillator cavity assembly using quartz dielectric loading. Experimental tests of one small assembly in an operational maser has been successfully carried out and confirms the theoretical analysis and also demonstrates that a relatively small, self oscillating, atomic hydrogen maser is indeed feasible.

The test bed for the new small cavity assembly was the Small Hydrogen Maser (SHM) previously developed for the United States Air Force which used electrodes surrounding the maser storage bulb to reduce the cavity size. The original SHM required active cavity gain to oscillate and the relatively poor performance achieved with this technique was reported [6]. Figure 20 is a picture of the SHM illustrating the small size and compact packaging of this maser. Figure 21 is a drawing showing the new cavity configuration upon which the new work reported here is based. There is an elongated copper cavity with a very heavy wall quartz atom storage bulb within a close fitting quartz cylinder. The bulb is fastened to the cylinder with three thin quartz shims on each end using thin layers of high vacuum epoxy as an adhesive. There is a thin layer of teflon between the quartz cylinder ends and the cavity ends for thermal expansion relief, and spring tension from the cavity end plates make a very rigid structure.

The inside dimensions of the original SHM cavity were 7.73 cm (6.09 inches) diameter by 22.86 cm (9 inches) long. As discussed in reference [2], the most important factor in establishing whether a particular hydrogen maser is a practical self oscillator is the product of filling factor (n') times cavity quality factor (Q). Computations have been made for a variety of cavities of differing lengths, bulb sizes, dielectric loading amount and cavity radius at resonance. Figure 22 illustrates the results for one particularly promising combination of cavity and bulb length and bulb inside diameter and shows the variation of n' x Q and cavity radius as the thickness of the quartz dielectric is varied.

It was established from the analysis that one feasible configuration would fit within the copper cavity originally used in the SHM. This is shown in the lower dotted lines in Fig. 22. Parts with the dimensions indicated were procured, the bulb coated with teflon, and the cavity assembled and tuned with the following results.

Q_1 = 27,300 (Loaded Q)

B = .062 (Coupling Coefficient)

Q_o = 29,000 (Unloaded Q)

n' = .38 (Calculated)

$n' \times Q_o$ = 11,070 (Using Experimental Q_o).

The calculated Q_o for this geometry was 30,544 giving

$n' \times Q_o$ = 11,607 (Calculated)

This is within the experimental error due to the approximations made in the analysis. The calculated cavity diameter was also in good agreement with the experimental diameter and the new quartz cylinder and bulb assembly fit neatly into the original SHM copper cavity.

The SHM has been reassembled using the new configuration and it is found that the maser oscillated reliably with relatively low flux (.04 moles of H_2 per year.) This is not as efficient as the larger Sigma Tau masers (.01 moles H_2 per year) but is excellent in relation to early maser designs and would give a hydrogen pump lifetime estimated as over 5 years using a 20 liter per second sputter ion pump.

The product of n' x Q indicated in Fig. 22 for the SHM is nearly the minimum for a reliable maser oscillator, and the new SHM experiment has been carried out primarily to establish the concreteness of the analysis and design concepts. For example, the product n' x Q for the large Sigma Tau (NRL) masers is well over 25,000 in comparison to the 11,600 for the SHM. The factors and dimensions for a better design than the present implementation of the SHM is also indicated in Fig. 22. This "improved design" would have a much lower threshold for the oscillation and better efficiency, yet the cavity is still quite small, only 17.15 cm (6.75 inches) diameter.

Limited testing of the SHM was done at NRL in conjunction with the tests of the two larger masers. It was found that the SHM required strong magnetic field settings in order to oscillate. The high field should result in increased sensitivity to external fields and limit stability. The magnetic problem was due to construction problems and is not inherent to small maser design. Data showing Allan Variance for averaging times of 1 second to 1000 seconds were taken using maser N1 as a reference, Fig. 23.

CONCLUSIONS

The two Sigma Tau masers delivered to NRL are working without major problems. The performance of maser N1 is very good with no measureable drift and good active maser short term stability.

Maser N2 is nearly as good but does show long term drift similar to other active masers. Sigma Tau Standards believes that some improvement will occur with longer periods of operation. Maser N1 was built about 1 year prior to N2 and also showed initial decays in IF level. The Small Hydrogen Maser did show the type of performance one would expect from a maser with a lightly coupled cavity. The flicker floor apparently reached at 100 seconds is probably due to the high sensitivity to magnetic field.

ACKNOWLEDGEMENTS

The NRL authors wish to thank Mr. Alick Frank of NRL for his assistance in setting up and conducting the experiments reported here. They also acknowledge WTTG Television in Washington for their support and assistance in the installation and operation of the television time transfer equipment.

Sigma Tau standards wishes to recognize the government contracts which supported the maser development reported here. The Light-Weight Hydrogen Maser effort (Small Hydrogen Maser) was sponsored by the Deputy for Electronic Technology (RADC/ET), Air Force Systems Command, under contract number F19628-79-C-104. The NRL maser development and procurement was supported by the Naval Research Laboratory under contract N00014-83-C-2015.

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ATTACHMENT 1

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3. S.R. Stein and G.A. Gifford, "Software for Two Measurement Systems," Proceedings, 38th Annual Symposium on Frequecny Control, 1984.

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5. To be published.

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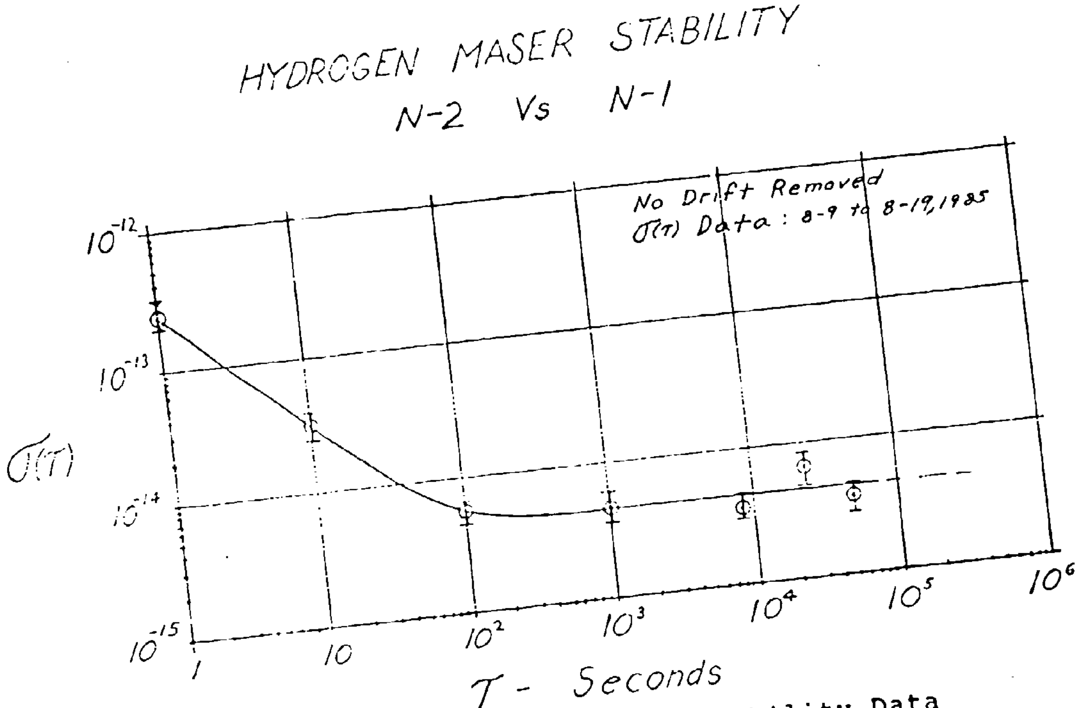
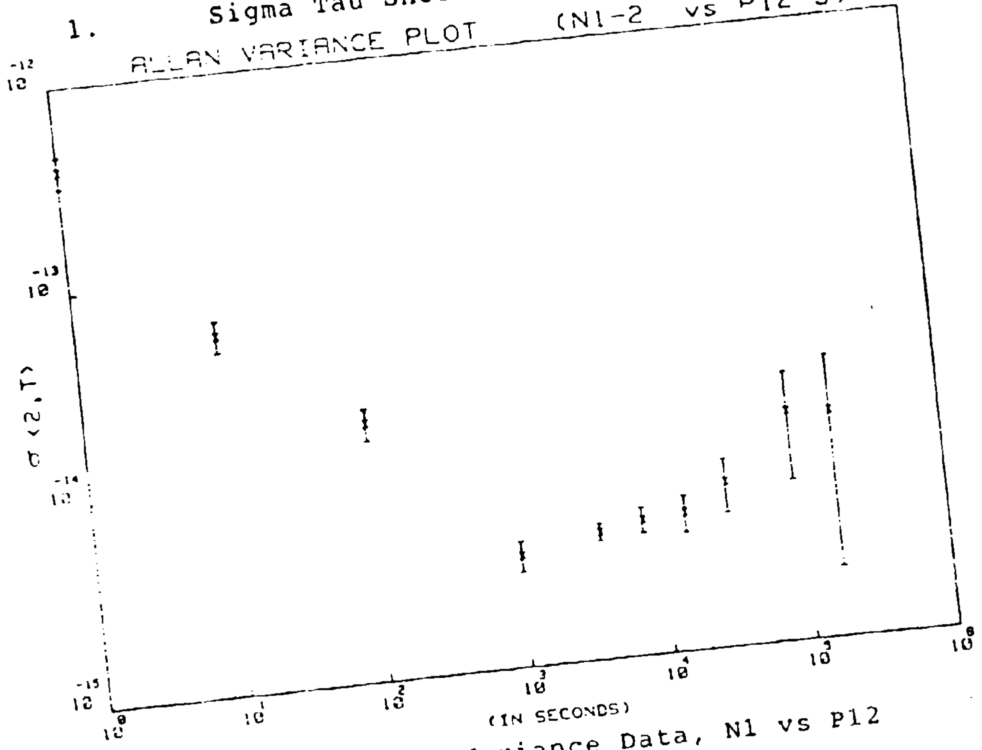
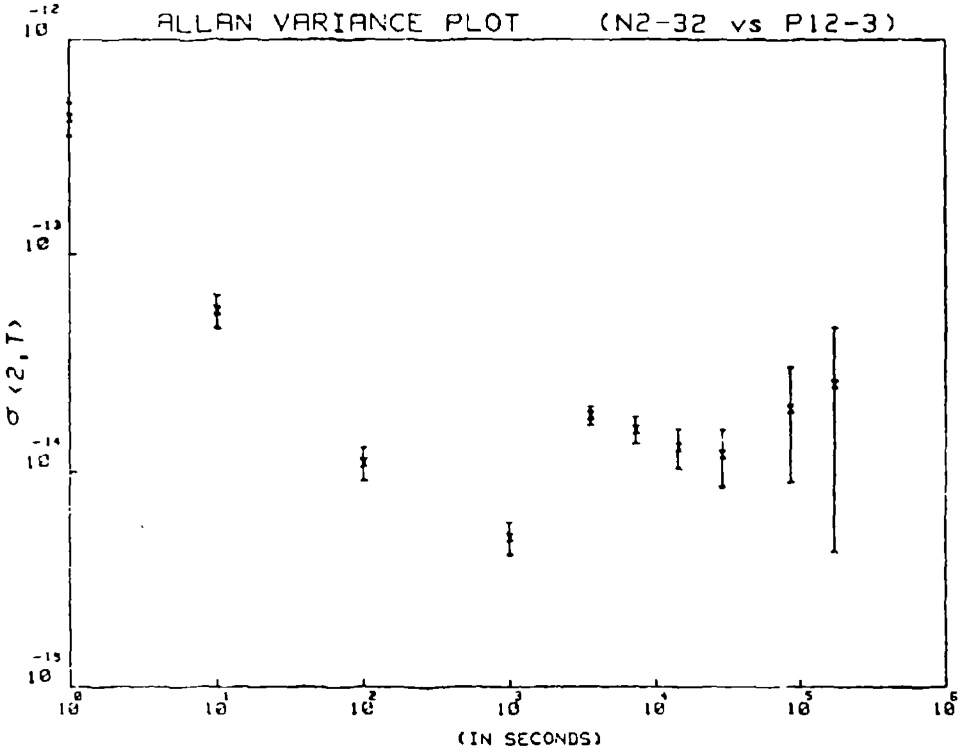
ATTACHMENT 1



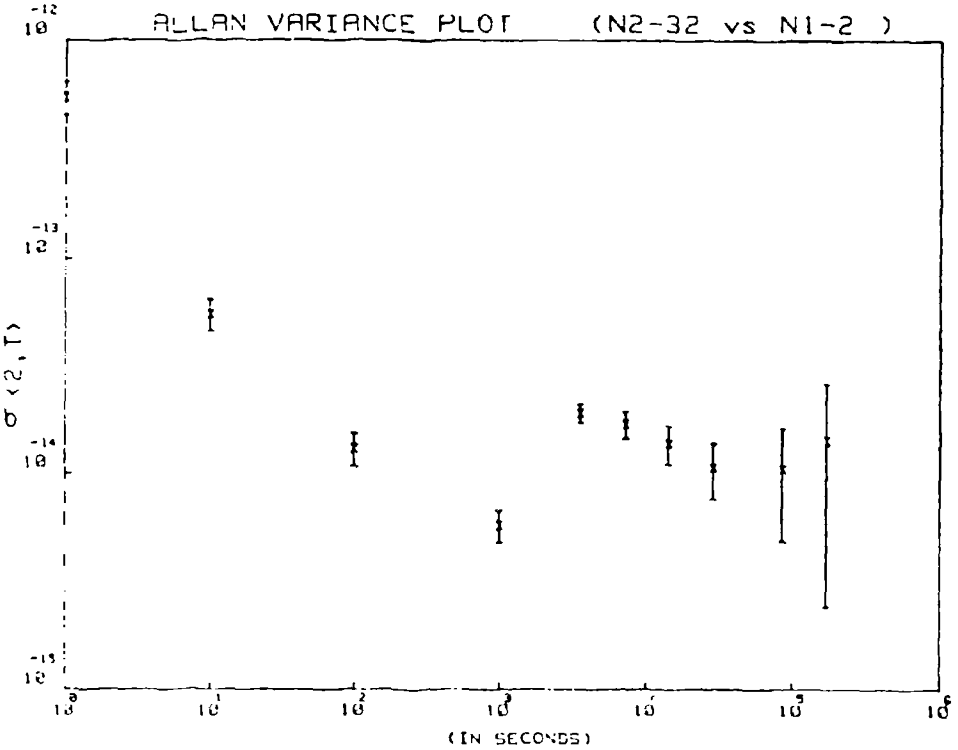
1. Sigma Tau Short Term Stability Data



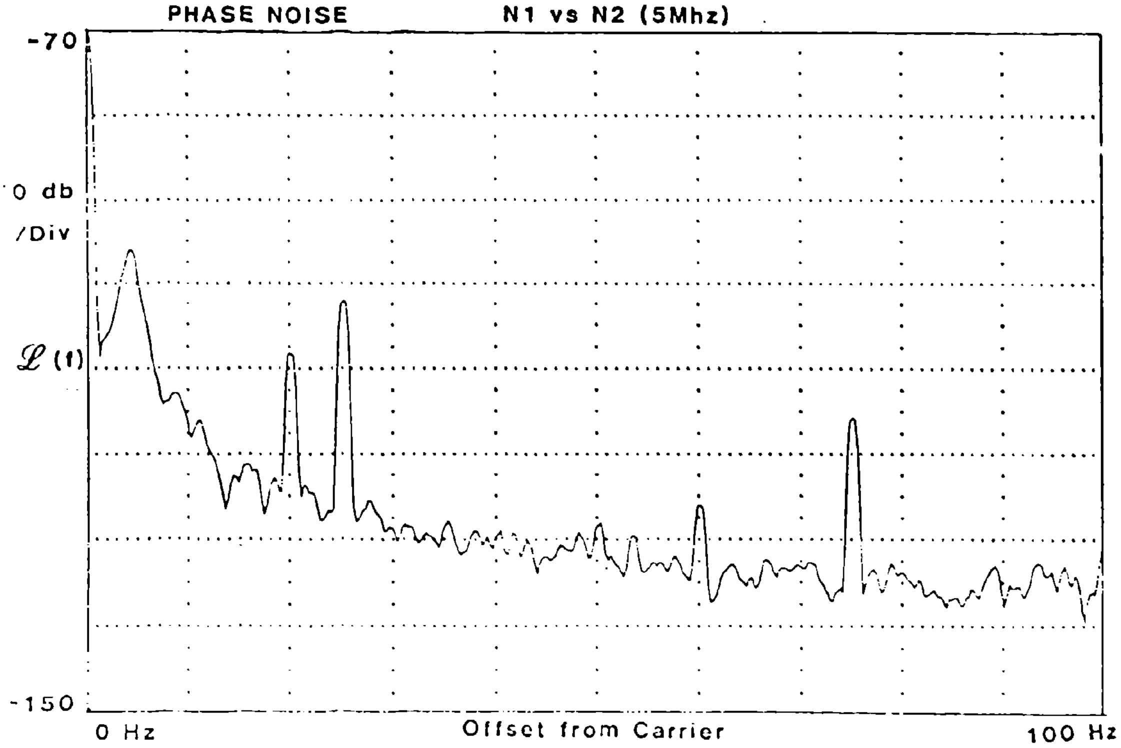
2. NRL Allan Variance Data, N1 vs P12



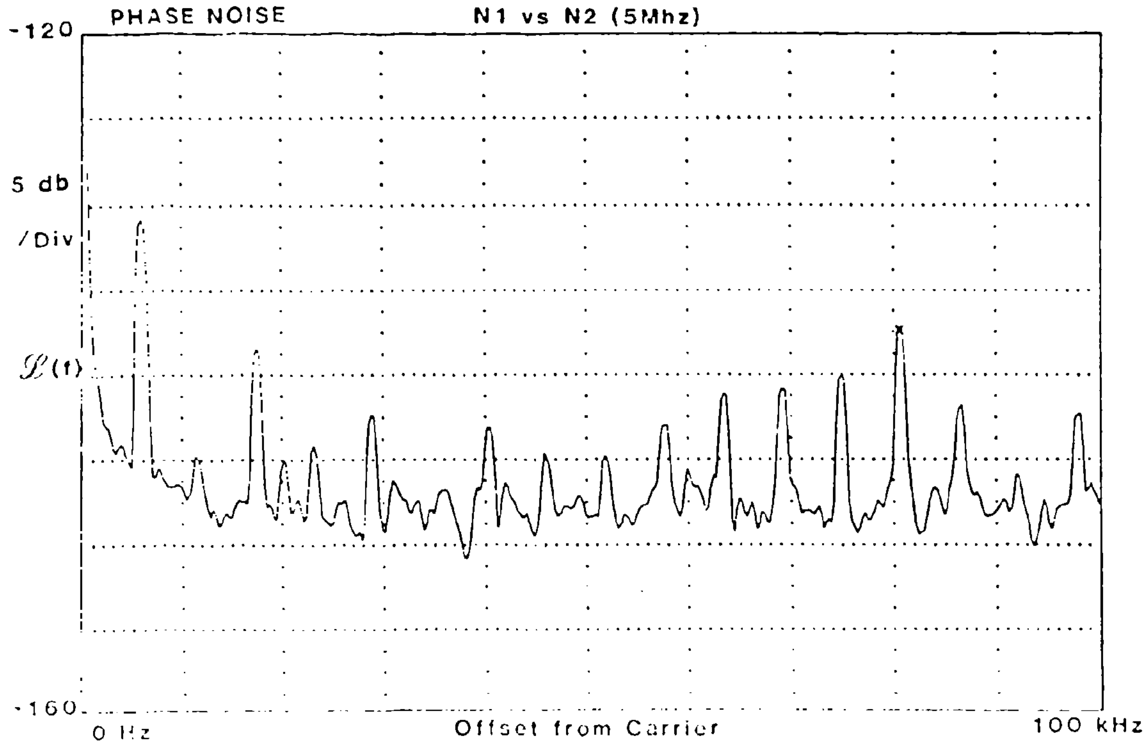
3 NRL Allan Variance Data, N2 vs P12



4 NRL Allan Variance Data, N1 vs N2

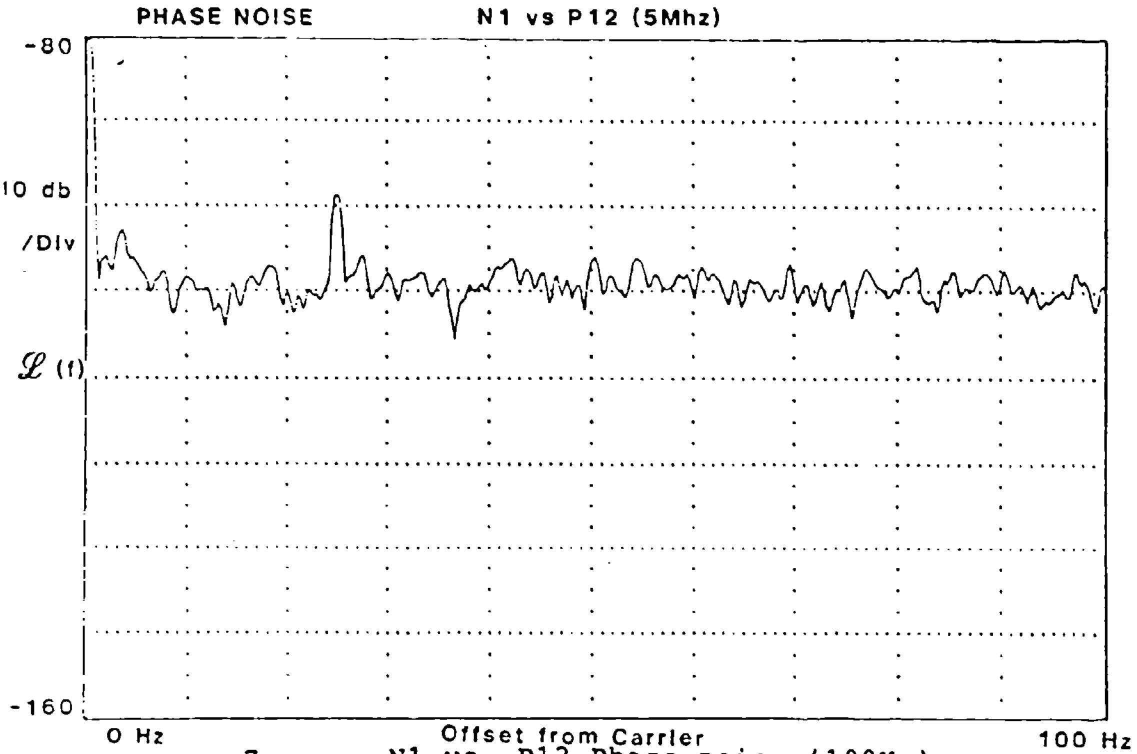


5. N1 vs. N2 Phase noise (100Hz)

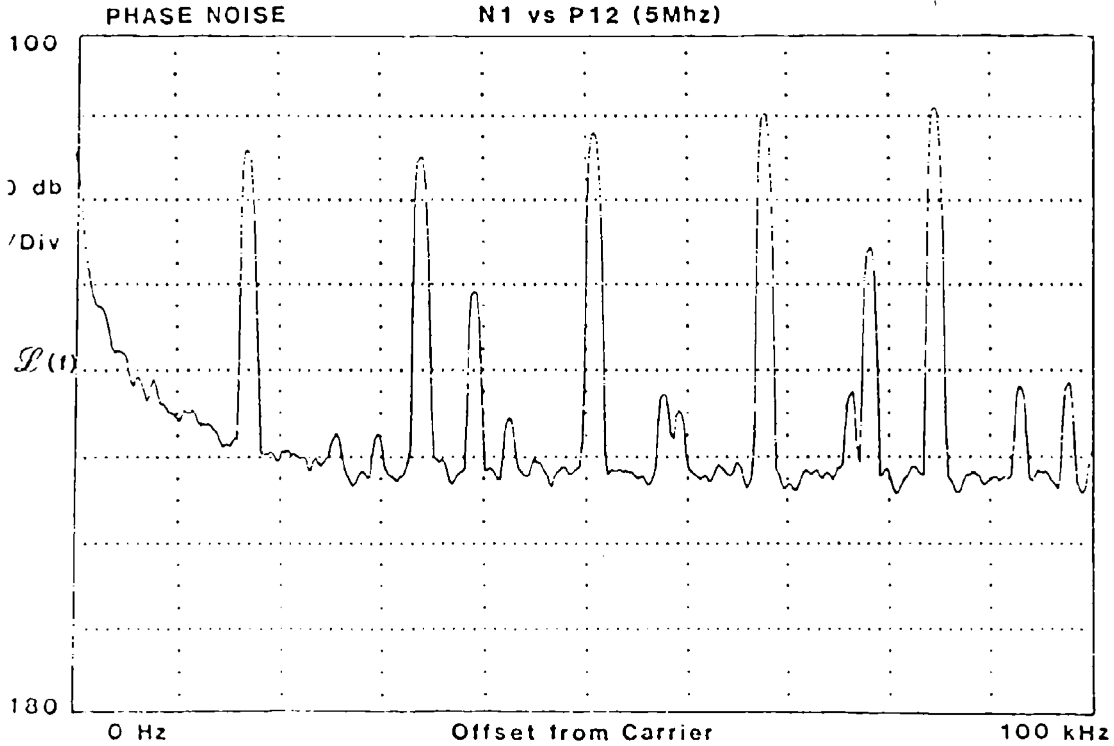


6. N1 vs. N2 Phase noise (100kHz)

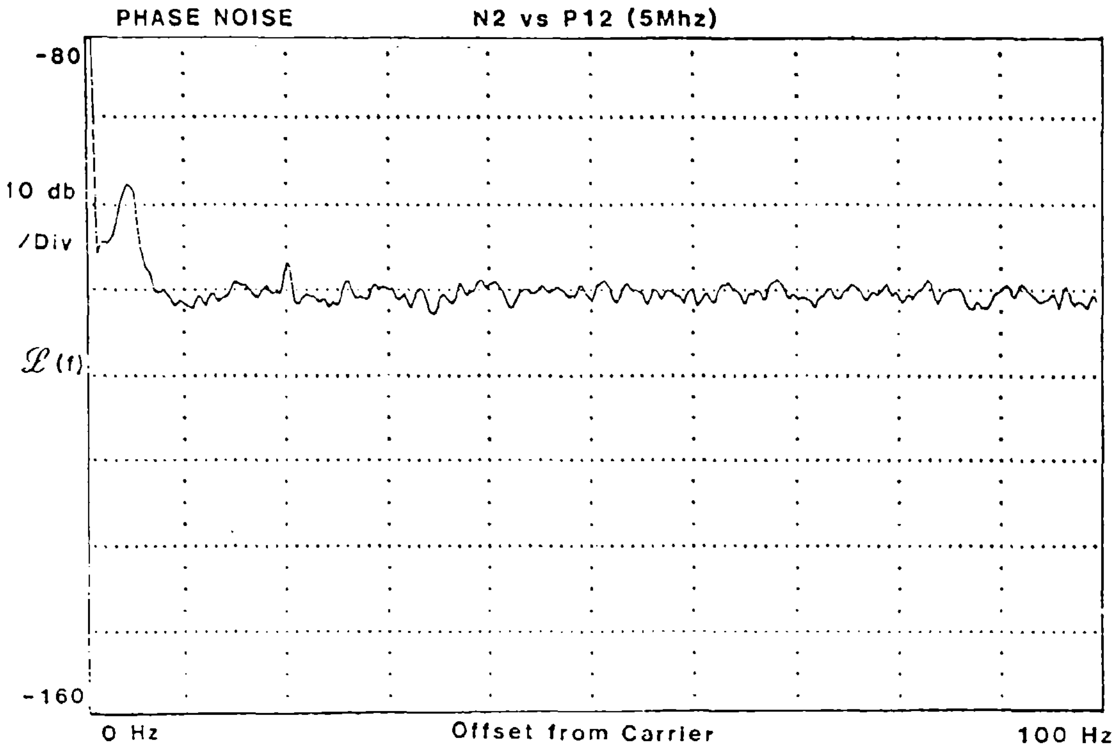
ATTACHMENT 1



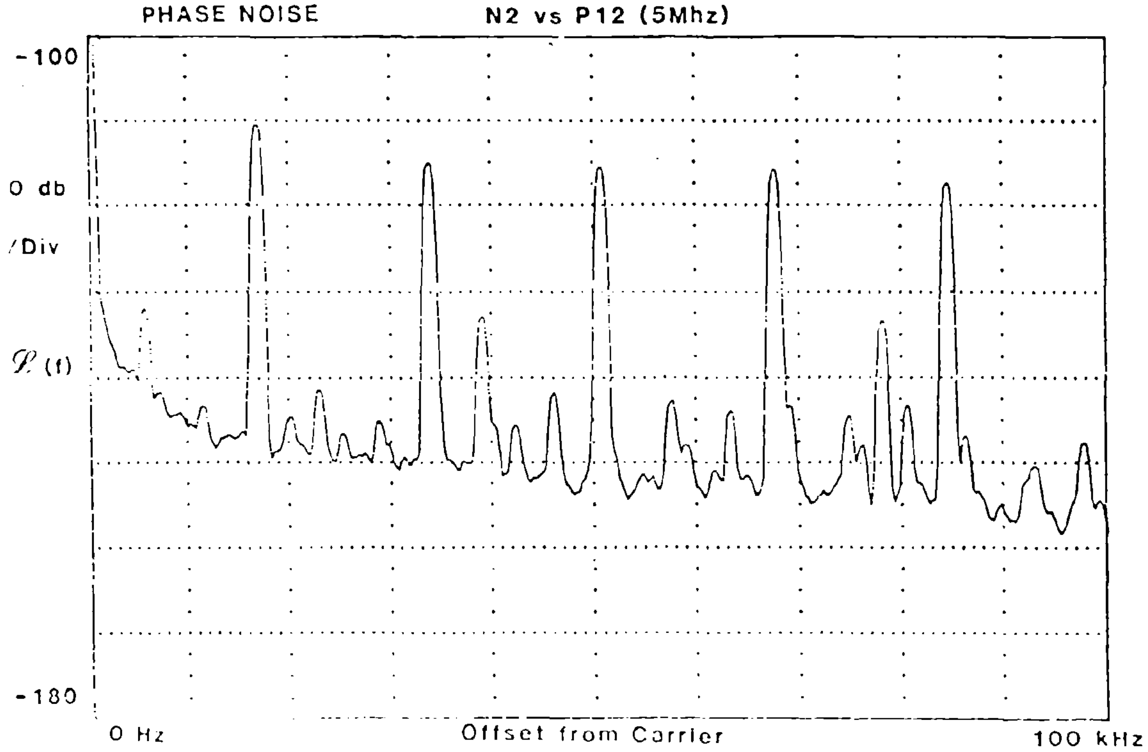
7. N1 vs. P12 Phase noise (100Hz)



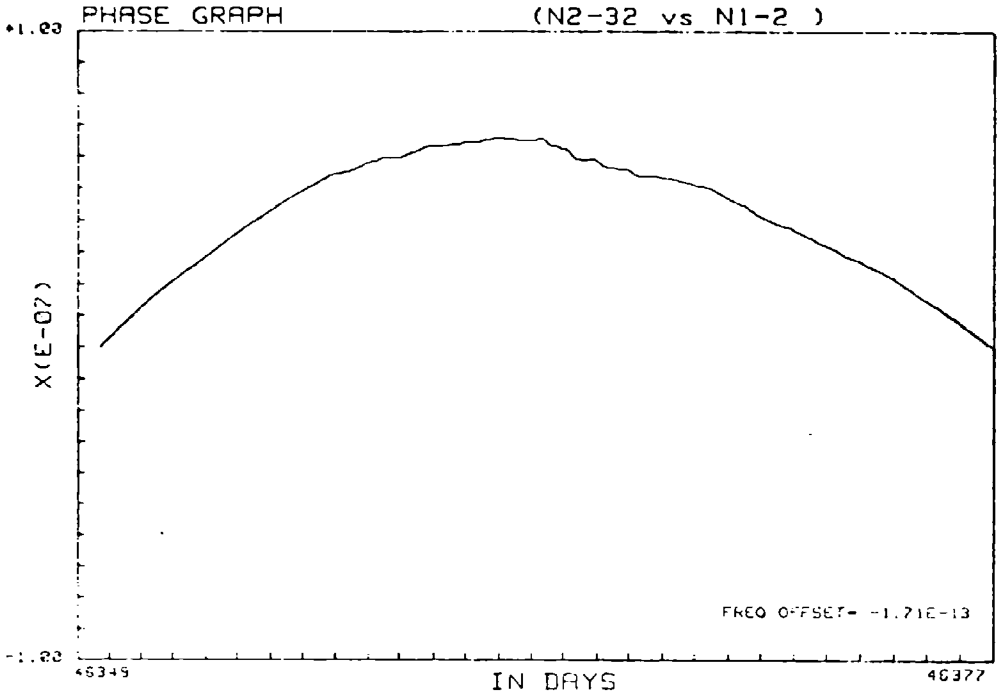
8. N1 vs. P12 Phase noise (100kHz)



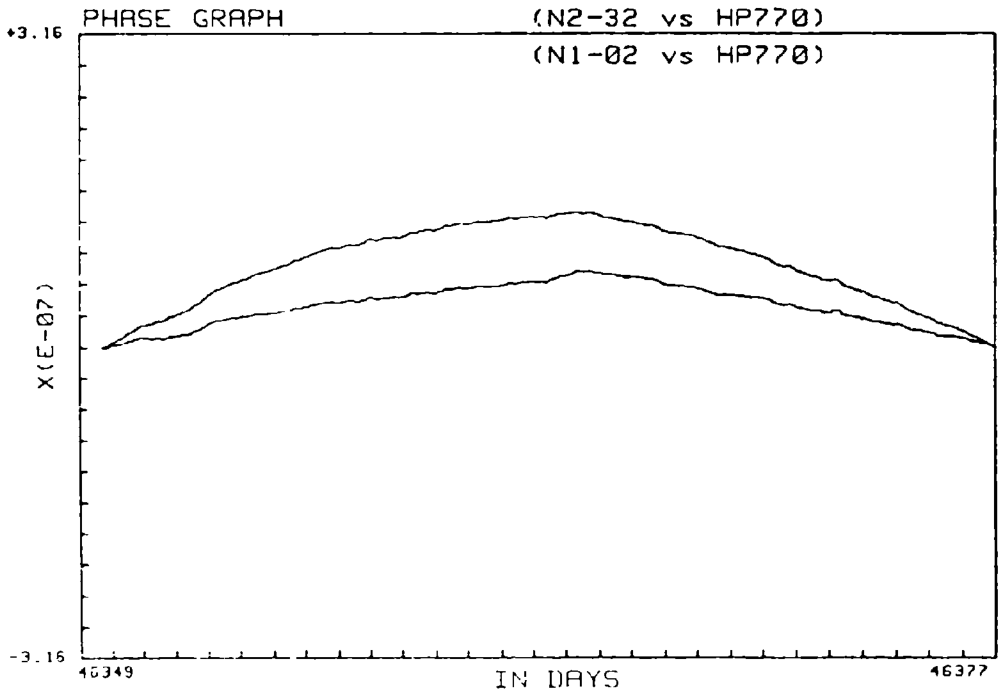
9. N2 vs. P12 Phase noise (100Hz)



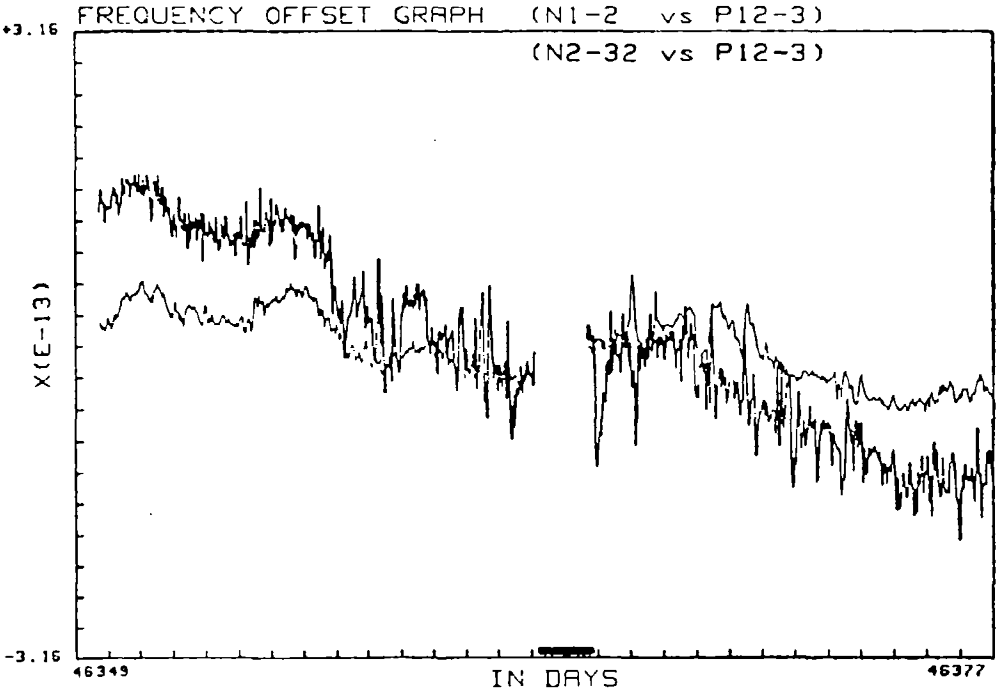
10. N2 vs. P12 Phase noise (100kHz)



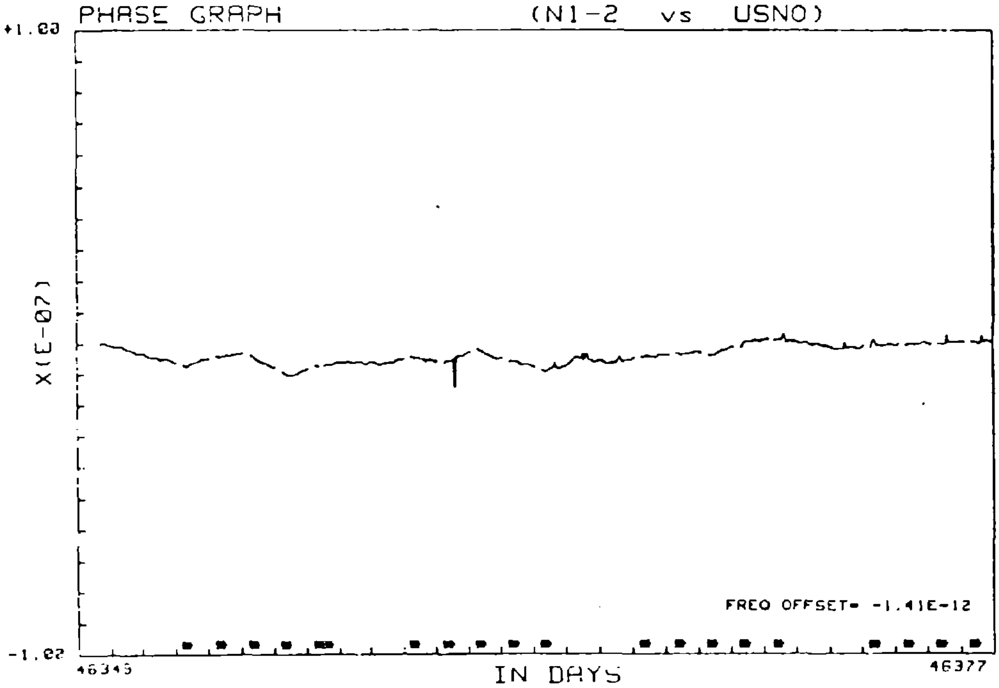
11. N1 vs N2 Phase Plot



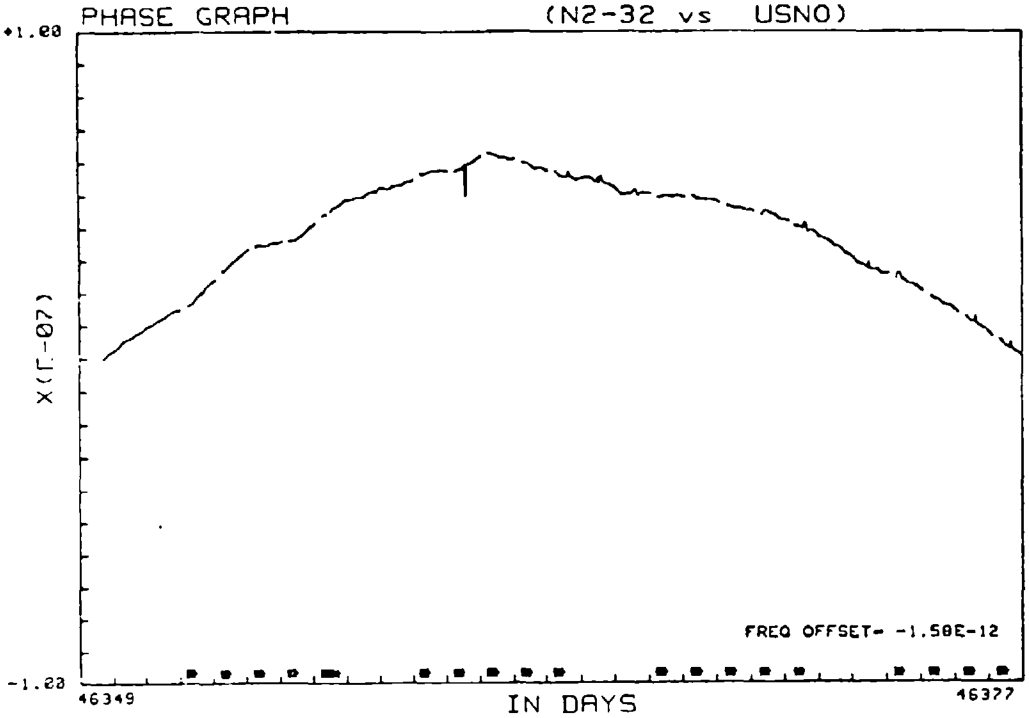
12. N1 and N2 vs CS770 Phase Plot



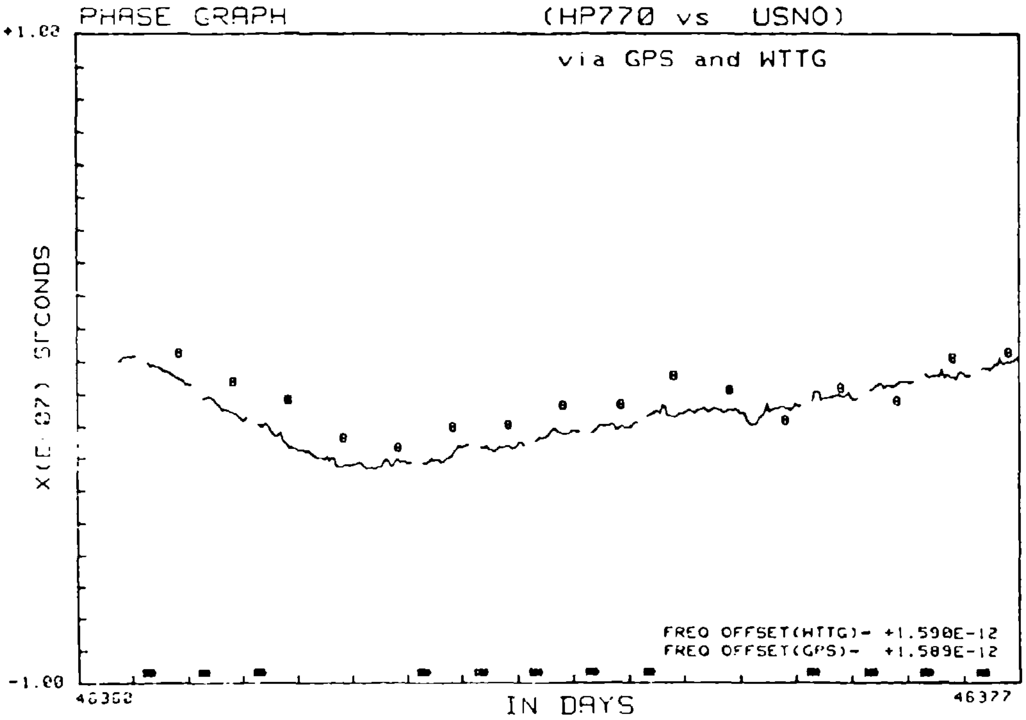
13. N1 and N2 vs P12 Frequency Offset Plot



14. N1 vs. USNO Phase Plot

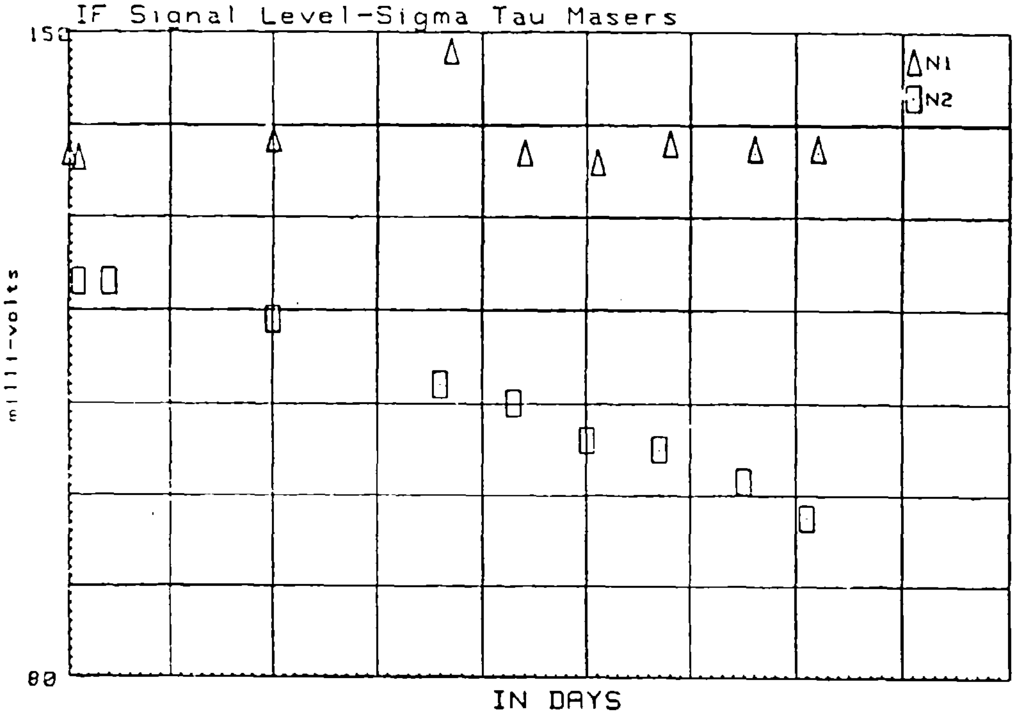


15. N2 vs. USNO Phase Plot

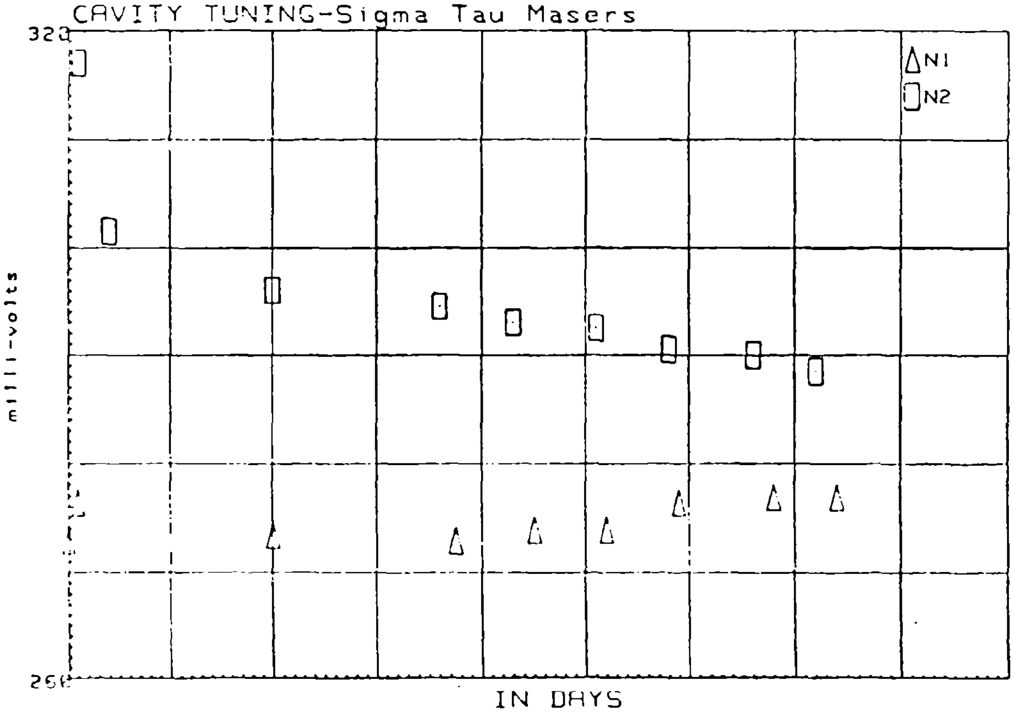


16. CS770 Phase vs. USNO via WTTG and GPS

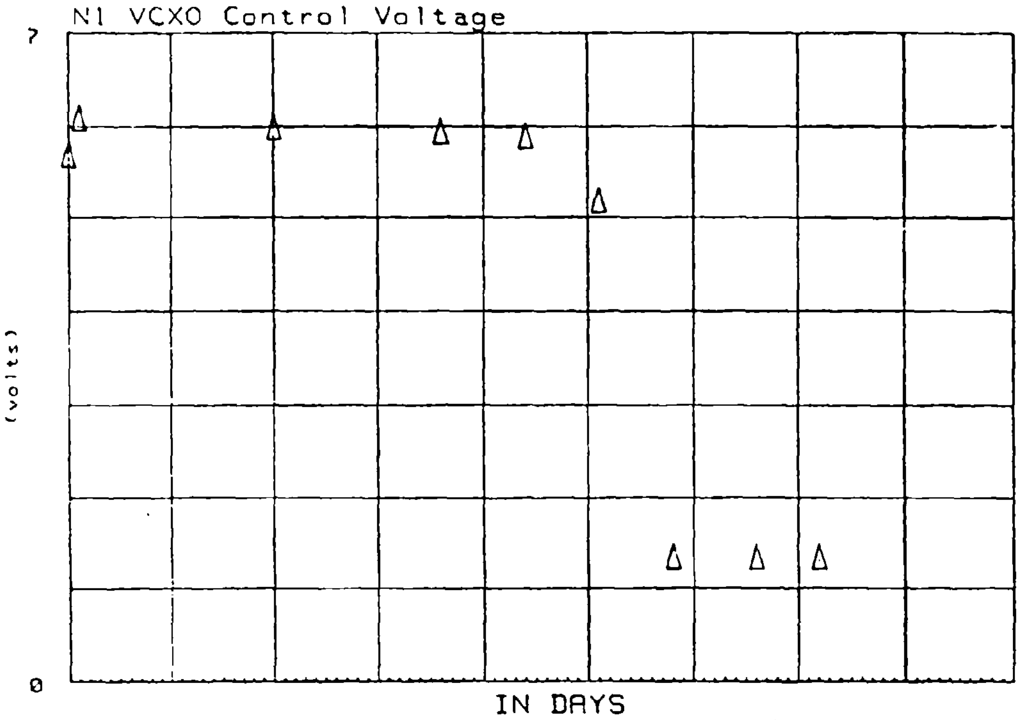
ATTACHMENT 1



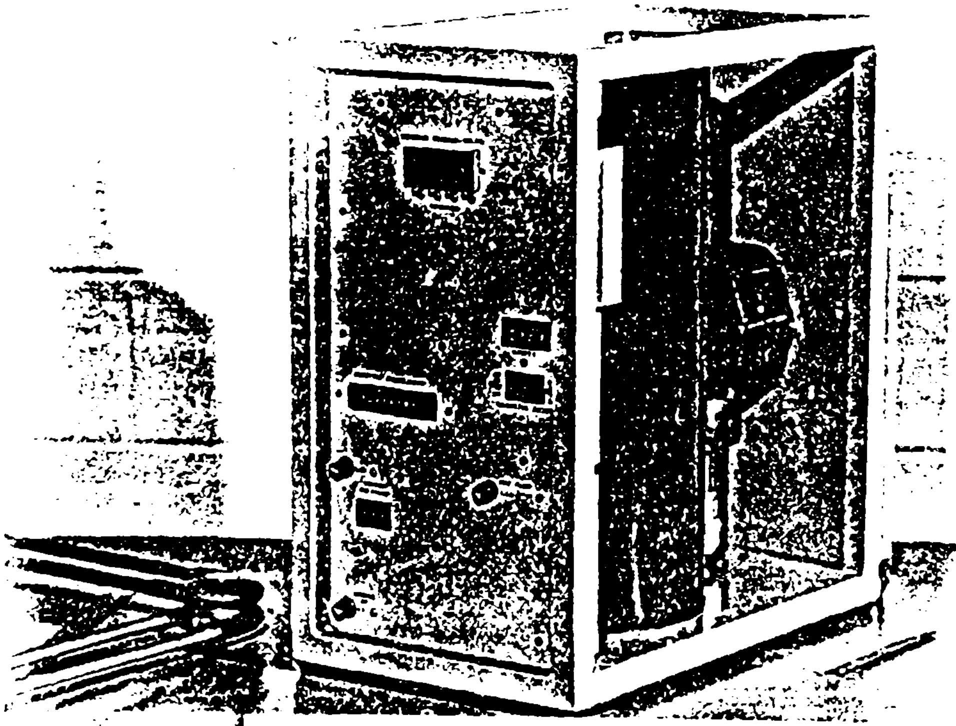
17. Maser IF Level



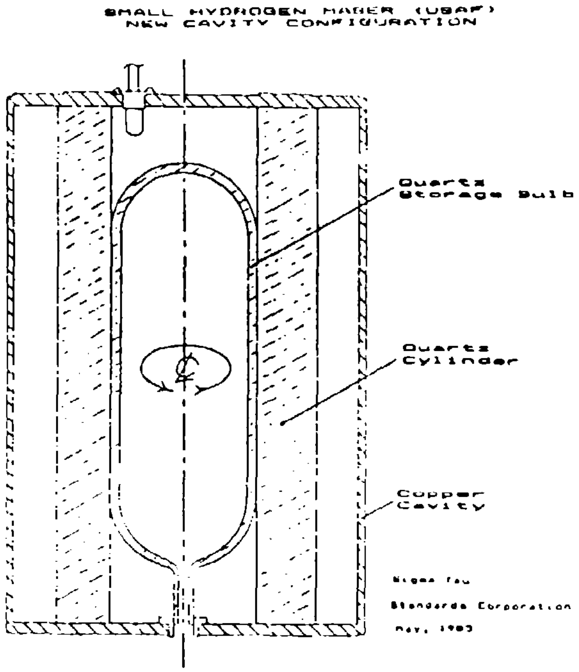
18. Maser Cavity Tuning



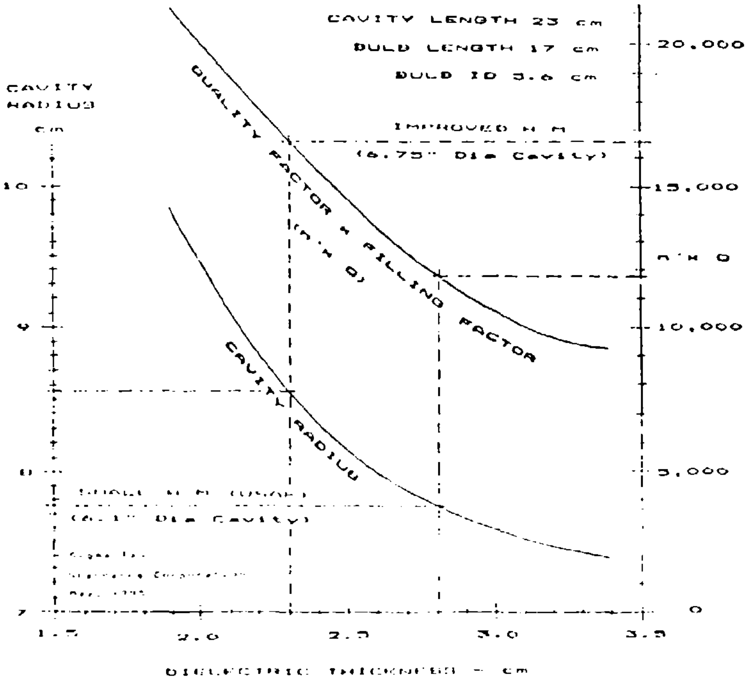
19. N1 VCXO Control Voltage



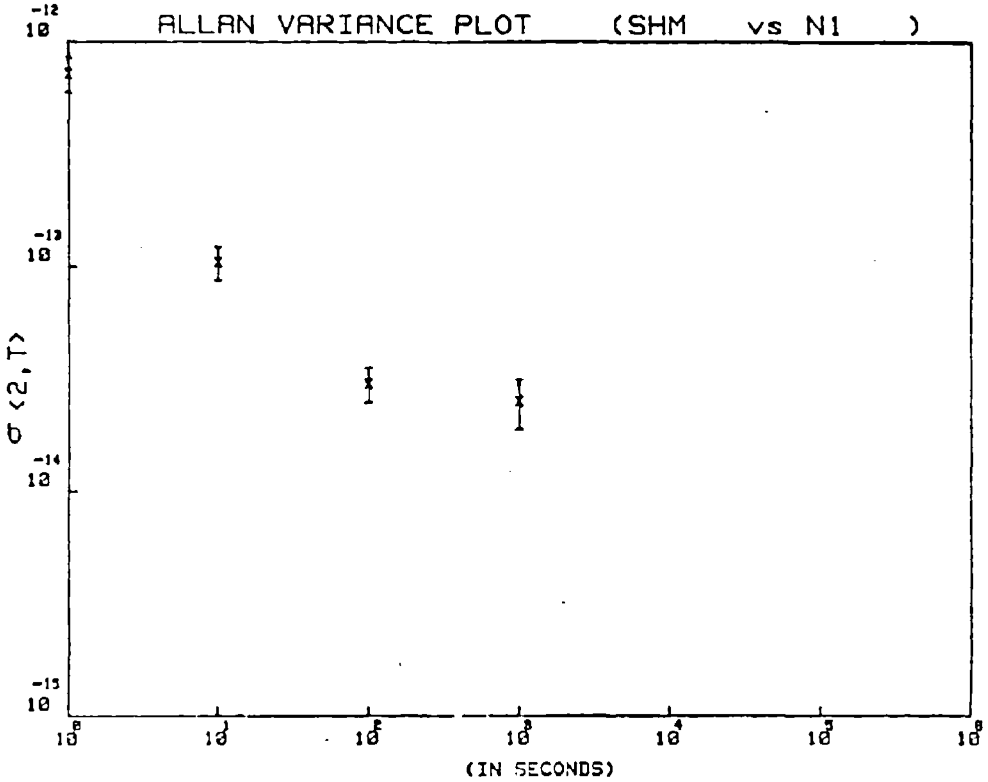
20. Small Hydrogen Maser Photo



21. Small Hydrogen Maser, New Configuration



22. Small Cavity Parameters



23. Small Maser Test Data

ATTACHMENT 2

ATOMIC HYDROGEN MASER ACTIVE OSCILLATOR CAVITY AND BULB DESIGN OPTIMIZATION

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ATTACHMENT 2

ATOMIC HYDROGEN MASER ACTIVE OSCILLATOR CAVITY AND BULB DESIGN OPTIMIZATION

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Sigma Tau Standards Corporation
Tuscaloosa, Alabama

ABSTRACT

The performance characteristics and reliability of the active oscillator atomic hydrogen maser depend upon "oscillation parameters" which characterize the interaction region of the maser: the resonant cavity and atom storage bulb assembly. With particular attention to use of the cavity frequency switching servo (1) to reduce cavity pulling, it is important to maintain high oscillation level, high atomic beam flux utilization efficiency, small spin exchange parameter and high cavity quality factor. It is also desirable to have a small and rigid cavity and bulb structure and to minimize the cavity temperature sensitivity. In this paper we present curves for a novel hydrogen maser cavity configuration which is partially loaded with a quartz dielectric cylinder and show the relationships between cavity length, cavity diameter, bulb size, dielectric thickness, cavity quality factor, filling factor and cavity frequency temperature coefficient. The results are discussed in terms of improvement in maser performance resulting from particular design choices.

INTRODUCTION

In an atomic hydrogen maser, hydrogen atoms are produced in an RF discharge source from which they emerge and pass in a beam through a magnetic state selector, with atoms in the proper hyperfine energy level passing to a quartz storage bulb mounted within a cavity resonant at the hydrogen frequency wherein maser action occurs, producing a CW output signal at the frequency of 1,420,405,751.689,3xx Hz. Figure 1 illustrates the major elements of the physical structure of masers currently constructed at Sigma Tau Standards Corporation. Several of the advantages of this general configuration were described in Reference 1. The optimization of the cavity assembly through computer analysis of the relevant maser oscillation parameters will be the primary subject of this paper.

CAVITY DESIGN AND ELECTROMAGNETIC FIELD DIAGRAM

The cavity configuration used in the Sigma Tau hydrogen masers is illustrated in Figure 2. A copper cylinder and copper end plates form the cavity walls. A relatively thick circular cylinder of quartz is held by spring tension between the end plates, and the quartz atom storage bulb is secured to the quartz cylinder using quartz shims and hard epoxy. The quartz cylinder provides dielectric loading to reduce the outer diameter of the cavity as well as the temperature sensitivity, and at the same time provides rigid support for the bulb and a fixed spacing of the cavity end plates. The electromagnetic field mode is the TE011 mode of the usual hydrogen maser active oscillator. Figure 2 also illustrates the orientation of the electric and magnetic field lines.

Figure 3 shows a diagram of the cavity and bulb assembly which is the model used for subsequent computations. The region within the inner diameter of the storage bulb is Region 1 with the dielectric constant of vacuum. In computing the filling factors, integrations of the z axis magnetic field were performed numerically over the inside volume of the bulb. Region 2, with the dielectric constant of fused quartz, includes the quartz wall of the bulb as well as the wall thickness of the quartz cylinder. The approximation is used that the quartz wall of the bulb ends is equivalent to the effect of the extra wall thickness at the ends of the cylinder, and this is a very adequate approximation since the cavity fields are relatively weak in the end regions and the bulb wall is relatively thin. Region 3, with the dielectric constant of vacuum, extends from the quartz cylinder to the copper side wall of the cavity.

OPERATIONAL EQUATIONS OF THE HYDROGEN MASER

Reference (2) presented the basic operational equations for the hydrogen maser oscillator, and the maser equations presented herein will either be taken from or derived from that reference. By combining equations (15) and (9) of Reference 2, the following equation is obtained for the relative power radiated by the hydrogen atomic beam:

$$P/Pa = 1 - I/Ith - 3q - 2q^2(I/Ith).$$

In this equation, P is the radiated power, Pa = the power available from the beam if the maser were 100 percent efficient, I is the beam intensity (atoms/second), Ith is the flux required for oscillation if spin exchange could be neglected, and q is the spin exchange parameter defined in Reference (2).

Spin exchange is due to collisions between hydrogen atoms within the maser storage bulb and is the main factor which limits the possible oscillation level and line Q of the hydrogen maser. Figure 4 illustrates the severe limitation on beam utilization efficiency as the spin exchange parameter becomes large. The dependence of the spin exchange parameter on the cavity assembly configuration may be expressed (from Ref .2, Eq. 11) as:

$$q = K1/(n'x\ Qc)$$

where K1 is a constant (approximately equal to 1,000), Qc is the loaded quality factor of the cavity, and n' is the "filling factor," which is defined as:

$$n' = \frac{Vb\langle H\rangle^2 b}{Vc\langle H^2\rangle c} .$$

In the foregoing equation, Vb is the bulb volume, Vc the cavity Volume, $\langle Hz\rangle b$ is the z axis magnetic field averaged over the bulb volume and $\langle H^2\rangle c$ is the average of the square of the magnetic field over the volume of the cavity.

Considering only those factors which depend on the cavity configuration, Ith may be expressed as:

Ith = K2x(bulb dia.)/(n'x Qc).

Therefore both the spin exchange parameter and the flux required to oscillate depend upon the product of n' and Qc. The loaded quality factor of the cavity, Qc, is given by:

Qc = Qo/(1 + Pc/Po)

where Pc is the power coupled from the cavity which is available to the receiver input amplifier and Po is the power dissipated within the cavity.

In a practical hydrogen maser oscillator it is very desirable that the coupling of the receiver to the cavity be light to reduce cavity frequency dependence on receiver impedance changes or other external environmental effects, and so Pc/Po is typically a small fraction (of the order of .1 to .3). The above considerations indicate that it is highly desirable to maximize the product of n' and Qo to obtain an efficient and reliable maser oscillator.

ELECTROMAGNETIC FIELD ANALYSIS

The electromagnetic field analysis follows conventional procedures and will not be given in detail in this paper. In outline, we start from Maxwell's equations for the curl of the electric and magnetic fields in material media and use the expressions for the curl in cylindrical coordinates. The general known solution for the electric field is expressed in terms of Bessel's functions of the first and second kinds of orders 0 and 1, and by application of appropriate boundary conditions, differentiations and integrations, several simultaneous equations are obtained which describe the electric and magnetic field coordinate components in the separate cavity regions identified in Figure 3. A computer was then programmed to obtain subroutines for the fields and the subroutines were used in further calculations to obtain the data presented in the pages which follow.

Typical results for the field analysis are illustrated by Figures 5 and 6, which show the electric and z axis magnetic fields for a cavity 12 inches long with a bulb 4.13 inches in diameter having several different thicknesses of quartz cylinder.

Q x n', CAVITY SIZE AND TEMPERATURE COEFFICIENT

In the curves which follow it has been assumed that the dielectric loss factor of quartz is .000,1 and the dielectric coefficient is 3.75. Also, the electrical conductivity of copper = 2.0 microohm-cm and the expansion coefficient of copper = 1.7 x 10-5. The length of the bulb for the 12 inch long cavities is 9.0 inches, and the assumed shape is a straight central section with hemispherical ends. This shape is not quite optimum, but is a practical approximation which more detailed calculations show is very close to optimum. For cavity lengths other than 12 inches, the bulb length was made proportionately greater or smaller. In calculating the cavity frequency temperature coefficients, both the expansion coefficient of quartz and the variation of the dielectric coefficient of quartz with temperature have been ignored since these have a small effect compared to the thermal properties of copper.

It is interesting to observe the separate behavior of the quality factor and the filling factor as the thickness of the quartz dielectric is increased. The general form of the curves for all cases considered is exemplified by the case of the 12 inch long cavity and 4.13 inch diameter bulb shown in Figure 7. While the quality factor continuously decreases with increased dielectric loading, the filling factor rises to a peak in the range of .5 to 1.5 cm before decreasing. Therefore the use of thin-walled quartz bulbs in conventional oscillating hydrogen masers is not in general the optimum configuration to obtain the highest value of (n' x Q).

Figure 8 illustrates the variation of (Q x n') and cavity radius for several different lengths of cavity and one bulb diameter. This figure shows that there is a significant improvement in these parameters with longer cavities, and also that the optimum conditions occur with a relatively thick quartz cylinder. Figures 9 through 13 show the effect of use of different diameter bulbs and different thicknesses of quartz in cavity lengths of 18, 14, 12, 10 and 8 inches.

One of the motivations for adding quartz dielectric loading to the cavity is to reduce, as much as possible, the cavity frequency temperature sensitivity. Figures 14, 15, and 16 show the cavity frequency temperature coefficient as a function of dielectric thickness for several interesting cases. Figure 14 shows the temperature coefficient for a fixed cavity length of 12 inches and three different bulb radii. For reference, a copper cavity without loading would have a temperature sensitivity of approximately 24.1 KHz/Degree C. Figure 15 shows the result for a bulb radius of 5.25 cm and two different cavity lengths, and Figure 16 shows the result for a 4.25 cm bulb and three cavity lengths.

DISCUSSION OF RESULTS

The analysis and results presented in this paper were undertaken to optimize the hydrogen maser cavity and bulb design based upon the general information represented in Figures 1, 2 and 3. A primary consideration has been that successful use of the cavity frequency switching servo technique requires very good maser output signal to noise ratio and the best possible efficiency in use of the power available in the state selected atomic hydrogen beam. It is evident that these goals can be achieved in masers with different application requirements.

For example, if small size and portability are not too important, and the highest possible line Q and smallest wall shift are desired, a large diameter bulb and long cavity would be the logical choice. As shown in Figure [illegible], with an 18 inch long cavity and a 6.75 cm radius bulb the best (Q x n') value occurs for minimum quartz thickness. The minimum practical bulb wall is approximately .15 cm, and using a relatively thin quartz cylinder of .25 cm wall, the cavity radius would be about 12.5 cm (9.85 inch diameter cavity), and (Q x n') = 27,000. Using a cavity coupling coefficient of .25 one would calculate from the equations previously given that the spin exchange parameter q = .046. This would be a very efficient maser oscillator, and with the exception of the high Q copper cavity is very similar in size and bulb volume to masers constructed in the past at NASA, Goddard Space Flight Center (3).

To make somewhat smaller size masers without compromizing efficiency or stability significantly, one might choose a 12 inch long cavity. It is [illegible] Figure [illegible] that the improvement in (Q x n') is not great when increasing the length beyond 12 inches. For a 5.25 cm radius bulb (4.13 inch diameter) and .5 cm dielectric thickness, the resultant cavity radius would be about 11.1 cm ([illegible] inches diameter) and the calculated spin exchange parameter with .35 cavity coupling is .039; these are the dimensions and parameters for the masers reported in Reference 1. These masers have extremely good efficiency, and are the first hydrogen masers to successfully use the cavity frequency switching servo technique to control cavity pulling. As cavities shorter than 12 inches are chosen, there is an increasing penalty in both (Q x n') and cavity diameter. For the larger bulb sizes in short cavities the maser becomes less efficient, and if the cavity wall material has a realized electrical conductivity much less than that of copper, a very borderline oscillator will result.

[illegible] copper as the cavity wall material has important advantages from [illegible] point of view. In addition to good electrical conductivity, [illegible], it has high specific heat which results in relatively [illegible] thermal mass. Systematic thermal perturbations are a most important [illegible] in attempts to improve stability for measuring intervals of [illegible] seconds and longer, and the large thermal capacitance reduces the rate at which the cavity frequency can change, and also relaxes the required response time of thermal control systems or automatic cavity tuning.

The cavity frequency temperature coefficients illustrated in Figures 14, 15 [illegible] are relatively low in comparison to an unloaded metal cavity. In [illegible] the average cavity frequency is controlled in our present designs [illegible] temperature; this has the advantage of a relatively wide [illegible] cavity frequency control range, and the cavity coupling [illegible] frequency switching varactor are automatically held at [illegible] by the control servo. If the cavity were made of a [illegible] material such as silvered fused silica, it would be necessary to control the average cavity frequency with a varactor; not only would this result in a non-linear and narrow frequency control range, it would introduce the possibility of changing the cavity Q's or receiver coupling coefficient when modulating the cavity frequency. So the use of a metal cavity with the cavity frequency switching servo is strongly indicated, and the temperature dependence shown by the figures is well suited to the requirements of cavity tuning.

CONCLUSION

The results presented in this paper provide guidelines for the design of cavity and bulb assemblies for hydrogen masers in an optimal fashion which are well adapted to use of the cavity frequency switching servo technique, as well as information which should be of more general interest for consideration of alternative maser cavity assembly design approaches. The two hydrogen masers described in Reference 1 were the first masers constructed using the new configuration. These masers also demonstrated the first use of the cavity frequency switching servo, and the stability results obtained show that unprecidented stability as well as the other advantages discussed in this paper can be realized. An example of the long term stability obtained in recent maser comparisons is illustrated in Figure 17. This figure shows the fractional frequency change for a thirty day period between the two hydrogen masers described in Reference 1. The slope of the frequency differences over this period is 5.8 x 10-16 per day, so the effect of drift on the daily frequency fluctuations is neglegible. Figure 18 shows the measured stability in a "Sigma Tau" plot using the two sample "Allan Variance" for intervals from one second to ten days. There has been no drift term removed, nor other modifications made to the data.

ACKNOWLEDGEMENTS

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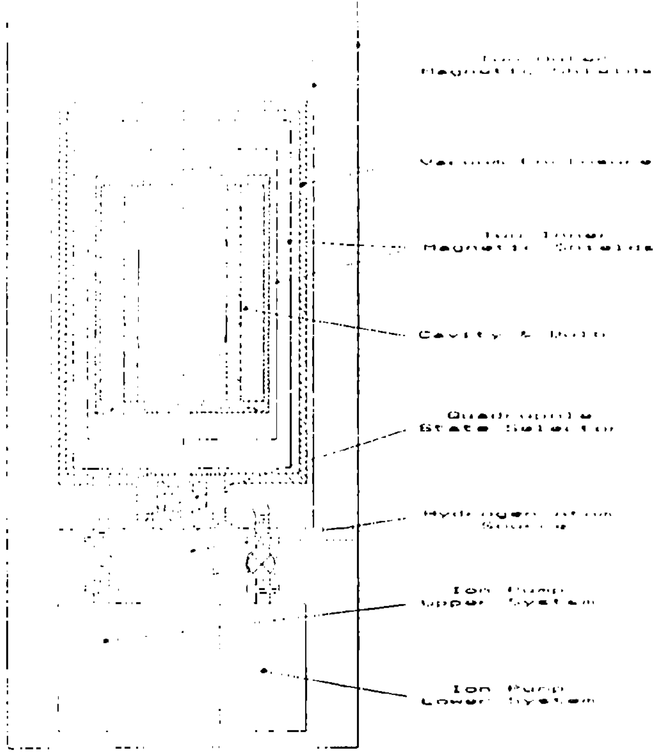
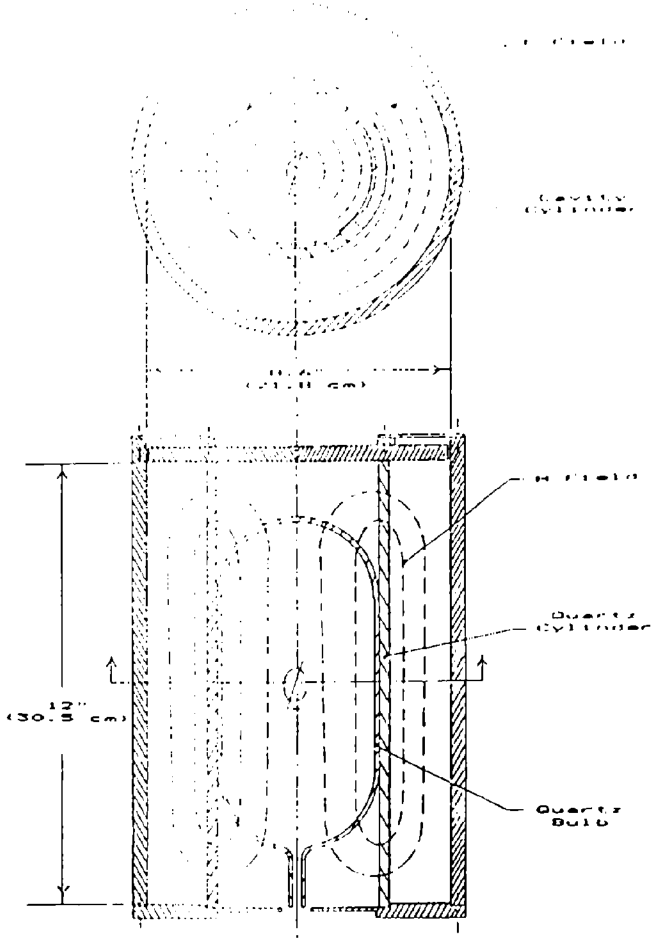
2. D. Kleppner, et al. "Hydrogen Maser Principles And Techniques," Phys. Rev., Vol. 138, No. 4A, A972-A983, 17 May, 1965.

3. Victor S. Reinhardt, et al. "NASA Atomic Hydrogen Standards Program - An Update," Proceedings, 30th Annual Symposium on Frequency Control, 1976.



HYDROGEN MASER ASSEMBLY

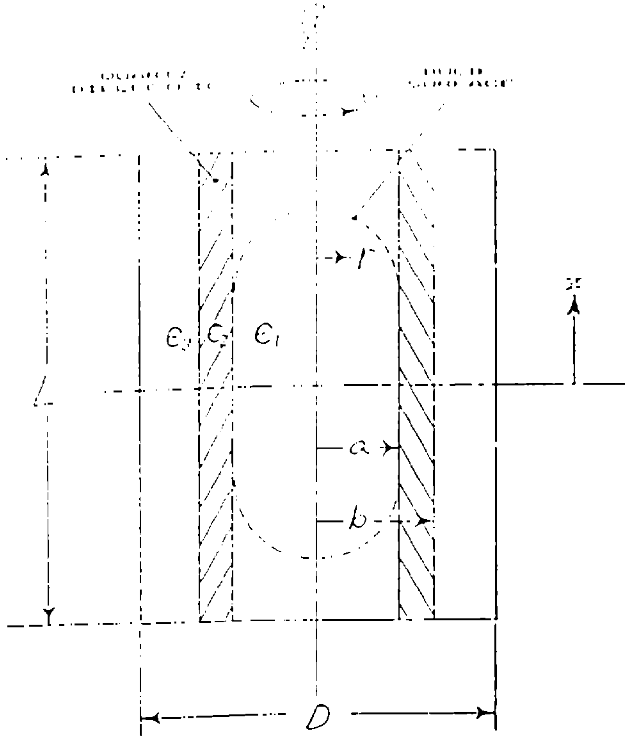
Figure 1



HYDROGEN MASER CAVITY

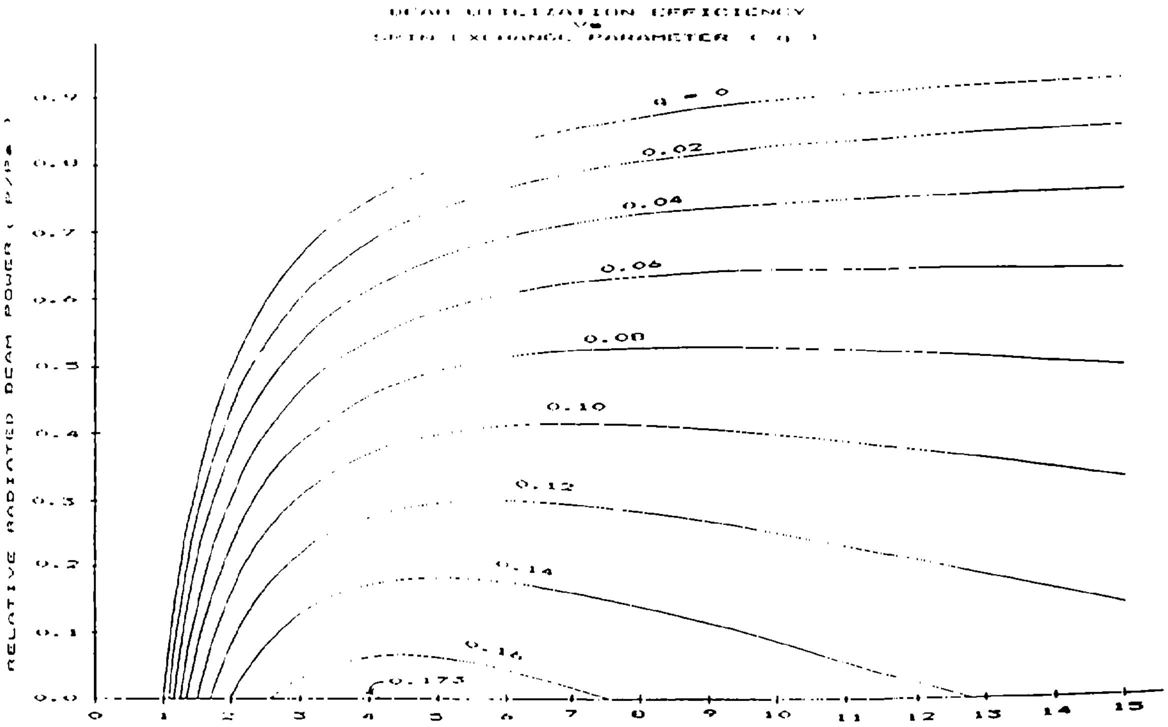
Figure 2

ATTACHMENT 2



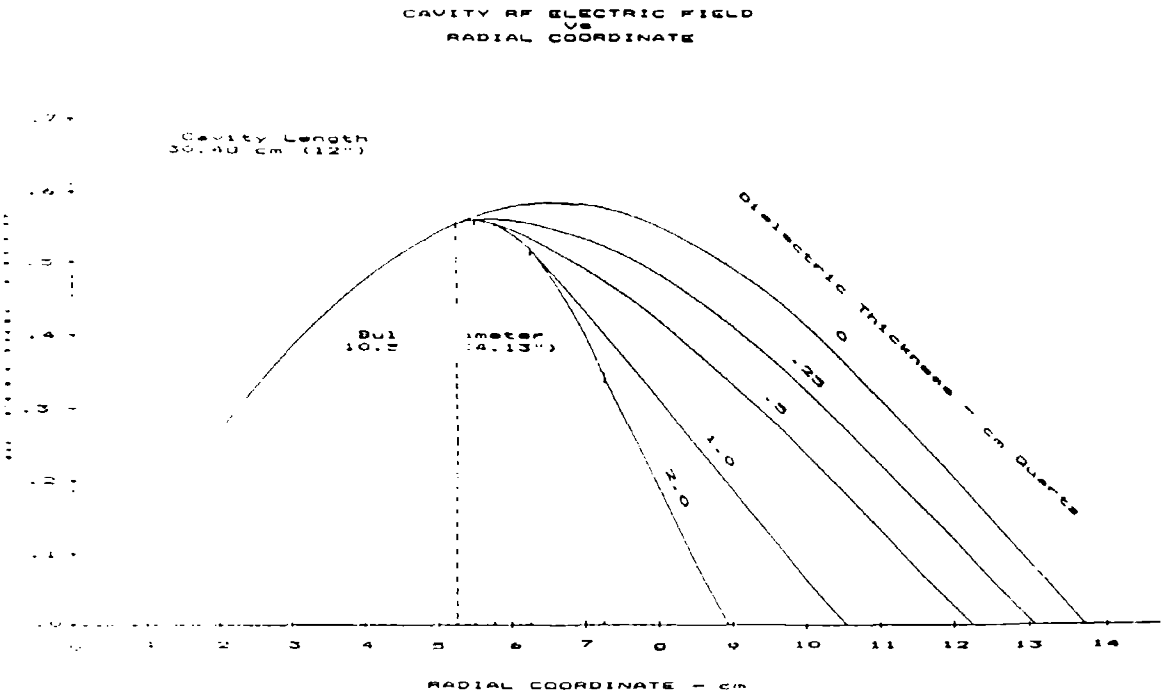
CAVITY ANALYSIS MODEL

Figure 3



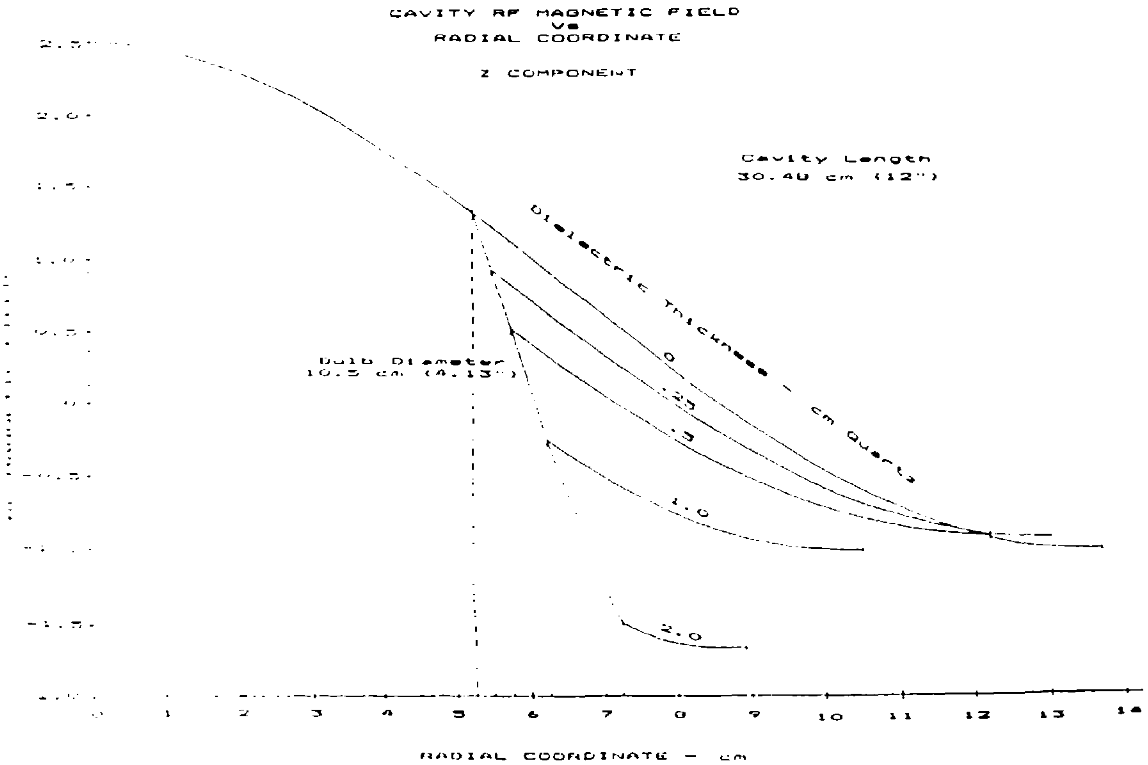
RELATIVE BEAM INTENSITY (I/Ith)

Figure 4



CAVITY RF ELECTRIC FIELD
vs
RADIAL COORDINATE

Figure 3



CAVITY RF MAGNETIC FIELD
vs
RADIAL COORDINATE

Z COMPONENT

Figure 4

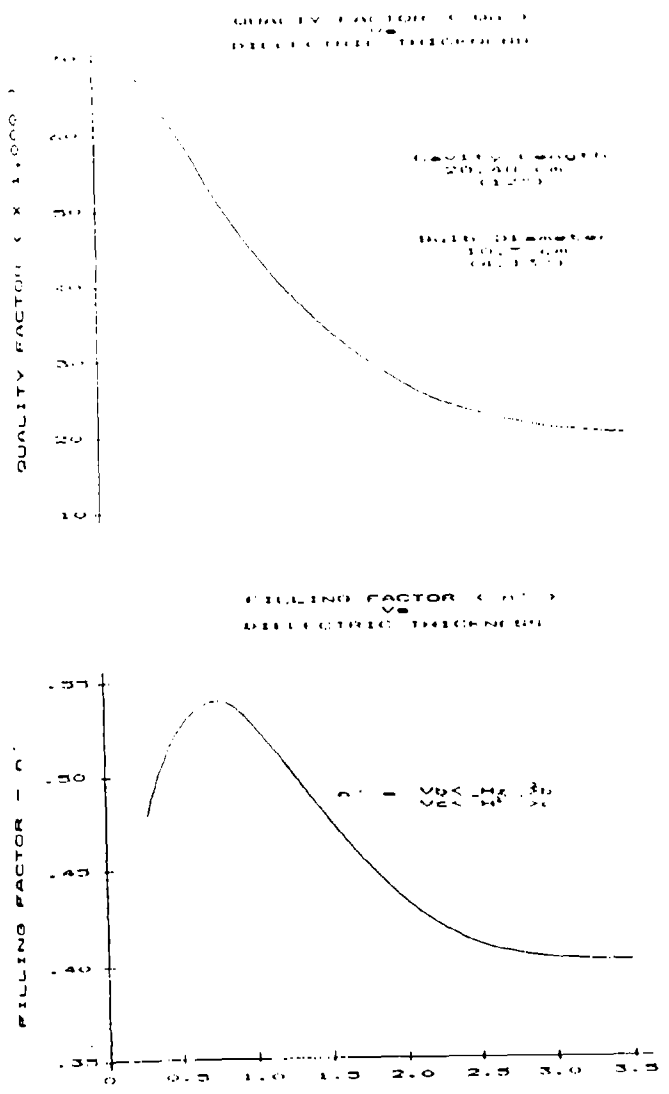


Figure 7

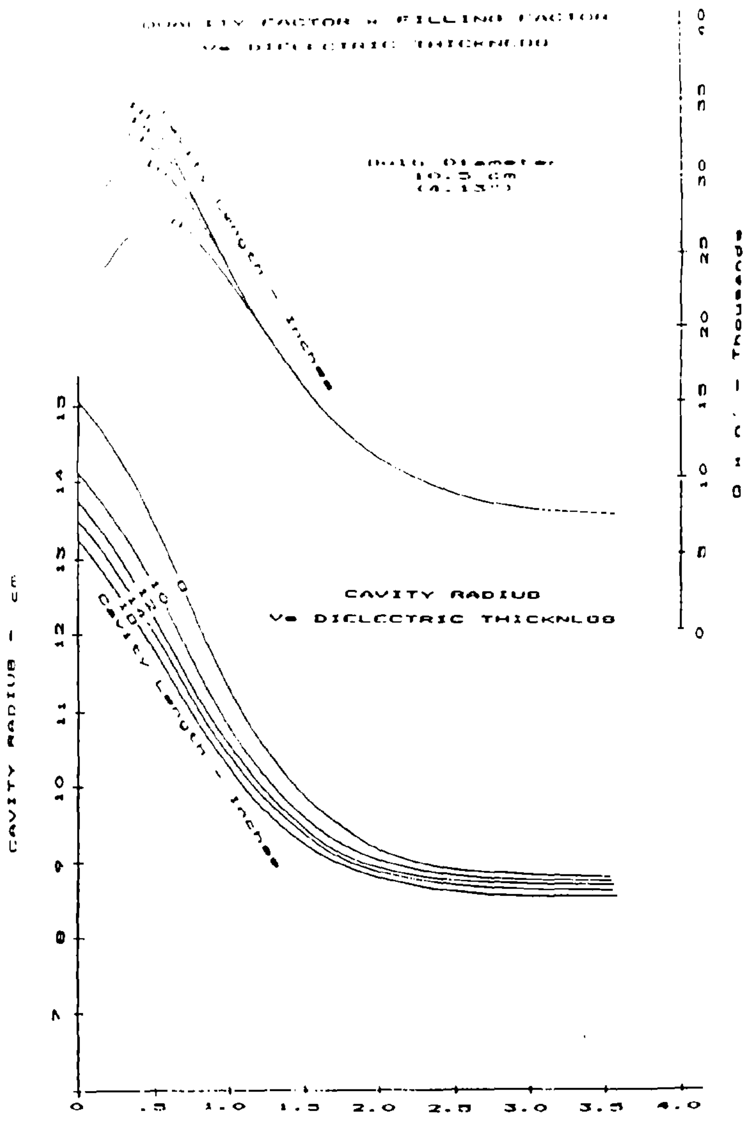


Figure 8

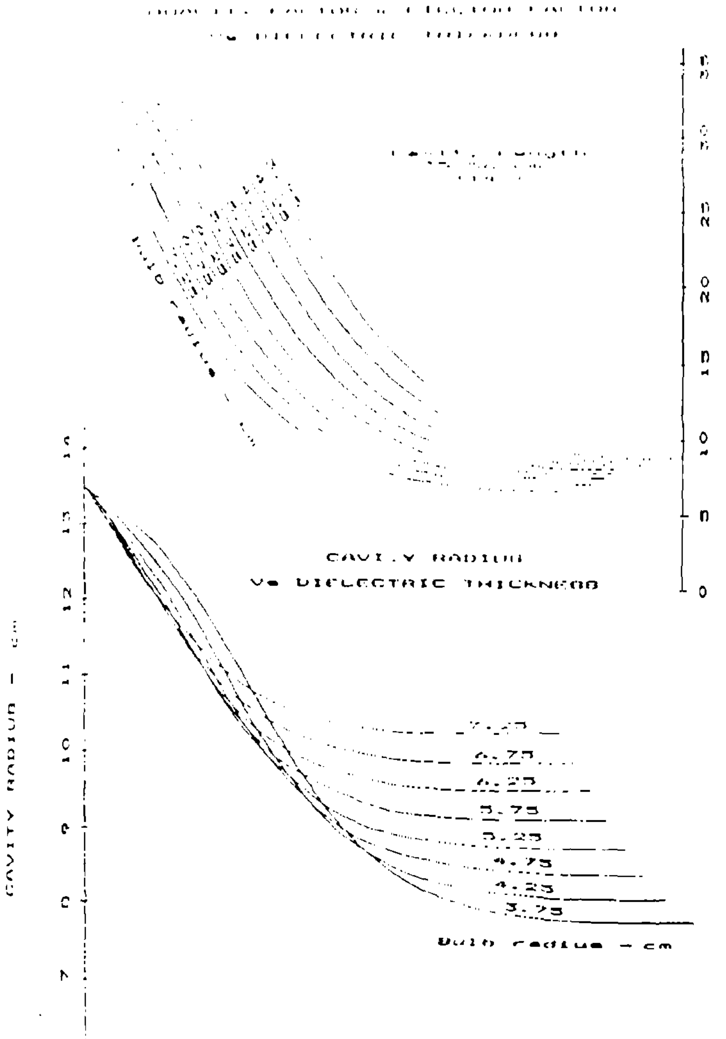


Figure 10

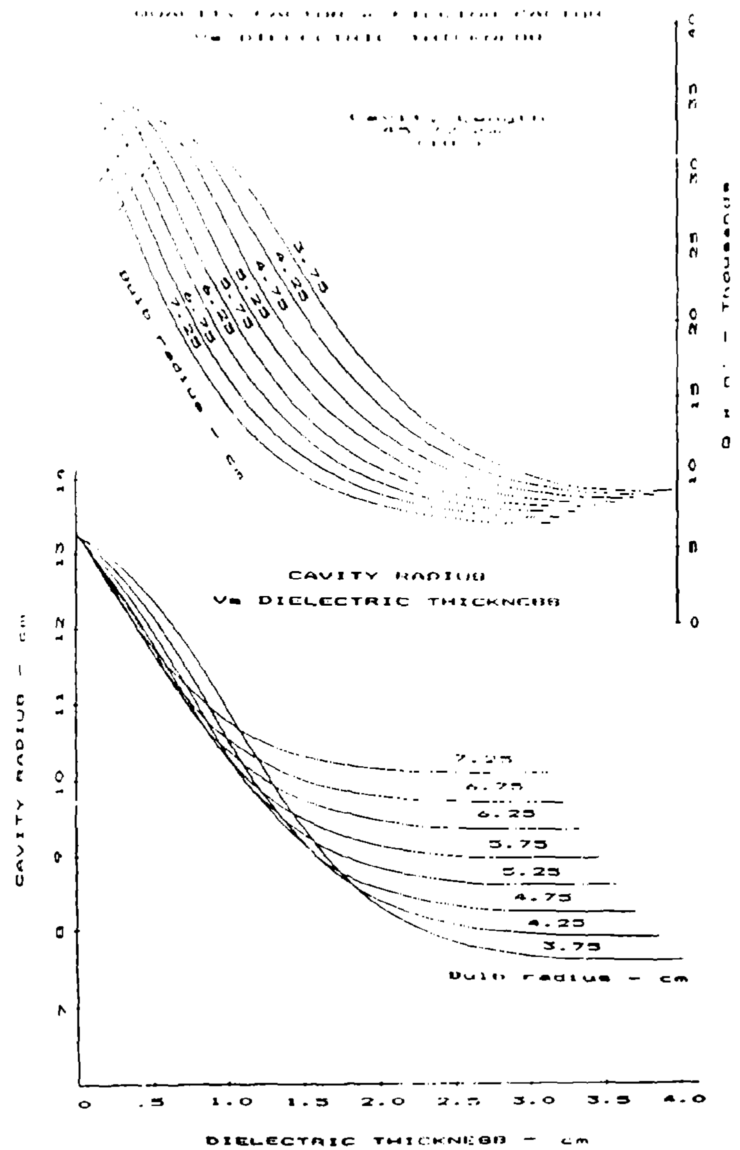


Figure 9

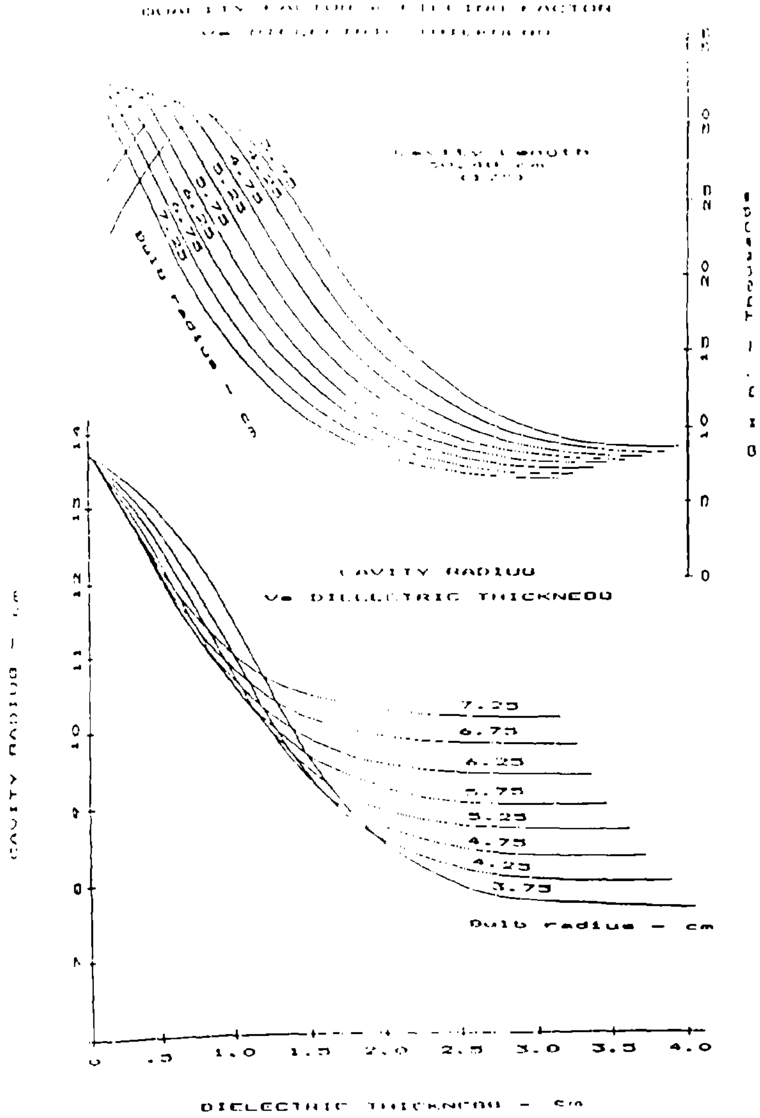


Figure 11

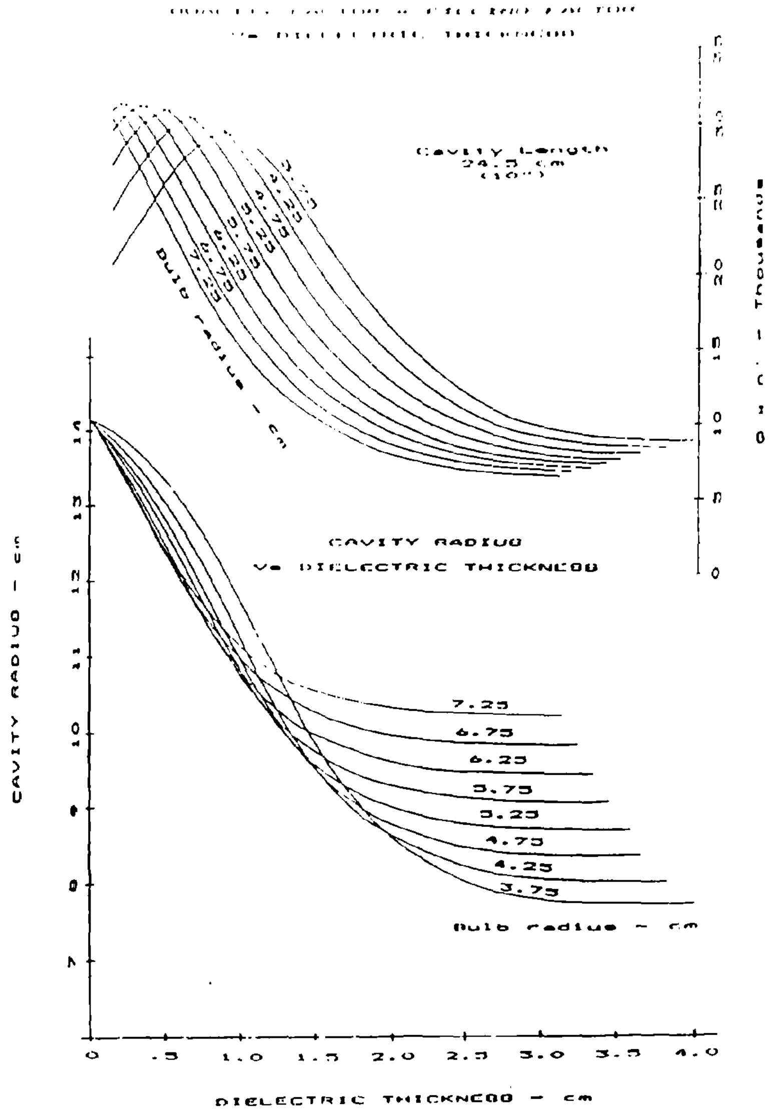


Figure 12

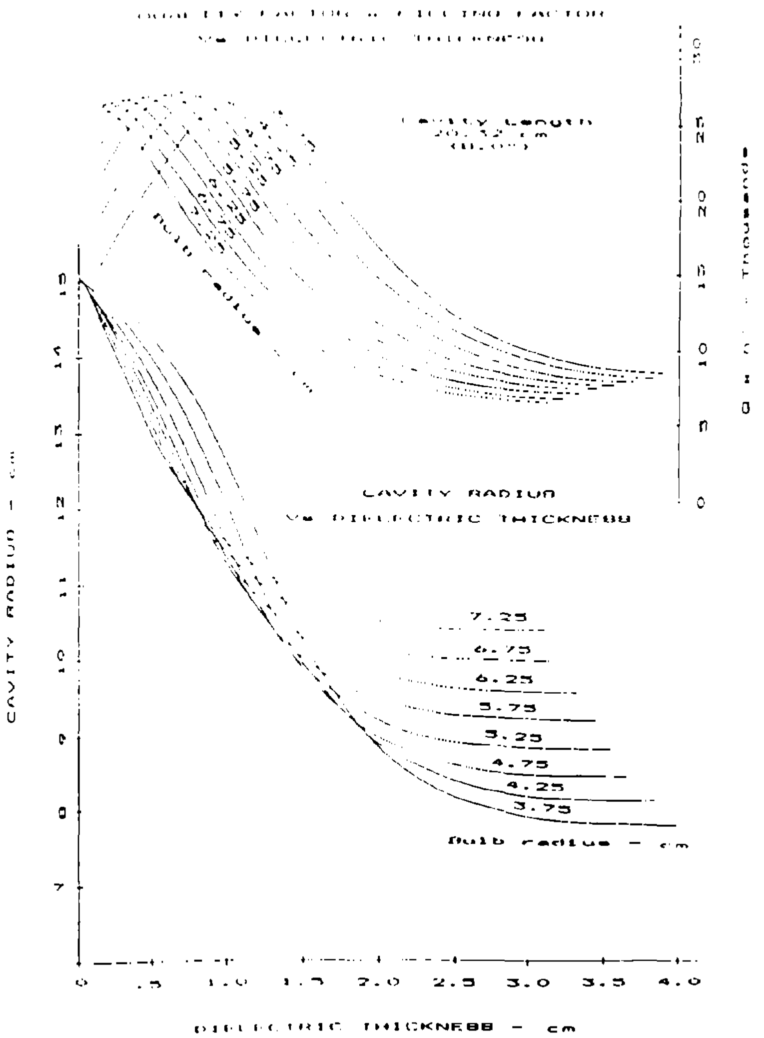


Figure 13

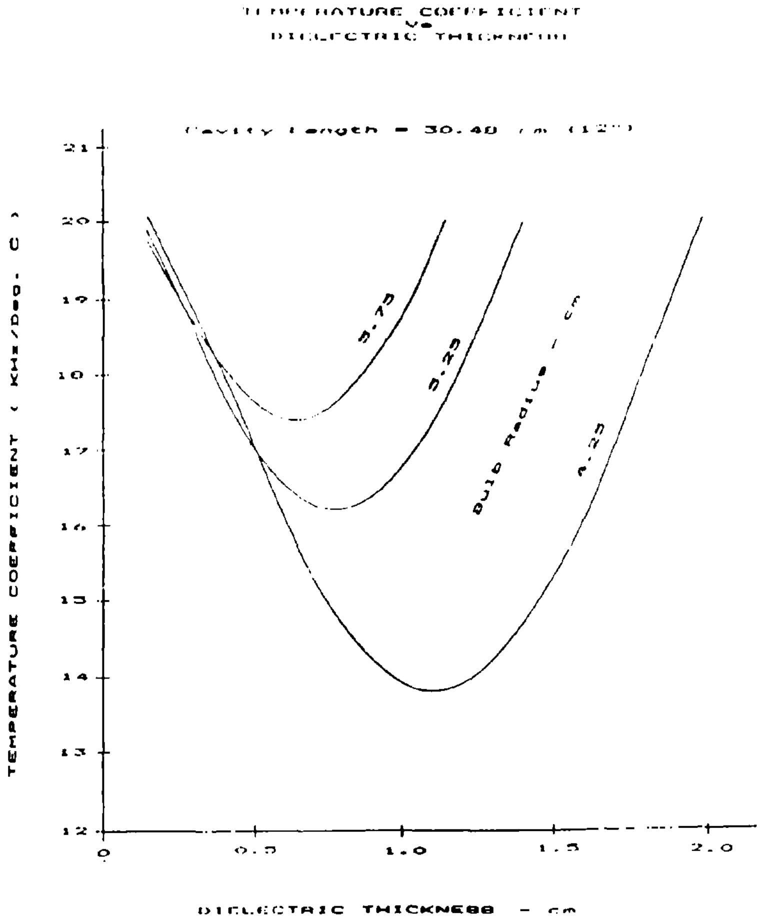


Figure 14

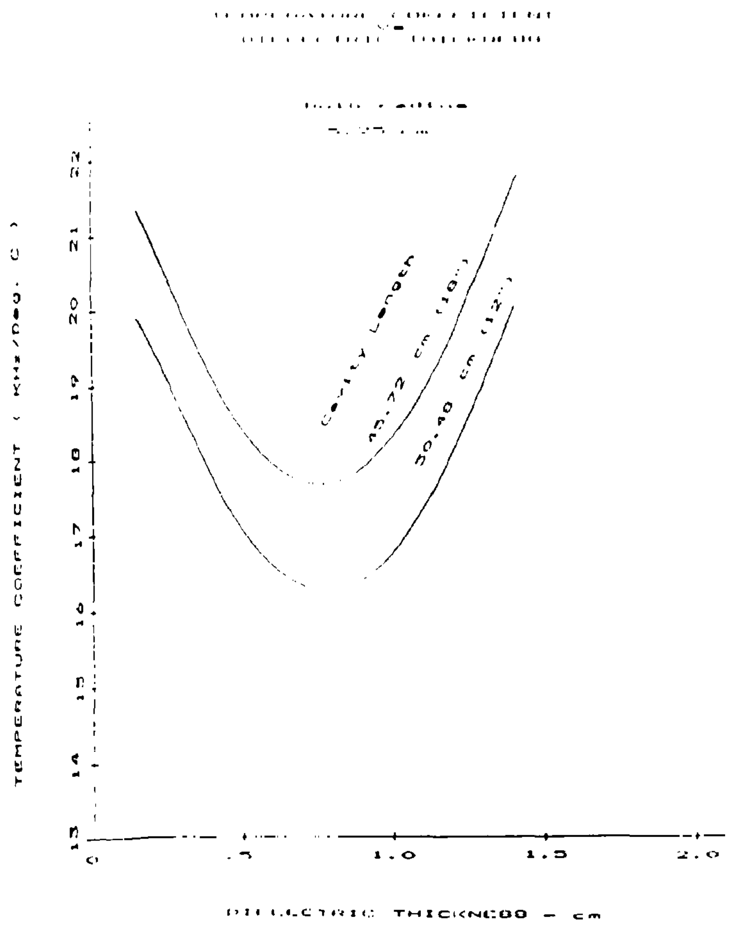


Figure 15

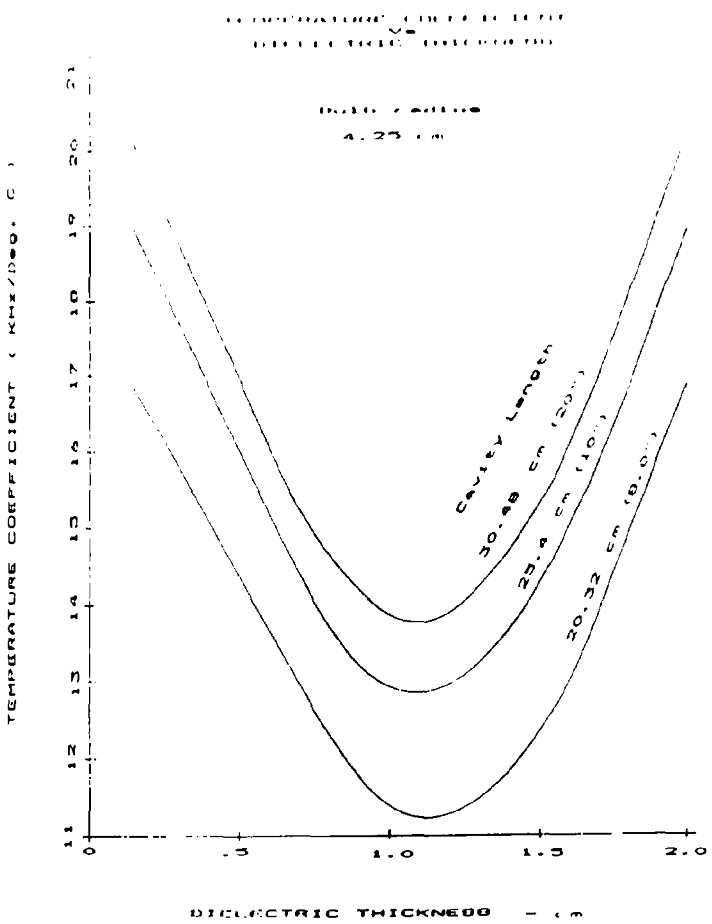


Figure 16

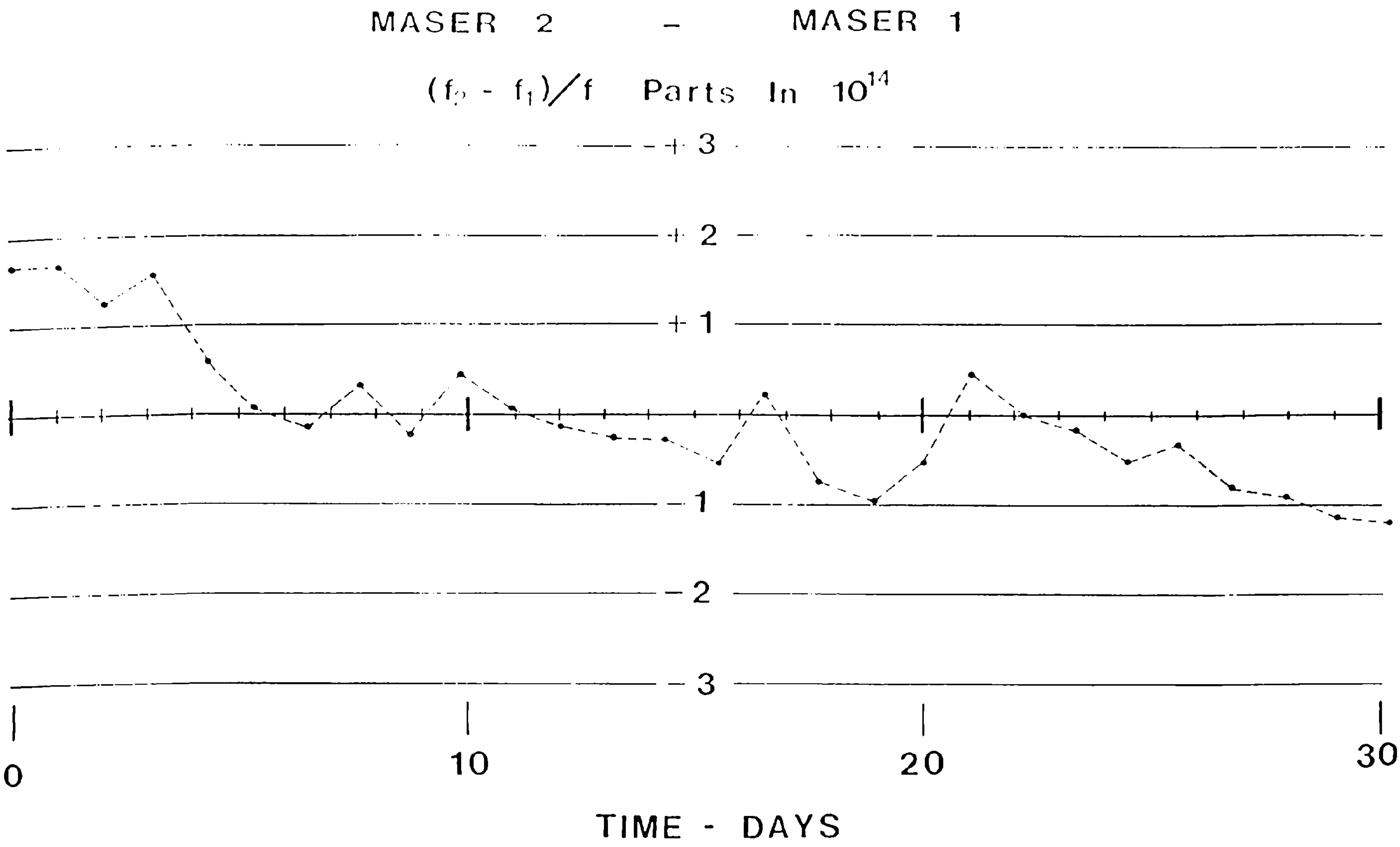


Figure 17

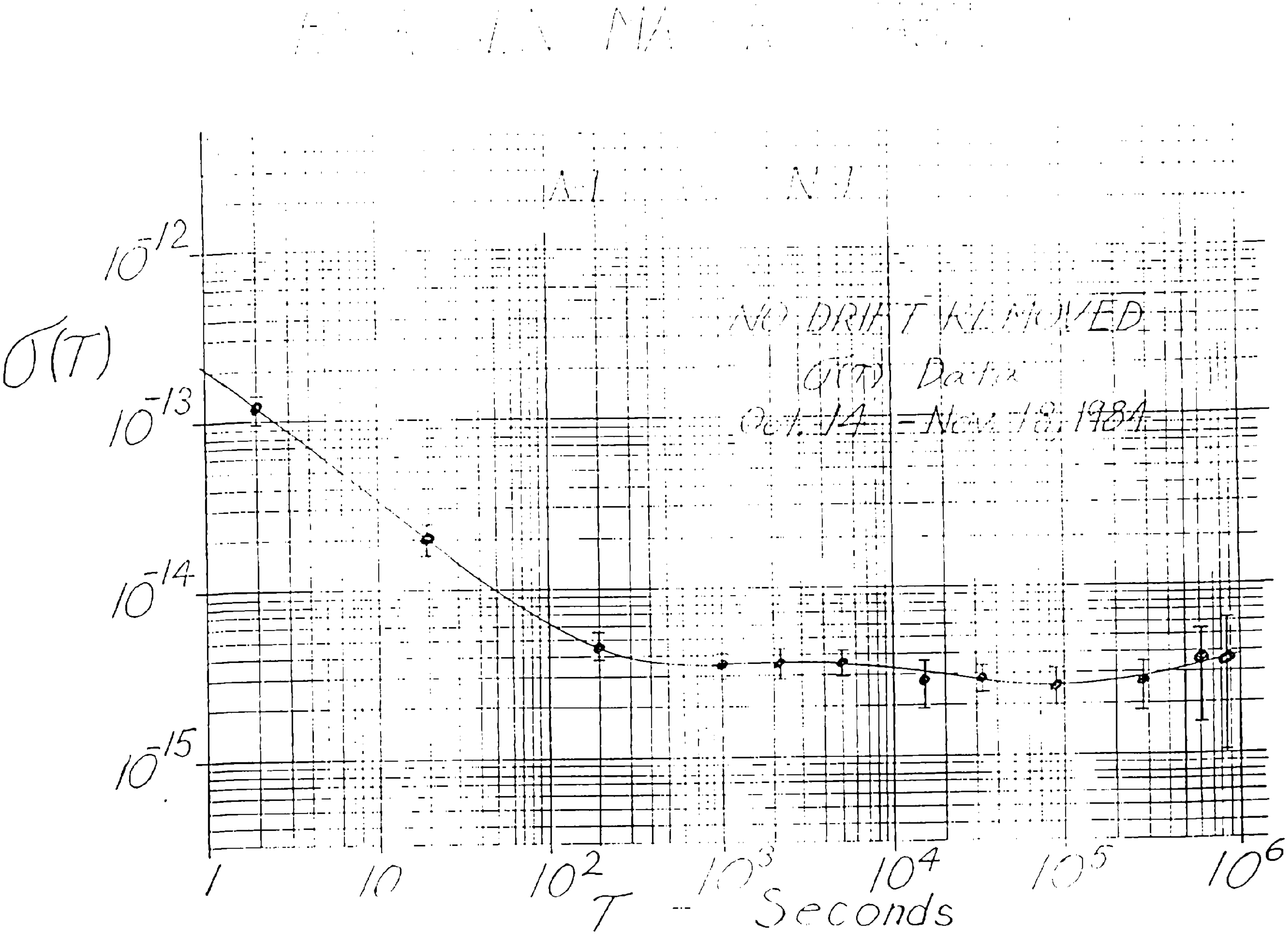

NO DRIFT REMOVED
σ(τ) Data
Oct. 14 – Nov. 18, 1984
σ(τ)
10⁻¹²
10⁻¹³
10⁻¹⁴
10⁻¹⁵
1
10
10²
10³
10⁴
10⁵
10⁶
τ – Seconds

Figure 18

REPORT OF INVENTIONS AND SUBCONTRACTS

(Pursuant to "Patent Rights" Contract Clause) (See Instructions on Reverse Side)

FORM APPROVED
OMB NO. 22-R160

1. NAME AND ADDRESS OF CONTRACTOR (Include Zip Code)

SIGMA TAU STANDARDS CORPORATION
P.O. BOX 1877, 1014 Hackberry Lane
Tuscaloosa, AL 35403

2. CONTRACT NUMBER
N000014-83-C-2015

3. TYPE OF REPORT (Check One)
☐ a. INTERIM ☒ b. FINAL

SECTION I - INVENTIONS ("Subject Inventions")

4. INVENTION DATA (Listed below are all inventions required to be reported) (If "None," so state)

(i) NAME OF INVENTOR(S)	(ii) TITLE OF INVENTION	(iii) CONTRACTOR DISCLOSURE IDENTIFICATION NUMBER OR PATENT APPLICATION SERIAL NUMBER	(iv) CONTRACTOR ELECTS TO FILE U.S. PATENT APPLICATION		(v) CONFIRMATORY LICENSE OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER	
			YES	NO	YES	NO
	Negative					

SECTION II - SUBCONTRACTS (Containing a "Patent Rights" Clause)

5. SUBCONTRACT DATA (Listed is information required but not previously reported for Subcontracts) (If "None," so state)

(i) NAME AND ADDRESS OF SUBCONTRACTOR (Include Zip Code)	(ii) SUBCONTRACT NUMBER	(iii) SUBCONTRACT PATENT RIGHTS CLAUSE	(iv) WORK TO BE PERFORMED UNDER SUBCONTRACT	(v) SUBCONTRACT DATES	
				AWARD	COMPLETION
	Negative				

SECTION III - CERTIFICATION

CONTRACTOR CERTIFIES THAT PROMPT IDENTIFICATION AND TIMELY DISCLOSURE OF SUBJECT INVENTIONS PROCEDURES HAVE BEEN FOLLOWED

DATE	NAME AND TITLE OF AUTHORIZED OFFICIAL (Print or Type)	SIGNATURE
Dec. 31, 1985	Harry E. Peters, President	Harry E Peters

DD FORM 882

EDITION OF 1 JUL 68 IS OBSOLETE

END

FILMED

3-86

DTIC