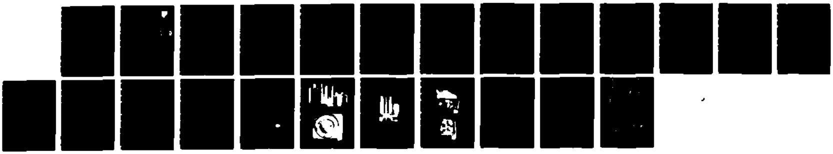
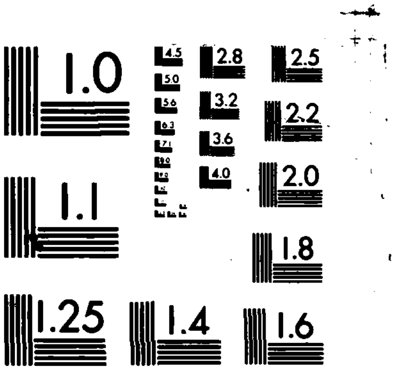
AD-A165 850 LIGHT-WEIGHT HYDROGEN MASER(U) SIGMA TAU STANDARDS CORP 1/1
TUSCALOOSA AL H E PETERS DEC 85 RADC-RR-85-262
F19628-79-C-0104

UNCLASSIFIED F/G 20/5 NL





MICROCOPY RESOLUTION TEST CHART

DARDS-1963-A

(12)

**RADC-TR-85-262**
**Final Technical Report**
**December 1985**

# *LIGHT-WEIGHT HYDROGEN MASER*

**Sigma Tau Standards Corporation**

**Harry E. Peters**

*APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED*

**ROME AIR DEVELOPMENT CENTER**
**Air Force Systems Command**
**Griffiss Air Force Base, NY 13441-5700**

86 3 26 004

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

# REPORT DOCUMENTATION PAGE

|  |  |
|---|---|
| 1a. REPORT SECURITY CLASSIFICATION<br>UNCLASSIFIED | 1b. RESTRICTIVE MARKINGS<br>N/A |
| 2a. SECURITY CLASSIFICATION AUTHORITY<br>N/A<br>2b. DECLASSIFICATION / DOWNGRADING SCHEDULE<br>N/A | 3. DISTRIBUTION / AVAILABILITY OF REPORT<br>Approved for public release; distribution unlimited. |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S)<br>N/A | 5. MONITORING ORGANIZATION REPORT NUMBER(S)<br>RADC-TR-85-262 |
| 6a. NAME OF PERFORMING ORGANIZATION<br>Sigma Tau Standards Corp.<br>6b. OFFICE SYMBOL (If applicable) | 7a. NAME OF MONITORING ORGANIZATION<br>Rome Air Development Center (ESE) |
| 6c. ADDRESS (City, State, and ZIP Code)<br>1014 Hackberry Lane, P.O. Box 1877<br>Tuscaloosa AL 35403 | 7b. ADDRESS (City, State, and ZIP Code)<br>Hanscom AFB MA 01731-5000 |
| 8a. NAME OF FUNDING / SPONSORING ORGANIZATION<br>Rome Air Development Center<br>8b. OFFICE SYMBOL (If applicable)<br>ESE | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER<br>F19628-79-C-0104 |
| 8c. ADDRESS (City, State, and ZIP Code)<br>Hanscom AFB MA 01731-5000 | 10. SOURCE OF FUNDING NUMBERS |

| PROGRAM ELEMENT NO. | PROJECT NO. | TASK NO. | WORK UNIT ACCESSION NO. |
|---|---|---|---|
| 62702F | 4600 | 18 | 30 |

11. TITLE (Include Security Classification)

LIGHT-WEIGHT HYDROGEN MASER

12. PERSONAL AUTHOR(S)

Harry E. Peters

| 13a. TYPE OF REPORT | 13b. TIME COVERED | 14. DATE OF REPORT (Year, Month, Day) | 15. PAGE COUNT |
|---|---|---|---|
| Final | FROM Mar 79 TO Jul 84 | December 1985 | 26 |

16. SUPPLEMENTARY NOTATION

N/A

17. COSATI CODES

| FIELD | GROUP | SUB-GROUP |
|---|---|---|
| 09 | 01 |  |
| 23 | 06 |  |

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Hydrogen, Atomic, Time, Maser, Frequency, Standard,

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Based upon a new approach to cavity resonator and atom storage bulb assembly design, experimental work was undertaken to develop a much smaller and lighter hydrogen maser frequency standard. An operational prototype maser of light-weight and small size resulted, but the new cavity and bulb design did not result in improved stability. Upon knowledge gained in this program (1) further work funded by other government agencies (2) has resulted in successful hydrogen maser oscillators having unprecedented frequency stability.

Notes:
1. H.E. Peters, "Experimental Results of the Light-Weight Hydrogen Maser Program," 36th Annual Symposium on Frequency Control (1982).
2. H.E. Peters, "Design and Performance of New Hydrogen Masers Using Cavity Frequency Switching Servos," 38th Annual Symposium on Frequency Control (1984)

|  |  |
|---|---|
| 20. DISTRIBUTION / AVAILABILITY OF ABSTRACT<br>☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS | 21. ABSTRACT SECURITY CLASSIFICATION<br>UNCLASSIFIED |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>HERBERT G. LIPSON | 22b. TELEPHONE (Include Area Code)<br>(617) 861-3297<br>22c. OFFICE SYMBOL<br>RADC (ESE) |

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

# SUMMARY

## A. OBJECTIVE OF THE CONTRACT

The objective of this contract was to develop an atomic hydrogen maser frequency and time standard which was smaller, lighter, and more stable than existing hydrogen maser standards.

## B. TECHNICAL PROBLEM

Atomic hydrogen maser standards exhibit exceptionally good stability, reproduciblity, and accuracy, and are potentially useful in a wide range of important applications; but heretofore these standards have been too large, unwieldy, and expensive for widespread operational use. The large size has been due to the relatively long wavelength of the 21 centimeter hydrogen transition and the correspondingly large size of the maser cavity, magnetic shields, vacuum enclosure, and other structures.

If a means for reducing the cavity size could be realized without unduly degrading the cavity quality factor and other important maser oscillation parameters, the utility of the hydrogen maser would be greatly improved. A promising means to reduce the cavity size was presented in the paper, "Small, Very Small, and Extremely Small Hydrogen Masers," by H. E. Peters.[3] The basic scheme was to attach copper electrodes to the quartz storage bulb in such a manner as to create a relatively small distributed LC resonant circuit within an outer conducting cylinder. Calculations indicated that a factor of 8 or more reduction in cavity volume might be realized while maintaining adequate oscillation conditions in such a design. The present contractual effort is the result of an unsolicited proposal to prove out the new technique and to develop a prototype standard to illustrate the design and to measure the performance obtained.

## C. GENERAL METHODOLOGY

First, a range of sizes of cavities and quartz storage bulbs with different electrode structures were tested and evaluated to establish the most promising geometrical configuration. Next, a breadboard assembly of a maser was constructed, and newly designed electronic subsystems were fabricated and tested. Finally, an operational hydrogen maser was constructed and experimental work was performed to optimize systematic parameters and measure the performance.

## D. TECHNICAL RESULTS

The "Small Hydrogen Maser," (SHM) which was the deliverable item under this contract, demonstrated that an operational maser could be constructed which was smaller and lighter than previous designs. The maser had low power consumption, was economical in use of hydrogen, and the electronic components and maser physical subsystems were successfully designed to fit in a compact package. A problem arose, however, with the most crucial element, the cavity resonator; the realizable cavity Q was too low to achieve oscillation conditions. To overcome this problem, an active cavity gain circuit was designed to fit within the cavity. The maser then oscillated readily, but measurement of the cavity frequency for extended periods indicated that some means to automatically stabilize the cavity frequency would be required. After consideration of several possible methods, a novel and heretofore untried technique for cavity tuning was conceived which theoretically would provide the required stability.

The new cavity servo technique was successfully demonstrated on two newly designed hydrogen masers constructed by Sigma Tau Standards Corporation for the Naval Research Laboratory[4] and the Applied Physics Laboratory of The Johns Hopkins University,[5] with additional financial support from NASA, Goddard Space Flight Center. Unprecedented long term stability was achieved and the results were presented in a paper "Design and Performance of New Hydrogen Masers Using Cavity Switching Servos," by H. E. Peters.[2]

A breadboard system of the cavity switching servo was also installed on the SHM, and the frequency response was observed using a wide range of system variables. It was not possible to stabilize the SHM cavity with this servo for the following reasons.

1. The transistor amplifier in the cavity gain circuit amplified thermal noise and other spurious noise within the circuit bandwidth. To switch cavity frequency in this maser, the reactances of the transistor were changed periodically by varying the bias voltages. This also changed the spurious pickup and introduced erroneous amplitude modulation coherently with the desired detuning signal.

2. Due to the method of attaching the copper electrodes to the quartz bulb, the cavity frequency did not vary smoothly with temperature; there was hysteresis and non-linearity in the frequency versus temperature characteristic.

3. Since the cavity was relatively light, the thermal capacitance was small, and short term temperature fluctuations required rapid correction rates which were not feasible with the SHM system.

The SHM stability could be improved in several ways, but this would require additional research and development effort. First, a different method of modulating the cavity frequency should be used, such as a separate coupling loop with a varactor diode as is used on the NRL and APL masers. Second, the bandwidth of the cavity gain amplifier circuit would have to be narrowed. Third, the copper electrodes would need to be attached to the bulb in a manner such that the temperature characteristic was single valued and monotonic. Fourth, the receiver system would need to be modified to optimize the cavity servo system.

## E. CONCLUSIONS

Although a great deal of new hydrogen maser technology was developed in the course of this program, it was not possible to meet the stability goals with the unit constructed for delivery. Further research would improve upon the present results, but it is evident that the short term stability will not be as good as that of larger bulb masers due to the need for electronic cavity Q enhancement to oscillate; nor will the long term stability ever be quite as good either. Another important factor is that the small maser is much more difficult to construct and adjust, and would be more prone to reliability problems in use.

The new maser designs illustrated by the NRL and APL standards which arose from the experience of the Light-Weight Hydrogen Maser Program are superior in all respects except size and weight to the SHM, and yet they are much smaller and more stable than previous full size maser designs. It is therefore recommended that further research, development, and production of hydrogen masers be directed toward these improved designs, and that further effort with masers using the SHM cavity design be discontinued unless size and weight considerations far outweigh performance.

# INTRODUCTION

The Light-Weight Hydrogen Maser Program was a five year project which involved development of a new compact hydrogen maser based upon design principles illustrated in the paper "Small, Very Small, and Extremely Small Hydrogen Masers," which was presented at the 32nd Annual Symposium on Frequency Control in 1978.[3]

During the first six months of the program experiments with cavities and storage bulbs with various electrode configurations were performed to determine the most promising configurations, and a breadboard test maser and associated electronics systems were designed. The next twelve months were spent constructing the breadboard maser and the associated subsystems and making the first operational tests of the maser. At this point the design of a "deliverable prototype" hydrogen standard, which we have named the "Small Hydrogen Maser" (SHM) was finalized and the next tweleve month period was occupied with construction and first operational test of this unit. Two papers,[6,7] presented at the 34th and 35th Annual Symposium on Frequency Control described, in part, the work up to this point. During the next six month period, further measurements and evaluations of the maser were made, and additional work towards developing a means to stabilize the maser cavity with an automatic servo system was undertaken. Results obtained up to this time were presented in a paper,[1] "Experimental Results of the Light-Weight Hydrogen Maser Program," presented at the 36th Annual Symposium on Frequency Control in June 1982.

Contract extensions since March 1982, on a no cost to the government basis have resulted in the development of a new and fundamentally important method to stabilize the cavity frequency of hydrogen masers which was very successful with two newly designed masers of the large storage bulb configuration.[4,5] Results with these new masers were presented at the 38th Annual Symposium on Frequency Control.[2] Use of the new cavity servo on the SHM were not successful. Although the SHM design could be modified and improved by methods discussed later in this report, it would require additional research and development effort. In light of recent success with new masers which avoid the problems associated with the SHM cavity design, we have not encouraged further government support for very compact masers, and the present effort is now terminated.

While we have not been successful in producing a hydrogen maser which meets the original stability goals, the SHM research has achieved success in many areas of hydrogen maser technology which are being used currently in other hydrogen masers. The most significant developments resulting from this program are discussed in the following sections.

## SIGNIFICANT CONTRACT DEVELOPMENTS

In order to achieve the size, weight, power consumption, and other performance goals of the Light-Weight Hydrogen Maser Program it has been necessary to develop several new or improved maser subsystems, some of which are listed below.

New Cavity and Bulb Configuration

Miniature State Selectors

Efficient Beam Optics

Miniature, Low Pressure, Hydrogen Supply

Hydrogen Purifier and Controls

Active Cavity Gain Circuit

Efficient, Compact, Electronics

Convenient Instrumentation and Packaging

A New Cavity Tuning Servo

The work on the Light-Weight Hydrogen Maser Program has a significant impact on hydrogen maser technology in general. For example, development of the new cavity tuning servo is applicable to both large and small hydrogen masers, and its use can remove the requirement for a separate stable tuning reference which is needed to tune the maser when using the previous spin-exchange auto-tuning method. In addition, new levels of long term stability may now be achieved without compromising the excellent short term frequency stability of the maser.

## CAVITY AND BULB EVALUATIONS

To realize a hydrogen maser much smaller than those constructed in the past, the size of the cavity which confines the electromagnetic radiation emitted by the hydrogen atom must somehow be reduced below the size of an unloaded cavity resonant at the hydrogen frequency. In the present work inductive and capacitive structures in the form of metal electrodes are attached to and surround the quartz bulb which stores the state selected atoms of the hydrogen beam. In a cavity so loaded there are typically a great many resonant modes, some of which may be degenerate, and exact computational methods are impossible due to the complexity of the geometry. Thus, after first approximations were made as in reference (3), it was necessary to set up promising test configurations and make laboratory measurements of frequency, Q, mode geometry, and coupling by the use of RF magnetic and electric field probes and swept frequency techniques.

During the first six months of the program a large range of cavity sizes, bulb sizes, and electrode configurations were tested. The required mode (analogous to the TE011 mode in an unloaded cavity) has been identified and the parameters measured in cavity assemblies as small as 2.5 inches in diameter by 4.4 inches long up to 6.6 inches diameter by 11.0 inches long. From 33 experimental configurations using different combinations of cavity and bulb size and 1, 2, 3, 4, and 8 electrodes of various lengths, the most promising configurations were as follows. Dimensions are in inches.

| CAVITY SIZE | | BULB SIZE | | ELECTRODES | | | Q |
|---|---|---|---|---|---|---|---|
| D | L | D | L | D | L | N | |
| 6.6 | 11.0 | 3 | 7 | 3 | 5 | 8 | 16,800 |
| 6.0 | 10.0 | 2 | 7 | 2 | 5 | 4 | 12,000 |
| 5.0 | 8.5 | 2 | 7 | 2 | 5 | 4 | 11,200 |
| 2.5 | 4.4 | 1.5 | 3 | 1.5 | 1.9 | 2 | 4,100 |

The configuration chosen for the SHM used a 2 inch diameter by 7 inch long bulb with hemispherical ends. The cavity inside dimensions are 6.0 inches diameter and 9.0 inches long. Four copper foil electrodes 5.0 inches long with .14 inch gaps are cemented to the bulb with a thermosetting metal to glass adhesive (Palmer Products P-752) with heat, pressure, and vacuum. The bulb is coated internally with FEP-120 Teflon prior to attachment of the electrodes. The cavity Q measured for the completed assembly was 10,200. Test of cavity frequency versus temperature under vacuum gave a temperature sensitivity of approximately 5 KHz per $^{o}$C ($3.5 \times 10^{-6}$ / $^{o}$C fractionally.)

## CAVITY Q ENHANCEMENT

To achieve oscillation an active cavity Q enhancement method was developed which could be located directly within the cavity and controlled by DC bias voltages. It was anticipated that this system would avoid the instabilities inherent in past attempts to use active gain to enhance the cavity Q wherein two RF coupling loops are used to connect through coaxial cable to amplifiers, phase shifters, and band pass filters located external to the cavity environment. The present circuit uses a single low noise transistor connected to two small coupling loops inside the cavity top. One variable capacitor tunes one of the loops to limit the amplifier bandwidth and gain to be near the maser frequency and reject unwanted mode frequencies. The circuit Q is low in comparison to the cavity unenhanced Q and the frequency of the cavity with Q enhancement follows, to the extent presently determined, the frequency of the unenhanced cavity.

With the active Q enhancement circuit it has been possible to increase Q values from 10,000 (unenhanced) up to approximately 100,000. With two bias connections, it has also been found possible to smoothly vary the frequency over a range of approximately 150 KHz while simultaneously maintaining the Q at the desired value.

## NEW CAVITY TUNING SERVO

Since the hydrogen maser was invented it has been a tantalizing dream to lock the cavity to the maser frequency in a simple way and so eliminate cavity pulling. Cavity pulling has been the most serious limitation to the stability of the maser for measuring times greater than approximately 1,000 seconds, and elimination of this effect would result in quite unprecedented frequency stability. Spin-exchange tuning has been used very successfully in the past,[8] but this requires a separate stable tuning reference, large variation in beam intensity, and long integration times. People working with both passive and active masers have used another cavity tuning scheme wherein a separate search signal is injected into the cavity with the frequency alternating between two values approximately at the half power points of the cavity resonance. The signal transmitted by the cavity is sampled, and amplitude variations are detected as a signal source for a servo system.[9,10,11] This system has the serious disadvantage of having relatively high power RF signals near the maser frequency which perturb the radiating hydrogen atoms, and additionally requires external RF components and at least two coaxial connections to the cavity; the problem of environmental isolation is severe and this system is extremely difficult to engineer in a manner which does not in itself disturb the cavity frequency.

To describe the physical basis of the present approach to cavity tuning, the interaction of the radiated beam power with the cavity impedance is illustrated in Figure 1. The signal output V appears as though it were coupled through a resonant impedance Z and fed by a constant current source. The constant current source derives from the oscillating magnetic moment of the assemblage of atoms within the maser storage bulb and it is effectively constant for times short compared to the relaxation time of the atom.

In the new method of tuning, the cavity frequency is square wave modulated and a non-tuned condition is evidenced by a corresponding modulation of maser signal amplitude as observed at the maser receiver. This is illustrated in Figure 2. The cavity frequency is switched between $f_1$ and $f_2$ at a typical rate of twenty-five Hertz. If the average cavity frequency is not equal to the maser frequency, there is a modulation ($V_2$ - $V_1$) produced on the output amplitude. By synchronously detecting variations in the received signal amplitude and feeding them back, after appropriate amplification and integration, as frequency corrections to the cavity, the average cavity frequency, $f_c$ is made equal to the maser frequency.

Since cavity pulling of the maser is linear with cavity offset frequency, the average pulling effect is that of a cavity maintained at the average of the two modulation frequencies. The cavity pulling coefficient is therefore the usual relationship for an active hydrogen maser as given in Figure 2; when the cavity is tuned the average cavity frequency equals the maser frequency. Figure 3 is a block diagram of the overall servo system. There is a modulation generator which modulates the cavity frequency; the maser receiver IF amplitude is synchronously detected, amplified, averaged in a digital integrator, and fed back as a DC cavity correction voltage.

This somewhat simplified description requires elucidation well beyond the scope of the present report to take into account second order effects such as possible inequality of cavity Q's, differences in the modulation periods, spin-exchange pulling and the means to cancel it, random noise processes, systematic disturbances, and other potential problems or benefits. A brief discussion of the most important factor is contained in the next section. It should be emphasized that there is only one RF coupling to the cavity in this system - the usual receiver output coupling, and the tuning system itself requires only a few low frequency solid state circuits besides the means for varying the cavity frequency.

It should be emphasized that the cavity servo described herein is eminently applicable to conventional large bulb hydrogen masers as well as compact masers. Two critical conditions are required for its successful application; one is that the maser be operated well above threshold so that a good signal to noise ratio of the maser output signal is obtained, the second is that a convenient means for rapidly modulating the cavity resonance frequency while maintaining constant quality factor is available. In the SHM the active gain circuit bias voltages provided the proper cavity control; in the large masers, which do not use active cavity gain, a varactor diode in series with a coupling loop mounted within the cavity has been used successfully.

It should be pointed out that the ability to modulate the cavity frequency or Q in a reproducible manner facilitates other approaches, in addition to the one described herein, to tuning the cavity so as to stabilize it and eliminate cavity frequency offset. Thus if the cavity Q is modulated with the frequency held constant there is a phase modulation of the output signal when untuned which when nulled produces a null cavity frequency offset. This scheme has also been tried on the SHM, but with the present receiver configuration it produces larger probable errors.

## CAVITY SERVO NOISE PROCESSES

There are several potential noise sources or systematic biases which need to be considered to determine the accuracy or stability of cavity tuning and the possible correction rate of the servo. The most obvious potential error source is inequality of the cavity Q's at the two modulation frequencies $f_1$ and $f_2$. For stability, the Q's must only be relatively stable; this does not appear to be a serious problem because the frequency modulation is very small in comparison to the cavity center frequency.

For accuracy, the Q's may be calibrated upon initial operation of the maser so that the tuning point is located such that it just compensates for spin exchange pulling. This is done by the usual spin-exchange tuning procedure. Thus in subsequent operation spin-exchange pulling of the maser is compensated by the cavity calibrated offset. Small variations of the cavity tuned position may also be achieved by using small differences in the modulation period. With the above procedure the main concern is higher order systematic drift effects.

The cavity servo instability process of most obvious concern is the effect of maser output random amplitude variations as seen at the receiver. The most prominent source of random amplitude noise is the thermal noise power as increased by the noise factor of the cavity circuit and the maser receiver input stage. Letting N be the total noise factor and B the bandwidth of the servo system, the noise to signal ratio is given by

$$\frac{V_n}{V_s} = \sqrt{\frac{GKTBN}{2P}}$$

where P is the signal power coupled out of the cavity and G is the power gain of the cavity Q enhancement circuit. The bandwidth of the servo system is given by $B = 1/(2\pi\tau)$ where $\tau$ is the time constant of the servo system.

For a voltage signal of amplitude $V_n$, analysis of the cavity impedance function gives a corresponding offset in cavity frequency of

$$\Delta f_c = \frac{1+\Delta^2}{4\Delta} \cdot f_{cw} \left(\frac{V_n}{V_s}\right)$$

where $\Delta = (f_2 - f_1)/f_{cw}$, $f_{cw}$ is the cavity width at the half power points, and $V_s$ is the maser signal coupled from the cavity when the cavity average offset is zero.

If the cavity is offset by an amount $\Delta f_c$, the maser is pulled by an amount

$$\frac{\Delta f}{f} = \frac{Q_c}{Q_\ell} \cdot \frac{\Delta f_c}{f} .$$

From the above equations the maser fractional frequency instability induced by thermal noise is

$$\sigma_h(\tau) = \frac{K_c}{2Q_\ell}\sqrt{\frac{GkTN}{\pi P\tau}}$$

where

$$K_c = \frac{1+\Delta^2}{4\Delta} .$$

The minimum value of $K_c$ occurs for $\Delta = 1$, or $f_2 - f_1 = f_{cw}$. However, the average coupled power output, P, decreases with cavity offset, both due to the decrease in the coupling coefficient and due to the decrease in average radiated beam power when the modulation width is large. The best value for $\Delta$ has been estimated from experimental measurements at this time. In cavity tuning experiments with the SHM, values of $f_{cw}$ between 20 KHz and 40 KHz have been used, with $f_2 - f_1 = 6$ KHz. For an averaging time of 1,000 seconds, $P = 7 \times 10^{-13}$ watts, $G = 6$, and $N = 4$, the SHM servo limit due to thermal perturbing noise is calculated to be $\sigma_h(\tau) = 5 \times 10^{-15}$ for $f_{cw} = 20$ KHz, and $\sigma_h(\tau) = 7.5 \times 10^{-15}$ for $f_{cw} = 40$ KHz.

From the above it is apparent that the servo noise limit due to random thermal noise within the cavity should be very small, and that systematic disturbances which are too rapid or too large for servo system correction may be limiting factors for the SHM. A breadboard model of the new servo was installed on the SHM in March 1982 and transient system response tests indicated that it was working properly. After the two new masers constructed for APL and NRL were completed in December 1983 further experiments and tests were performed on the SHM to establish the actual stability obtainable. The results of these tests are discussed subsequently.

## SMALL HYDROGEN MASER PHYSICAL ASSEMBLY

Figure 4 is an assembly drawing of the physics unit of the SHM which identifies the main parts and gives the basic dimensions. Figure 5 is a picture of the physical parts prior to final assembly. Figure 6 is a bottom view which shows the source bulb, RF dissociator components, pressure gauge and hydrogen supply. Figure 7 is a picture of the vacuum enclosure, source assembly and Ion Pump. The weight of the assembled physics unit is approximately 50 pounds.

## SHM STATE SELECTION

The original concept for the SHM design did not anticipate use of the active cavity Q enhancement circuit. Thus, to achieve oscillation conditions it was essential that spin-exchange broadening of the atomic resonance line be avoided. To do this it was planned to use a novel system, using two state selectors, which focussed only the F = 1, m = 0 state into the storage bulb. A shielded region with magnetic coils was provided between the two state selectors wherein the F = 1, m = 1 state was changed to an F = 1, m = -1 state and was subsequently defocussed, while the F = 1, m = 0 state remained unchanged. In tests with the breadboard hydrogen maser it appeared that this state selection system worked. However, the overall efficiency was not very good and a very high source flux was required to get a reasonable signal. The beam was only detected by pulse stimulation and the maser would not oscillate. A contributing factor was that the achieved cavity Q was lower than anticipated.

With the realization of a practical circuit for cavity Q enhancement, two state selectors are not required. The SHM at present still uses the two state selectors as it was too late to change the spacings, however the coils and shielded region between the state selectors have been removed, and the second state selector has an aperture which is twice as large as the first one. Thus the effect is almost the same as use of a single unit.

The most efficient state selection system is one which uses a small tapered quadrupole configuration.[12] An example of a one inch long unit in shown in Figure 8. This unit is the same overall size as one of the state selectors used in the SHM, but the magnetic circuit has been designed so that the pole tip aperture, taper, and gaps may be adjusted after the state selector is assembled. While hydrogen flux utilization is not too large in the SHM, typically .05 moles $H_2$/year, this should be improved by a factor of about 4 with the use of the new state selector.

## HYDROGEN STORAGE AND SUPPLY

Hydrogen storage in a pressure vessel has been used very successfully in the past to contain an adequate supply for many years of hydrogen maser operation. Typically a one liter bottle with 1,000 PSI of hydrogen is used. The bottle contains about 3 moles ($H_2$) and would last 60 years in the small maser. However, such a large size bottle at high pressure is not desirable in a compact maser, nor should it be required, since recent metal hydride research has resulted in the availability of many alloy combinations which store high densities of hydrogen at relatively low pressure.

The hydrogen supply system of the SHM uses a small stainless steel bottle with a volume of 34 cc which contains 1.25 moles of hydrogen absorbed in 186 gms of an alloy of cerium free mischmetal and nickel. The hydrogen is valved to the source by a palladium-silver purifier and the source pressure is controlled by a servo system using a thermistor pirani gauge. The entire system is designed, constructed and assembled in-house, and requires only about 5 watts of total D-C power to operate.

## SHM PACKAGING, ELECTRONICS, AND CONTROLS

Figure 9 is a picture of the SHM within the mounting framework illustrating the electronics subsystems placement and controls arrangement. The electronics subsystems have been packaged in functionally separate modules, each of which may be uncovered for operational testing without disconnection of power. They may also be removed, repaired, or replaced as units in case of malfunction. The modules on the front panel are: 1. Vac-Ion Pump supply; this is a DC-DC converter which provides 3,000 volts for the pump, 2. The source pressure control module which automatically regulates hydrogen flow, 3. The receiver synthesizer; this supplies the 405 KHz reference frequency for the receiver phase lock loop - there are 11 decades of control which give a resolution of $\pm 5 \times 10^{-15}$ for the output frequency, 4. The receiver VCO and output buffer amplifiers, 5. The receiver local oscillator multiplier and IF amplifier module, 6. The module containing the magnetic field and cavity frequency controls, 7. The instrumentation read-out module. There are 16 read-out channels which are selected by 4 binary coded switches to provide visual indication of variables on a 4 ½ decade digital panel meter.

The power supply has been placed in a module mounted at the rear of the frame. The cover may be removed for changing connections or trouble shooting without disconnecting the power. Batteries for uninterruptable standby operation are placed in a separate external battery pack. For long term operation without A-C power, a 45 A-H capacity battery is used which will last for twenty hours.

## SHM STABILITY PERFORMANCE

In December 1983, construction of the new APL and NRL hydrogen masers was completed and it was possible to continue experimentation with the SHM using the other masers as a stable frequency reference. SHM cavity servo response and maser stability measurements were then made using several variations in the servo correction rates at different cavity register gain values, and with two different modes of varying the cavity frequency.

First, the stability without use of the cavity servo was examined. For one and ten second intervals the Allan variance was $2.5 \pm 1 \times 10^{-12}$. For longer periods, up to a day, the stability was erratic, with rather large random excursions in frequency. Over a four day measuring interval there was an approximately monotonic drift of $2.3 \times 10^{-13}$ per hour. Test were then made using the cavity servo with the cavity frequency controlled through the temperature control circuit. This was not successful for the apparent reason that the cavity frequency versus temperature characteristic of the SHM was not monotonic and had a wide hysteresis loop. The servo control voltage as well as the maser frequency varied between rather large extremes. Tests using the servo output to control the frequency through the cavity gain circuit were also very disappointing. Changes in the gain transistor bias not only changed the cavity frequency and modulation width, but it appeared to affect the cavity noise spectra amplified by the transistor circuit, and the variable noise amplitude modulation interfered with the maser signal modulation.

The above tests pointed to several factors which would need to be changed in the SHM design before the program stability goals could be met. These would require disassembly of the maser for modifications of the cavity and bulb assembly and incorporation of improvements in the cavity active gain circuit, as well as addition of a separate circuit with a varactor diode to use as an independent method for cavity frequency modulation. In the external electronics it would also be necessary to install a more advanced version of the cavity servo and to make improvements in the receiver circuit. However, in view of the recent success at Sigma Tau Standards Corporation with hydrogen masers using cavity and bulb assembly designs which avoid the problems encountered with the SHM, no further effort with the SHM has been recommended.

## CONCLUSION

Work on the SHM at Sigma Tau Standards Corporation has been completed at this time. However, the scientific knowledge and technical fallout have been very valuable in laying a foundation for the conception and realization of the new designs embodied in the APL and NRL masers. We have learned of the difficulties and complexities involved in the cavity and bulb configuration used in the SHM, and arrived at a new design which, though not quite as compact, has more than met the stability goals of the "Light-Weight Hydrogen Maser Development Program." For future efforts to attain the utmost stability in the smallest size atomic hydrogen maser devices we recommend that research and development efforts be directed along the lines of the new masers.

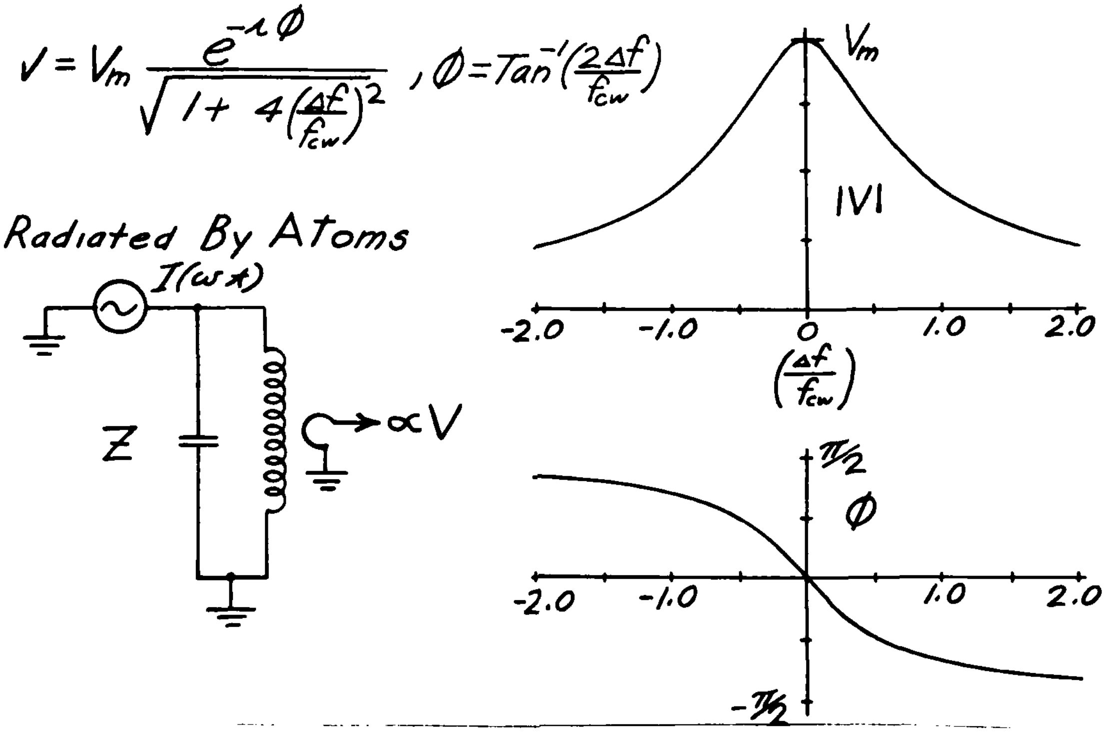


Figure 1. Interaction of Radiated Beam Power with Cavity Impedance.

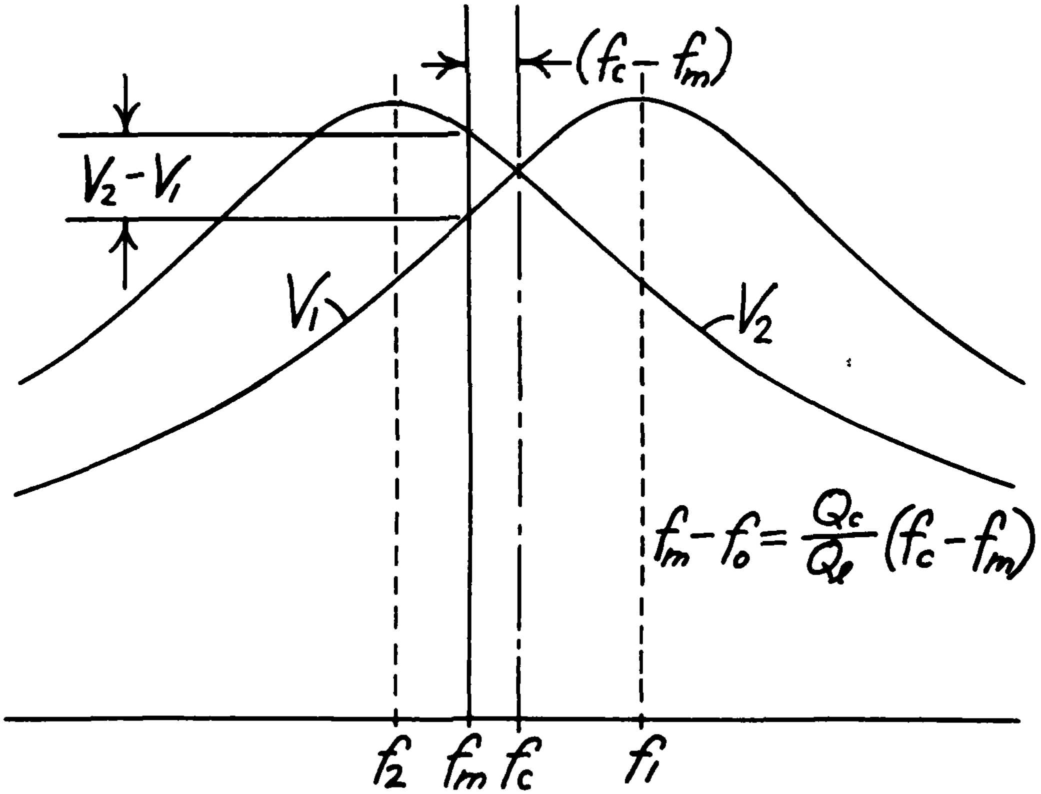


Figure 2. Signal Modulation Induced by Cavity Frequency Switching.

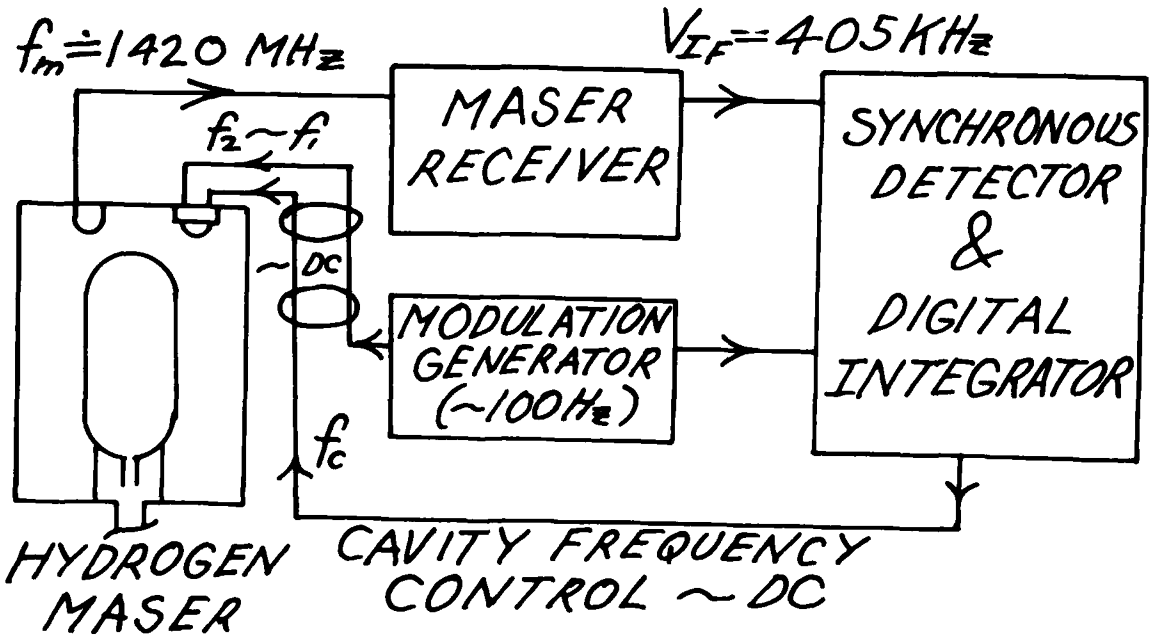


Figure 3. New Cavity Servo System.

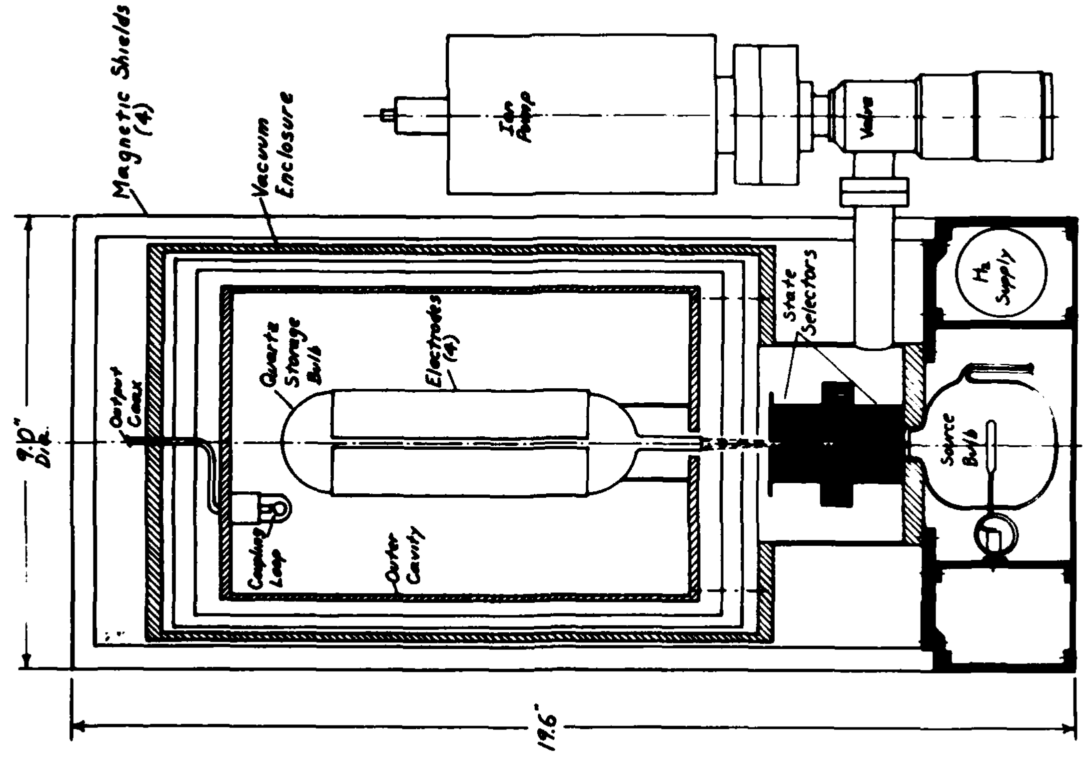


Figure 4. Small Hydrogen Maser Physics Unit.

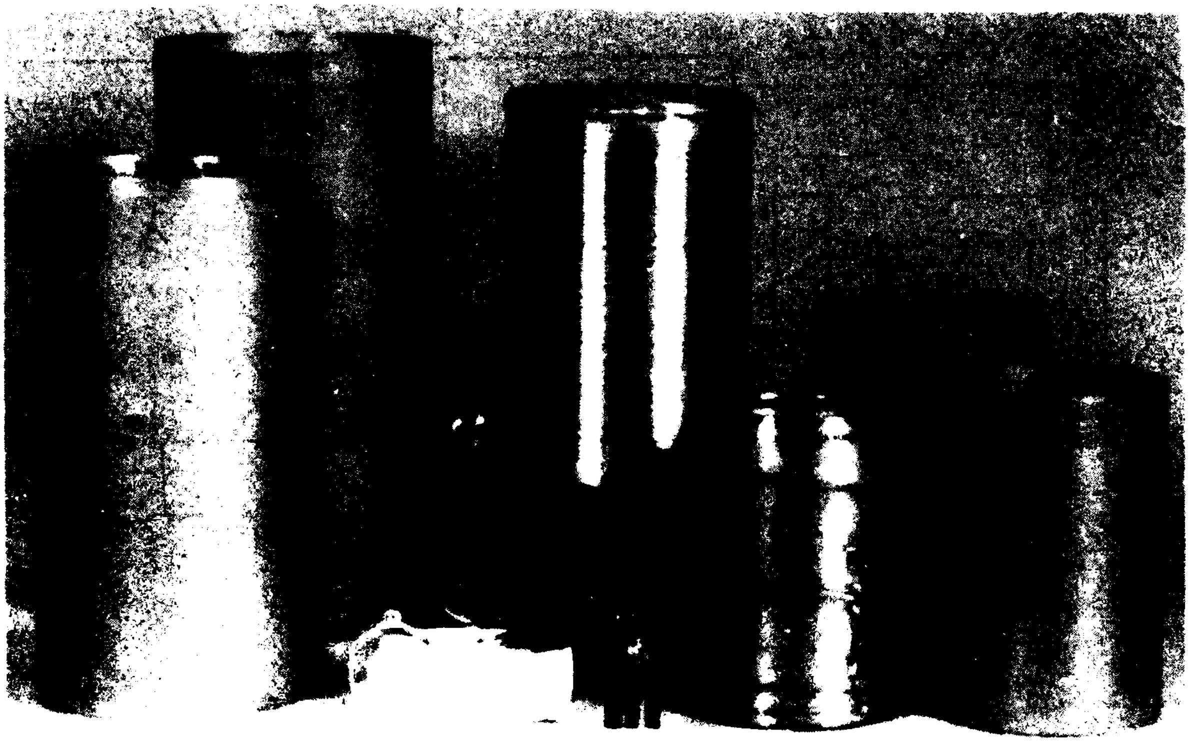


Figure 5. Small Hydrogen Maser Physical Parts Prior to Assembly.

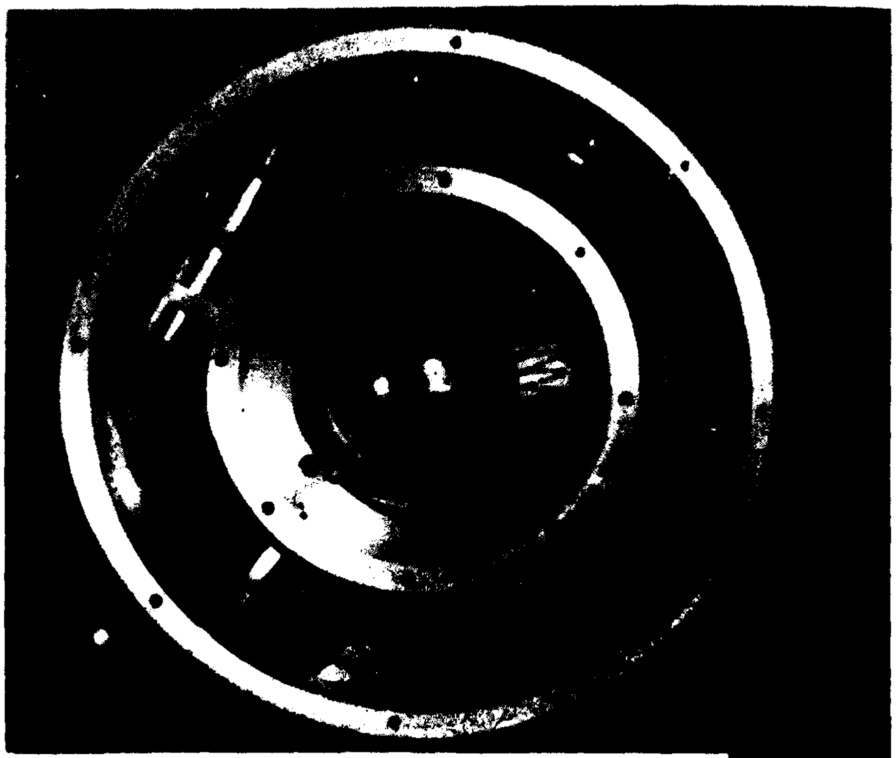


Figure 6. Bottom View of Source Assembly.

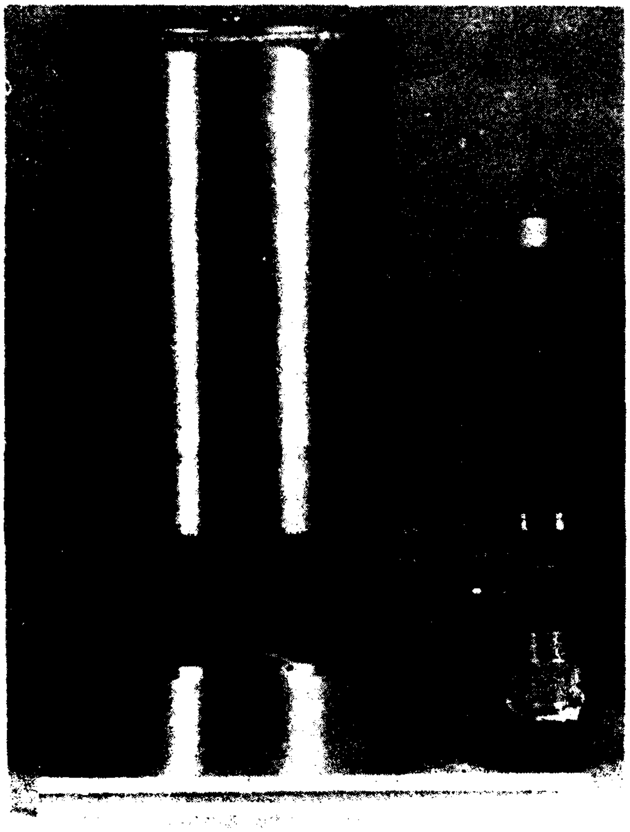


Figure 7. Small Hydrogen Maser Vacuum Enclosure and Ion Pump

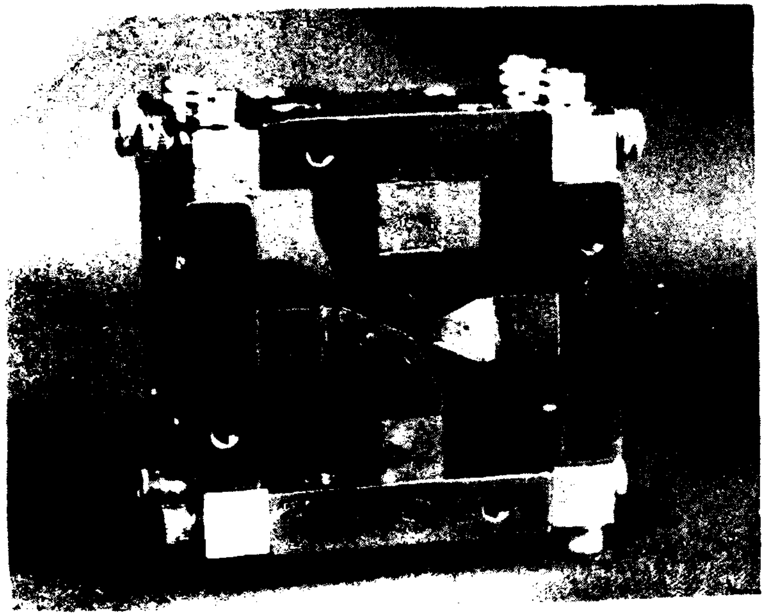


Figure 8. Miniature Quadrupole State Selector.

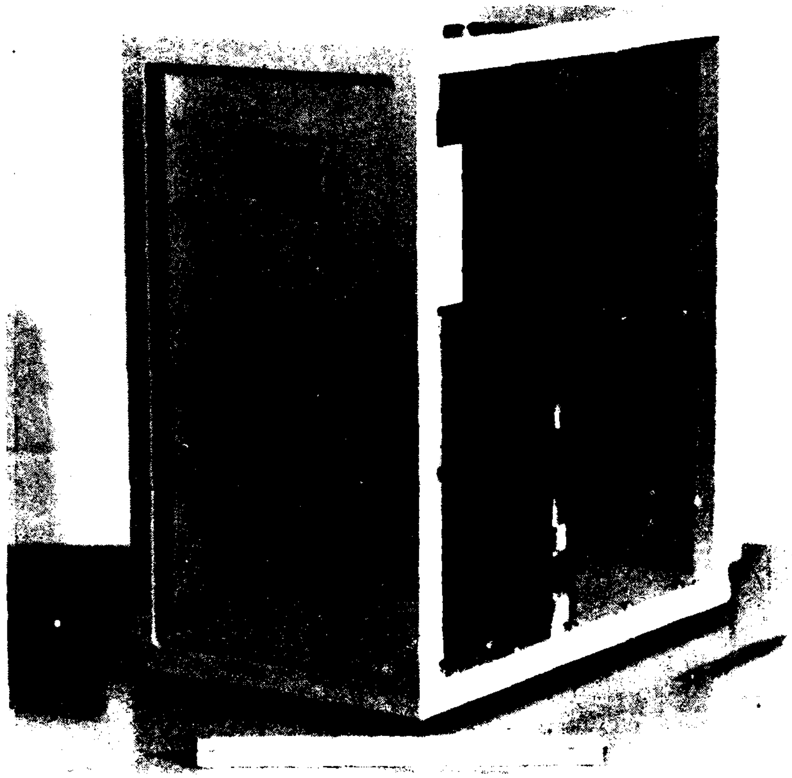


Figure 9. Small Hydrogen Maser Overall Assembly.

# REFERENCES

1. H. E. Peters, "Experimental Results of the Light-Weight Hydrogen Maser Program," Proceedings, 36th Annual Symposium on Frequency Control, June 1982.

2. H. E. Peters, "Design and Performance of New Hydrogen Masers Using Cavity Frequency Switching Servos," Proceedings, 38th Annual Symposium on Frequency Control, May 1984.

3. H. E. Peters, "Small, Very Small, and Extremely Small Hydrogen Masers," Proceedings, 32nd Annual Symposium on Frequency Control, May 1978.

4. The NRL Hydrogen Maser was funded by the Naval Research Laboratory under Contract N00014-83-C-2015.

5. The APL Hydrogen Maser was funded by the Applied Physics Laboratory of The Johns Hopkins University and NASA, Goddard Space Flight Center, under Contract 601748-S.

6. H. E. Peters, "New Hydrogen Maser Designs," Proceedings, 34th Annual Symposium on Frequency Control, May 1980.

7. H. E. Peters, "Feasibility of Extremely Small Hydrogen Masers," Proceedings, 35th Annual Symposium on Frequency Control, May 1981.

8. H. E. Peters, T. E. McGunigal, and E. H. Johnson, "Hydrogen Standard Work at Goddard Space Flight Center, "Proceedings, 22nd Symposium on Frequency Control, May 1968.

9. D. A. Howe, F. L. Walls, H. E. Bell, and Helmut Helwig, "A Small, Passively Operated Hydrogen Maser," Proceedings, 33rd Annual Symposium on Frequency Control, May 1979.

10. P. Lesage, C. Audoin, and M. Têtu, "Amplitude Noise in Passively and Actively Operated Masers," Proceedings, 33rd Annual Symposium on Frequenc Control, May 1979.

11. H. T. M. Wang, "An Oscillating Compact Hydrogen Maser," Proceedings, 34th Annual Symposium on Frequency Control, May 1980.

12. H. E. Peters, "Magnetic State Selection in Atomic Frequency and Time Standards," Proceedings, 13th Annual Precise Time and Time Interval Applications and Planning Meeting, Naval Research Laboratory, Washington, DC, 1981.

# MISSION
# of
# Rome Air Development Center

RADC plans and executes research, development, test and selected acquisition programs in support of Command, Control Communications and Intelligence ($C^3I$) activities. Technical and engineering support within areas of technical competence is provided to ESD Program Offices (POs) and other ESD elements. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, solid state sciences, electromagnetics and electronic reliability, maintainability and compatibility.

**Printed by**
**United States Air Force**
**Hanscom AFB, Mass. 01731**

END
DTIC
4-86