PASSIVE MASER DEVELOPMENT AT NRL

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ABSTRACT

The Naval Research Laboratory has been investigating the application of passive hydrogen masers to satellites. This effort has included development of a working small maser at NRL and contractual support of work at Hughes Research Laboratory and the National Bureau of Standards.

The NRL maser is of compact design suitable for the space environment. It is based on a dielectrically loaded sapphire cavity and uses a computer optimized set of four shields. The mechanical structure was developed in a cooperative effort with the Smithsonian Astrophysical Observatory. The servo design is a novel phase sensitive method which directly measures the phase dispersion of the interrogating signal as it passes through the cavity. Test results will be presented.

A brief synopsis of the results of the contractual work will also be presented.

INTRODUCTION

The Naval Research Laboratory is involved in development of passive maser technology for applications both in spacecraft and in ground stations. This represents a continuation of the work done previously in the TIMATION and GPS programs. The goal of this effort is to provide a clock for GPS and other potential users which is more stable at periods of several days and which is also capable of operating reliably in military environments. This project includes in-house development and also relies on outside technology development by other government and industry laboratories.

This program began in the early 1970's with the work by the Smithsonian Astrophysical Observatory (SAO) in the building of the first VLG-10 maser[1]. NRL also supported development of the first

VLG-11 masers at SAO[2] and directed the contractual program at Frequency and Time Systems which produced the first space qualified cesium clocks[3]. We are currently engaged in efforts to develop additional sources of space qualified cesium standards.

The space hydrogen maser program began several years ago with preliminary work to locate qualified aerospace industry sources to develop and manufacture a space qualified active maser. This work was taken on by Hughes Research Laboratory (HRL) and RCA in a competitive effort. Both contractors delivered operating, prototype masers[4,5]. HRL was selected to do additional work. It was at this point that the National Bureau of Standards (NBS) produced their passive maser[6]. The passive concept gave two distinct advantages over active masers. The first was the option of using a smaller, lower Q RF cavity. That meant a large reduction in weight and volume along with some simplification in pumping and magnetic shielding requirements. The second advantage was the possibility of achieving better long term performance due to the application of a cavity control servo.

The work on passive masers has since been in these areas. NRL and SAO have worked cooperatively to build a small passive maser. HRL has been contracted to follow other promising approaches to small masers while developing technology which might be used in other parts of the program. As originally defined HRL remains the link to major aerospace capabilities. NBS has been funded to continue their development of passive maser technology.

NRL Passive Maser

In 1978 the decision was made to build a small passive maser at NRL. This effort not only includes NRL but also support from other laboratories. This maser is viewed as a means of assembling the most promising parts of the existing technology and also as a way of extending knowledge in the areas where the existing work falls short of the goals. Like the NBS maser the basic approach is passive with separate servo controls for the hydrogen line and the cavity. As will be discussed in the section on the electronics, there are some differences in the application of these controls. The desired product is summarized as follows:

1. Suitable for military/space operating environment
2. Highly reliable
3. Long term stability of 1×10^{-14} at 10 days

4. Compact size
5. Low weight
6. Low power

To approach these goals the clock is examined in terms of its subassemblies.

1. Cavity and shields
2. Mechanical and thermal
3. Vacuum
4. Electronics

Cavity and Shields

The physics unit of the NRL maser consists of the hydrogen beam source and optics, magnetic shields, cavity thermal control, vacuum system and mechanical support for the microwave cavity. In the present configuration, this cavity operates in the TE_{011} mode and is loaded with single crystal (low loss) sapphire, figure 1. Three slots in the cavity cover plate provide the necessary coupling. The volume available in the cavity for the hydrogen atoms is 217 cm^3 and the surface of this volume is coated with FEP 120 teflon in order to minimize hydrogen-wall interactions. The hydrogen atom source consists of an rf dissociator from which the atoms emerge into a hexapole state selector magnet.

The magnetic shield set, consisting of 4 nested molypermalloy shields, was designed for a lightweight small-volume configuration (figure 2) with a substantial shielding safety factor to provide a frequency stability of 1 part in 10^{14} for any orientation in a 1 gauss field[7].

Mechanical and Thermal Design

The importance of the mechanical and thermal control designs is especially great when operation outside the laboratory is required. NRL has chosen to make use of the extensive experience available in this area at SAO. SAO's probe maser launch for the red shift experiment has given them a unique understanding of the requirements for spaceflight as applied to the Hydrogen maser. SAO has, under contract to NRL, designed, fabricated and delivered two units of a developmental model maser[8]. As input SAO was given the environmental requirements, the cavity/shield system, the vacuum system and hydrogen source system. The first design, the Exploratory Development Model (XDM), was delivered in 1979. A refined version of the XDM, the Advanced Development Model (ADM) is scheduled for delivery in late 1980.

Figure 3 shows the XDM design. The cavity is mounted to a Belleville spring to provide essentially constant force on the end plates. The cavity is enclosed in a separate vacuum can rather than using the cavity as the vacuum envelope. This adds weight and volume but allows greater isolation of the cavity from its environment. The entire assembly is designed to meet the GPS vibration (~ 19 g rms) requirement.

The thermal design is similar to that of the VLG series active masers using a multi-zone, double oven approach. The vacuum tank is the primary temperature control surface. A second oven is used to isolate the tank from external heat paths. The XDM masers used a conventional foam insulation between the shields. As an enhancement, the ADM masers use a vacuum type insulation which takes advantage of the vacuum environment of space to reduce heat loss and weight. The nominal oven power of XDM-1 is about 7.4 watts. For ADM-1, in vacuum, the measured power is 2 watts. While this superinsulation scheme is best applied in vacuum, it has been found also to provide excellent thermal stability in air at increased input power. The oven system was designed to provide a temperature stability of better than 5 millidegrees at the cavity. It may be argued that the cavity control servo reduces the need for such excellent thermal stability but for non laboratory applications this conservative design can greatly reduce system problems.

Pumping System-Hydrogen Supply

The design life of a space borne maser is five years of operation. Historically vacuum systems have been a weak area in maser reliablility. The ion pumps themselves do not thrive on pumping hydrogen and the required high voltage power supplies are also troublesome, particularly if vacuum operation is desired. The dissociator is likewise a sensitive area in masers[9]. While most contemporary masers show good dissociator life, they do tend to run hot and thus require forced air cooling. Fortunately, solutions are available for both problems.

Recently a very effective, high capacity hydrogen getter pump has become available. Both HRL and NRL have investigated these pumps for maser use [4,10]. Since the getter pump is a passive device it requires no external power after activation and is also inherently reliable. For the NRL maser, a combination pumping system using getters and multiple small ion pumps has been built. This system, more fully described elsewhere in these proceedings [10], pumps the primary hydrogen gas load with the getter and requires only a small ion pumping capacity to maintain the desired vacuum. Redundant ion pumps with isolated supplies further increase reliability.

There are several approaches to the problem of operating the dissociator in vacuum. A simple pyrex bulb design from HRL operates at under 50°C. Other designs are also being investigated. One obvious method to obtain cooling is to conduct heat away through the walls of the bulb. Pyrex, which is the most popular material in dissociators, has relatively poor thermal conductivity. HRL and RCA both experimented with quartz bulbs but to date there is little assurance that these will have long life. SAO has designed a pyrex bulb which runs cool by virtue of thick walls and short paths to heat sinks. A radical departure in design is being pursued at NBS. They propose a small dc discharge. Since there is no longer a requirement to pass RF energy through a wall, the choice of materials and configuration broadens. Such a design, if successful, would also have the advantage of reduced RF interference to the electronics.

ELECTRONICS

The servo subsystem consists of the electronic control to lock a voltage controlled crystal oscillator (VCXO) to the hydrogen hyperfine transition and the electronic control to tune the cavity symmetrically about the hydrogen line. NRL has devised a scheme to compare the phases of a set of coherent microwave frequencies, which are coupled through the dielectric loaded cavity, versus the VCXO.

The phase comparison technique uses a high percentage of digital circuits in the synthesis of the microwave frequencies and in the phase detection networks. The digital circuits reduce the necessity for analog adjustments, and offer low operating power consumption, reduced weight, compactness, and a broad environmental operating range. These features are ideal for space applications.

Figure 4 is a block diagram of the SERVO electronics.

The hydrogen line servo employs three microwave signals that are synthesized from the VCXO. These signals are time shared, coupled through the cavity, phase detected, and used to control the VCXO. One synthesizer frequency is at the hydrogen resonance. The others are symmetrical about the hydrogen resonance but well outside the hydrogen line width and still near the center of the cavity resonance width. This method is used to establish a phase reference for the hydrogen line.

The output of the set of frequencies coupled through the cavity is amplified, translated, phase detected, averaged in an up-down counter, transferred to a digital analog converter (DAC), and used to control the VCXO. These frequencies are all passed through the same broadband receiver and are translated with an offset set of frequencies from the synthesizer. The resulting signal frequency with plus or minus the phase of the hydrogen line or cavity line is narrowband filtered. The filtered signal is shaped in a zero crossing detector and phase compared with a signal divided down from the VCXO.

The output of the phase comparator is used to control an updown counter. Phase comparator output corresponding to the hydrogen resonance frequency is averaged for a period of time in an up count direction after a settling time. Phase comparator output corresponding to the symmetrical frequencies is averaged over one-half the period of the hydrogen resonance frequency each after a settling time in a down count direction. Transfer of the up-down counter contents to the DAC which controls the VCXO frequency is executed after completion of the up-down counter cycle.

The cavity line servo consists of three microwave signals which are synthesized from the VCXO. These signals are time shared with the hydrogen line signals during a period when the hydrogen servo is quiescent. One of the frequencies is the hydrogen transition frequency used with the hydrogen servo and the other two frequencies are symmetrical about this transition frequency and fall within the passband of the cavity resonance. The symmetrical frequencies are time shared and simultaneously coupled through the cavity with the hydrogen transition frequency.

The signals coupled out of the cavity are amplified and translated to an intermediate frequency (IF) with the same broadband circuits used with the hydrogen servo. This IF is detected, narrowband filtered, shaped with a zero crossing detector, and phase compared versus a signal divided from the VCXO. The phase comparator controls an up-down counter which averages the time shared signals after a settling time. Controls allow an up count corresponding to the composite lower symmetrical frequency and hydrogen transition frequency and a down count corresponding to the composite upper symmetrical frequency and hydrogen transition frequency. Transfer of the up-down counter contents to a DAC is executed upon completion of the up-down counter cycle. Tuning of the cavity is accomplished by controlling a varactor with this DAC output voltage. The varactor is coupled to the cavity and reactively tunes the cavity proportional to the DAC control voltage.

System Performance

The XDM masers from SAO have been used to experimentally verify system performance. The width of the hydrogen line under optimum pressure and magnetic field is 2.0Hz thus giving a line Q of 7×10^8. The phase slope at center frequency is about 6° per Hz. The stability of this maser measured at the output of the electronics is $7 \times 10^{-12}/\sqrt{\tau}$ for the range τ = 10 to 3000 seconds (figure 5). Work is currently underway to optimize the cavity servo and extend this stability level to better than 1×10^{-14}.

Outside Work

In addition to the work done with SAO, NRL has also contracted with Hughes Research Laboratory (HRL) and the National Bureau of Standards at Boulder (NBS).

The current contractual relationship with HRL has grown from the original competition efforts on the active maser. Following the shift in emphasis from the active to passive mode, HRL was directed toward small maser concepts and development of technologies applicable to small masers. Dr. Wang has previously reported on HRL maser development [11, 12]. HRL is presently working on Q-multiplier type servo using a small, slot loaded cavity. This maser was tested at NRL (figure 6). It had a stability of $2 \times 10^{-12}/\sqrt{\tau}$ for τ = 10 to 10000 seconds. HRL has also done investigations of getter pumping systems, free induction servo techniques and dissociator design.

NRL has been providing funding support to NBS for passive maser development. NBS has delivered one of the first small passive masers (figure 7) to NRL. This maser uses a ceramic loaded cavity.

It is a laboratory model which has relatively stringent requirements on its environment and operation. Tests at NRL show a stability of $2 \times 10^{12}/\sqrt{\tau}$ for $\tau = 1$ to 10,000 seconds. This is virtually identical to that of the Hughes maser, both are shown in figure 8.

NRL has also continued support of the VLG-11 maser program with the purchase of a third VLG-11 last year. Our tests on the VLG-11 confirm the published SAO data on performance in the 1 to 3000 second region. We have, however, observed that a new maser has a significant cavity tuning drift rate in the first 6 months to 1 year of its life. A brief series of tests have just been completed on two masers over a year old. In this case instead of finding a decrease in stability beyond 3000 seconds, there still is a gradual improvement as far out as 10000 seconds.

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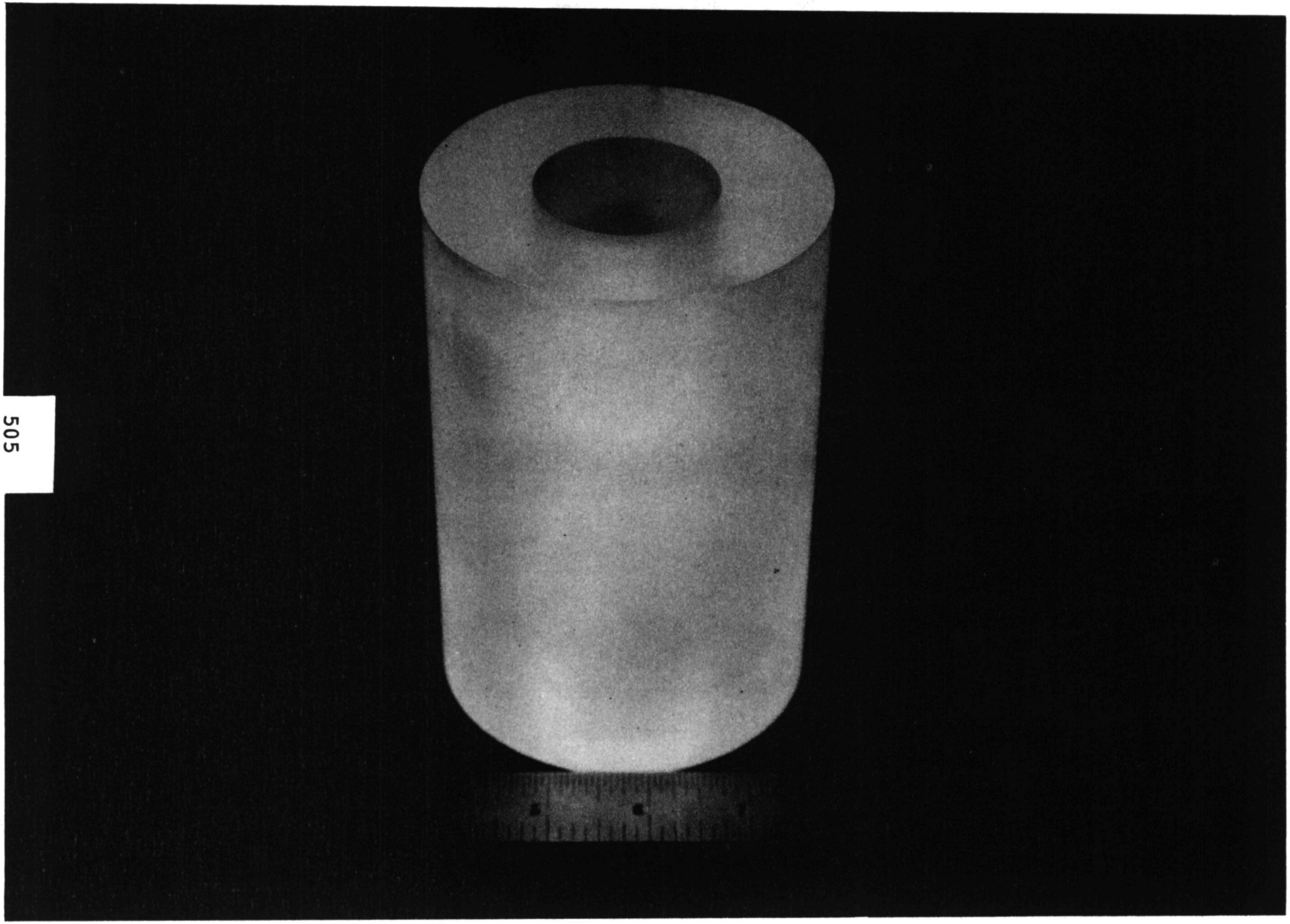

Figure 1 Sapphire Cavity

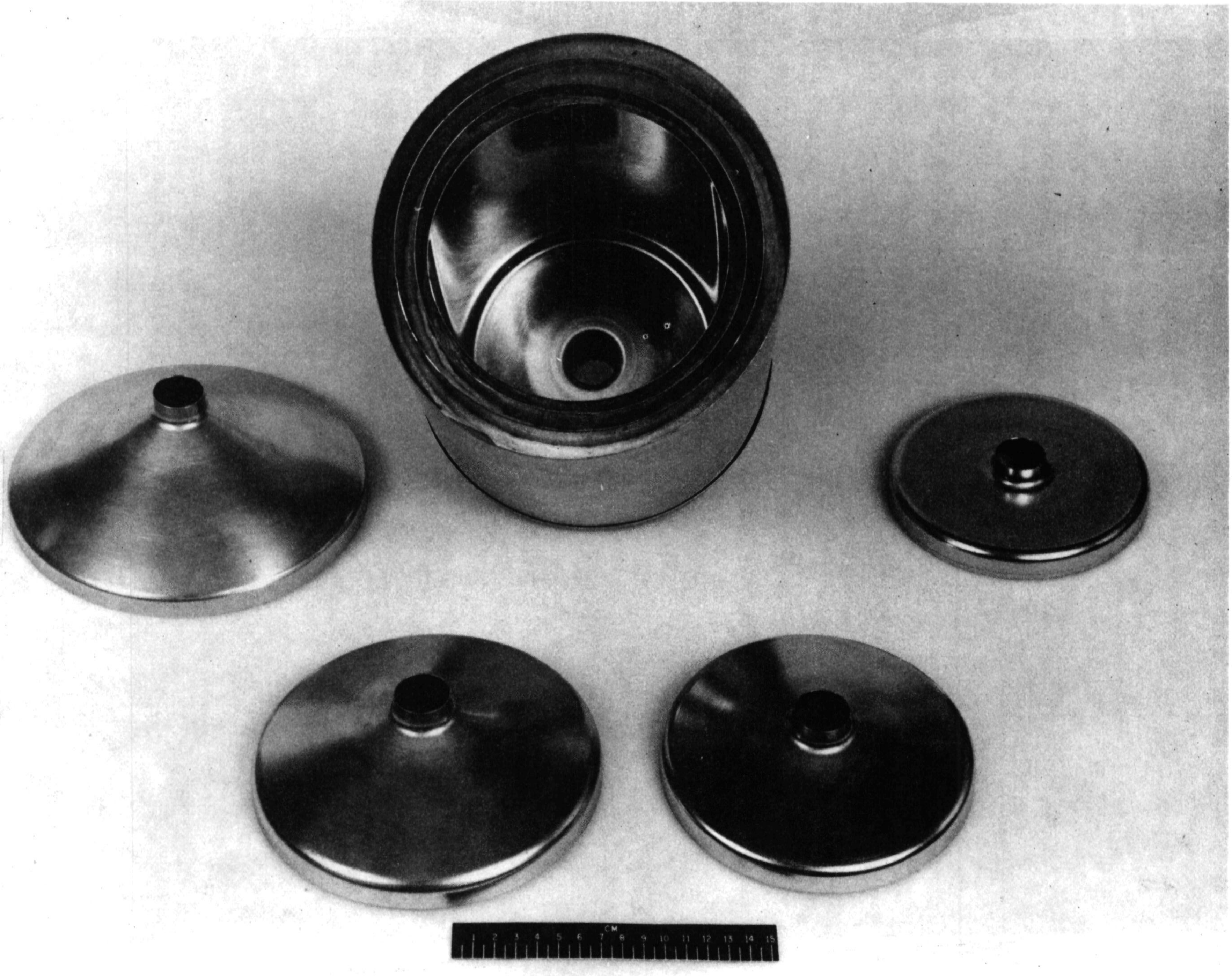

Figure 2. Shield Assembly

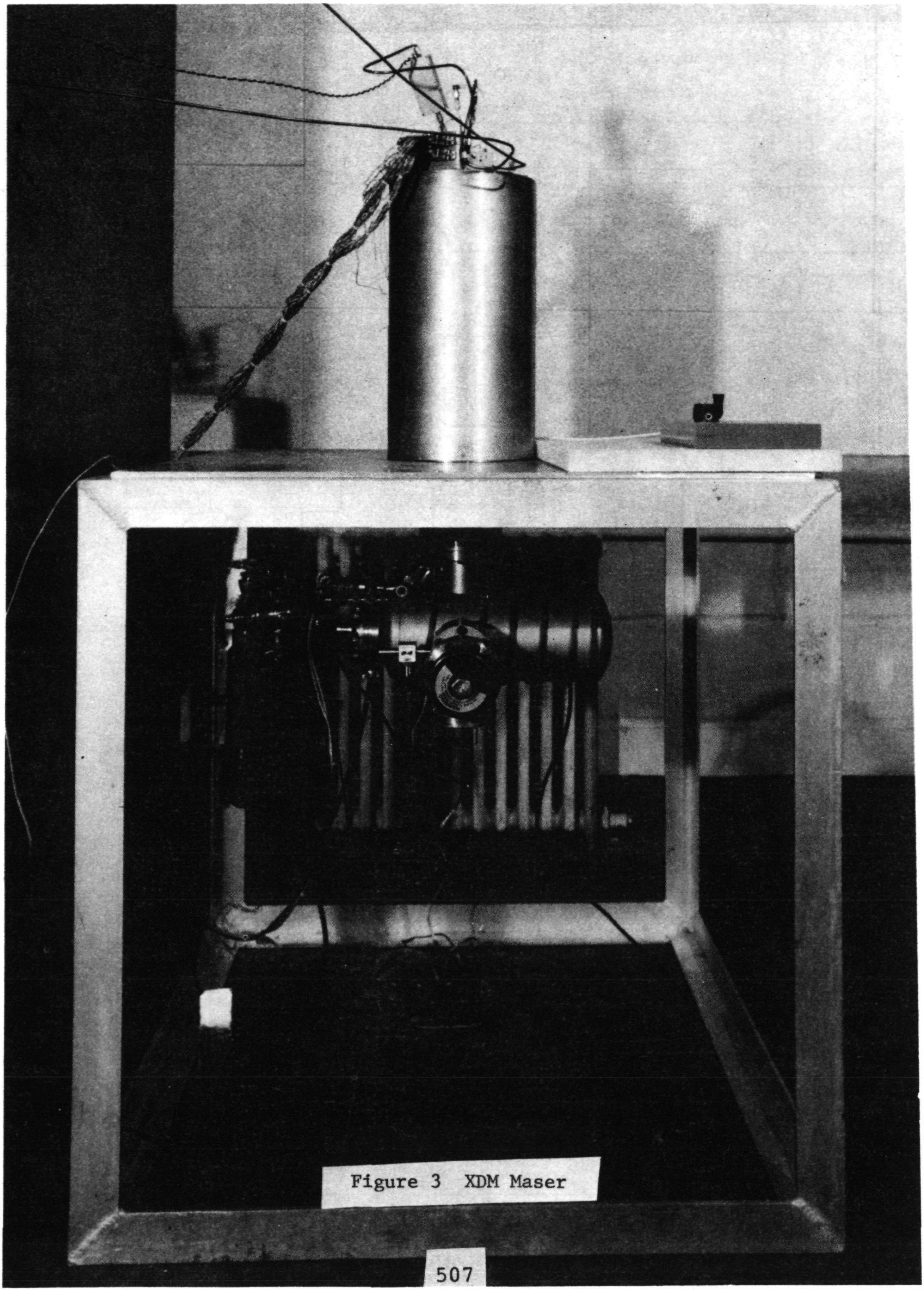

Figure 3 XDM Maser

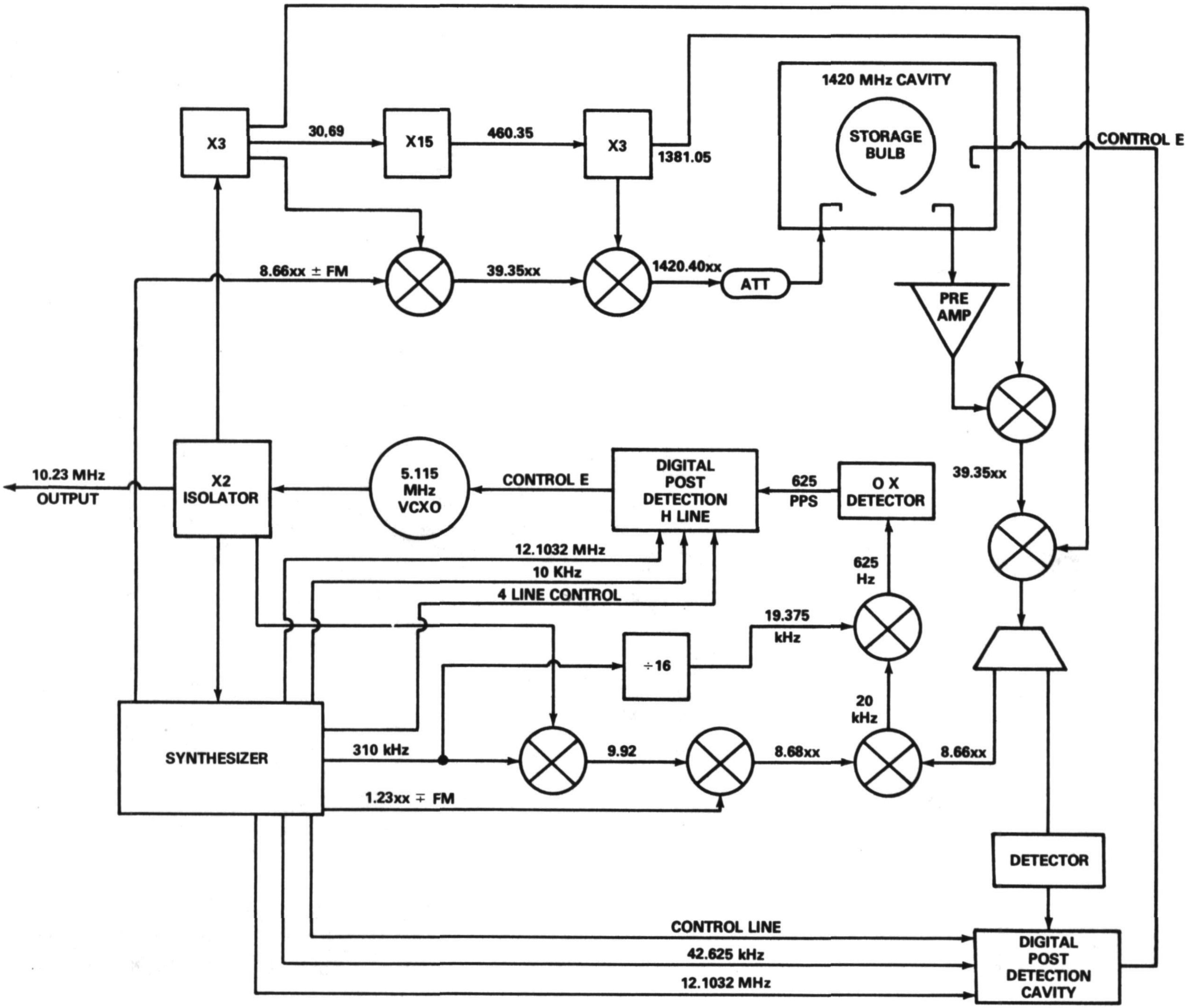

Figure 4 Block Diagram of Servo

NRL PASSIVE MASER

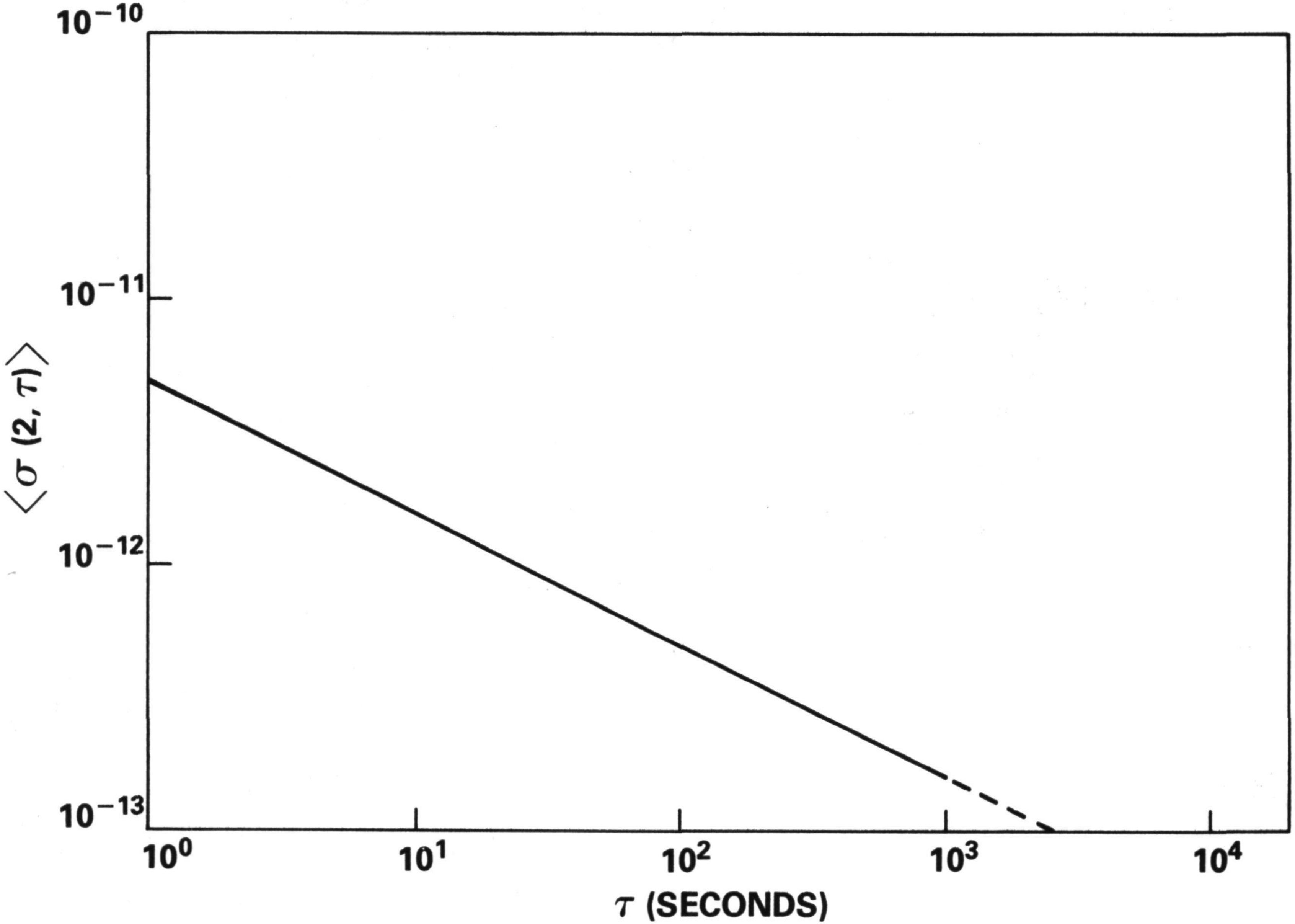

Figure 5 XDM Performance

Figure 6 NBS Passive Maser at NRL

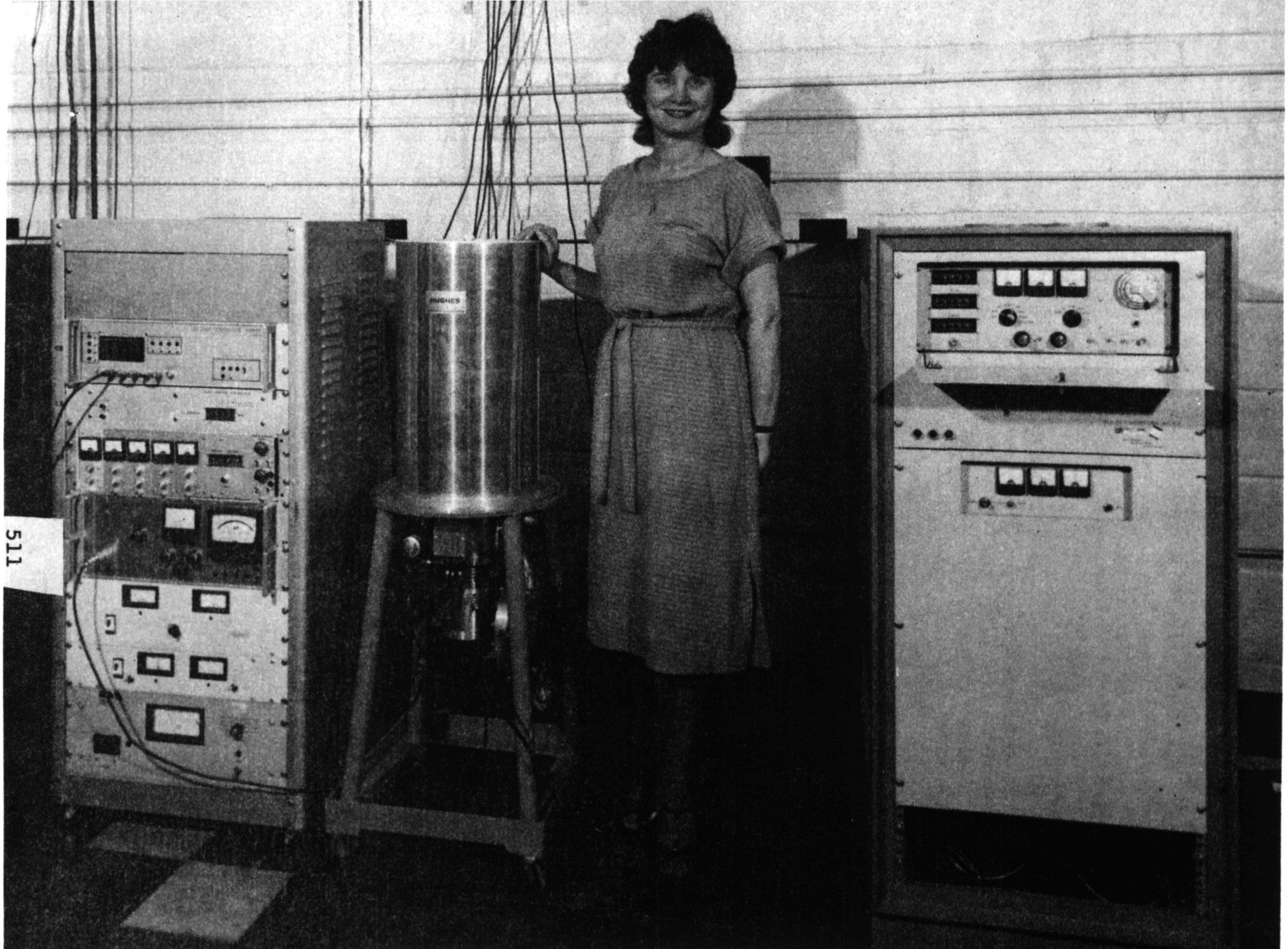

Figure 7 HRL Small Maser at NRL and SAO VLG-10

PASSIVE MASER PERFORMANCE

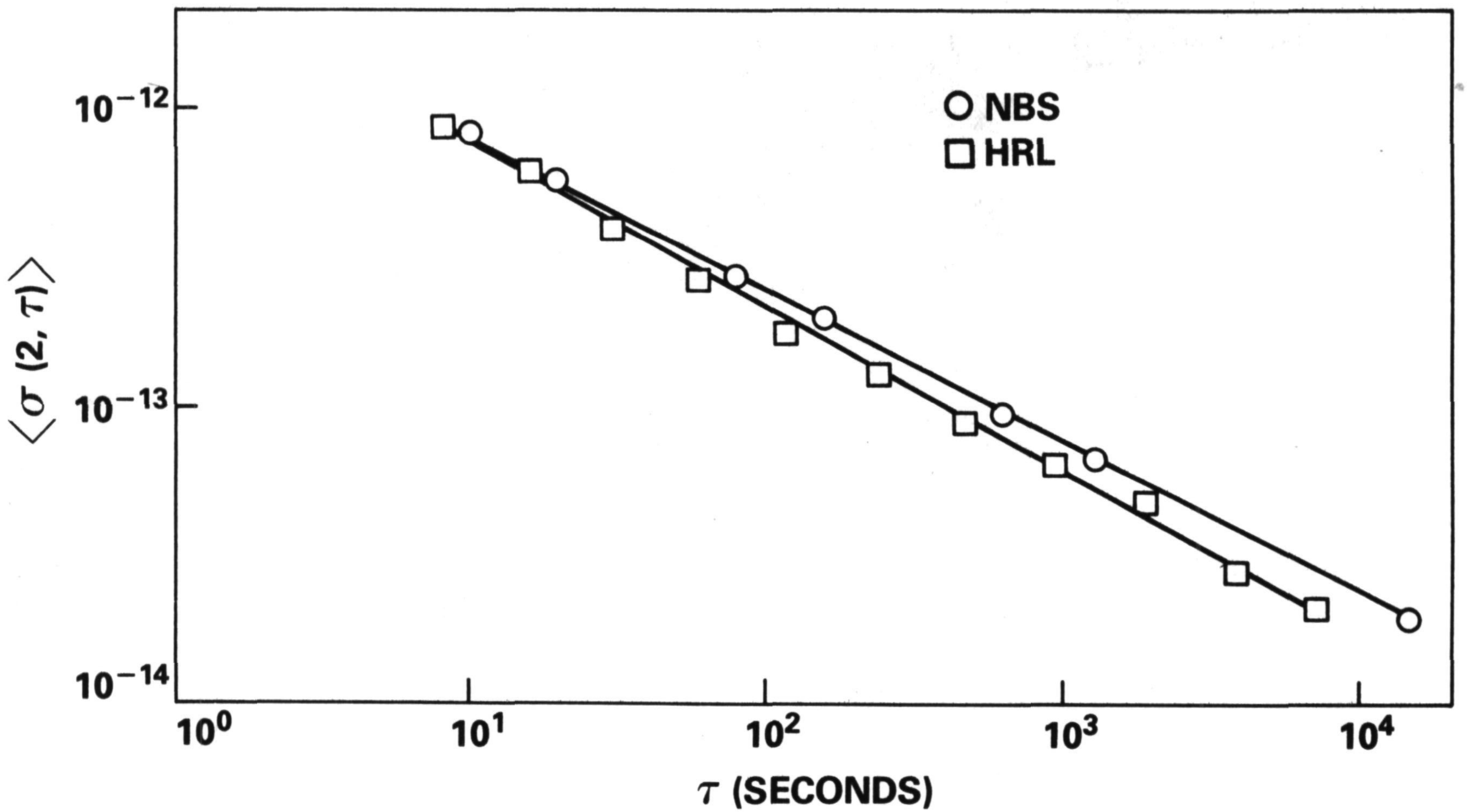

Figure 8 NBS/HRL Performance

QUESTIONS AND ANSWERS

MR. PETERS:

I just wanted to say that the maser that you showed us in Philadelphia was built by Harry Wang, Hughes Research.

MR. WHITE:

Oh, I am sorry, Harry. I got the wrong Harry indeed.