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 ($\sim$ 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 relia-blility. 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 re-
quirement 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 hyper-
fine 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.

499

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 comple-
tion 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 x
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 $7x10^{-12}/\sqrt{\tau}$ for the range $\tau = 10$ to 3000 seconds (figure 5).
Work is currently underway to optimize the cavity servo and extend
this stability level to better than 1 x 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
$2x10^{-12}/\sqrt{\tau}$ for $\tau = 10$ 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.

501

It is a laboratory model which has relatively stringent
requirements on its environment and operation. Tests at NRL
show a stability of $2 \times 10^{12} / \!\!/ \tau$ 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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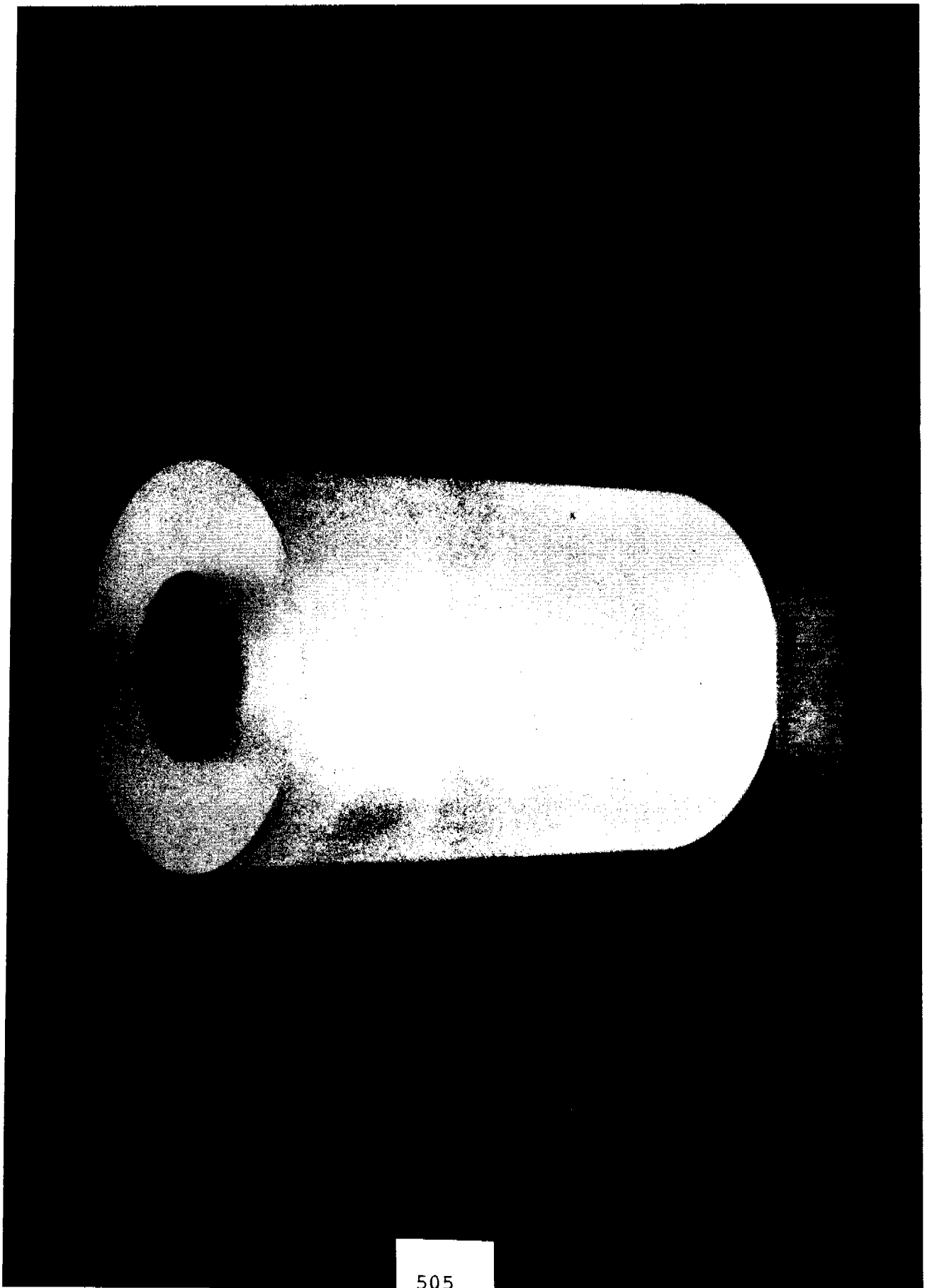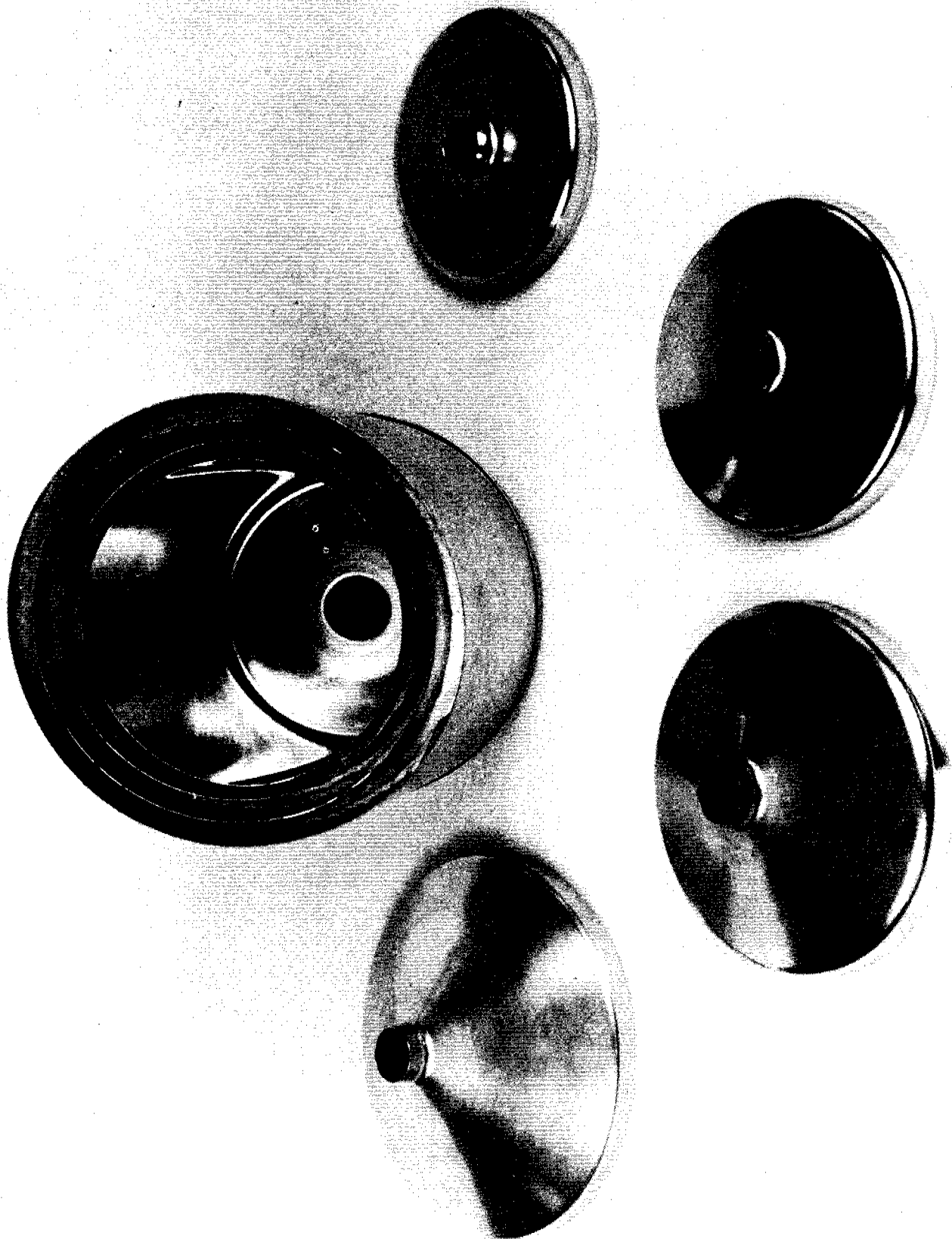   Proc 34th Annual Symposium of Frequency Control, 1980,
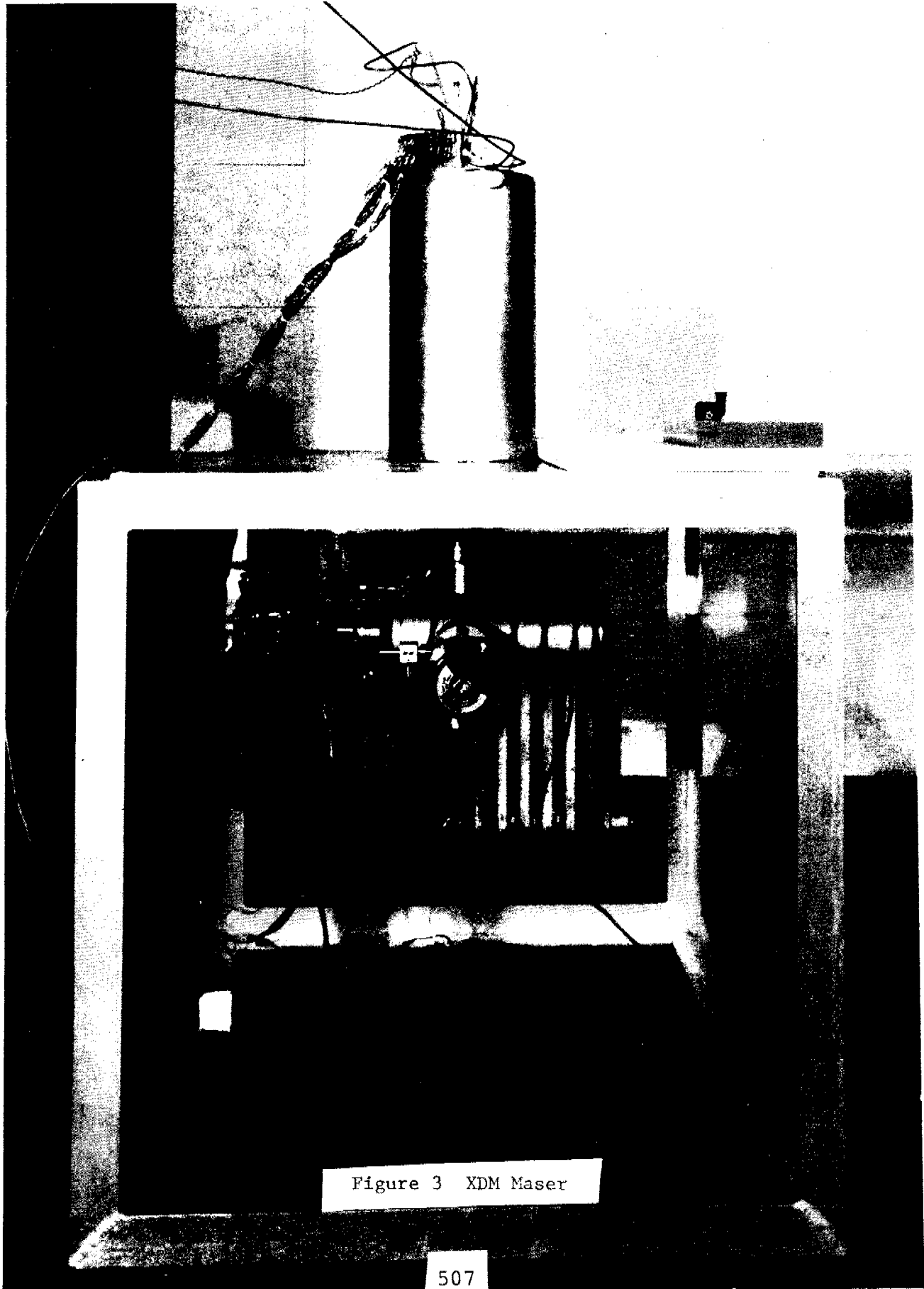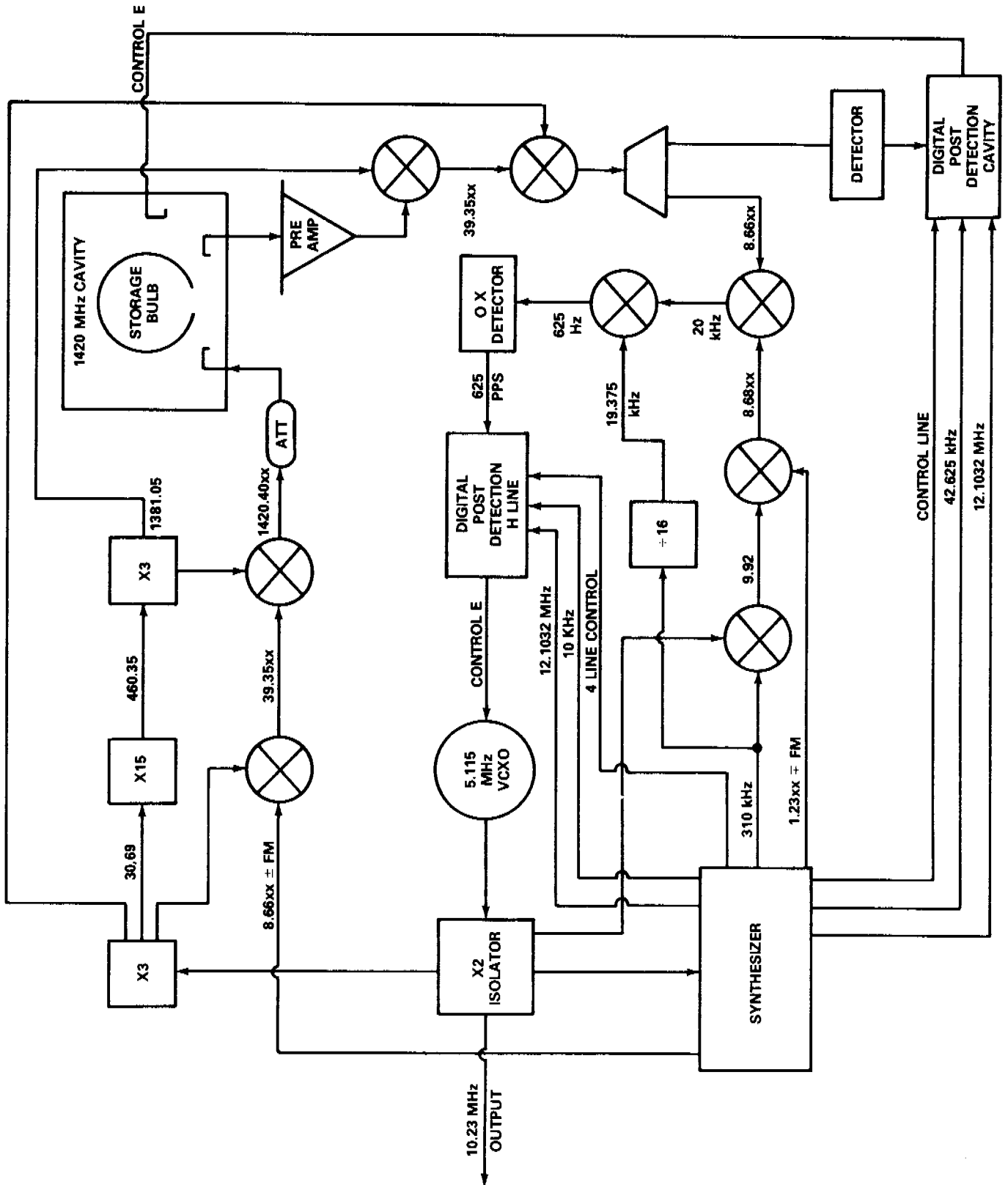   364-369.

Figure 1   Sapphire Cavity

506

Figure 3   XDM Maser

CONTROL E

1420 MHz CAVITY

STORAGE BULB

PRE AMP

DETECTOR

DIGITAL POST DETECTION CAVITY

39.35xx

8.66xx

O X DETECTOR

625 Hz

20 kHz

8.68xx

625 PPS

19.375 kHz

ATT

1420.40xx

1381.05

X3

460.35

X15

30,69

X3

DIGITAL POST DETECTION H LINE

CONTROL E

12.1032 MHz

10 KHz

4 LINE CONTROL

÷ 16

39.35xx

8.66xx ∓ FM

5.115 MHz VCXO

X2 ISOLATOR

10.23 MHz OUTPUT

SYNTHESIZER

9.92

310 kHz

1.23xx ∓ FM

CONTROL LINE

42.625 kHz

12.1032 MHz

508
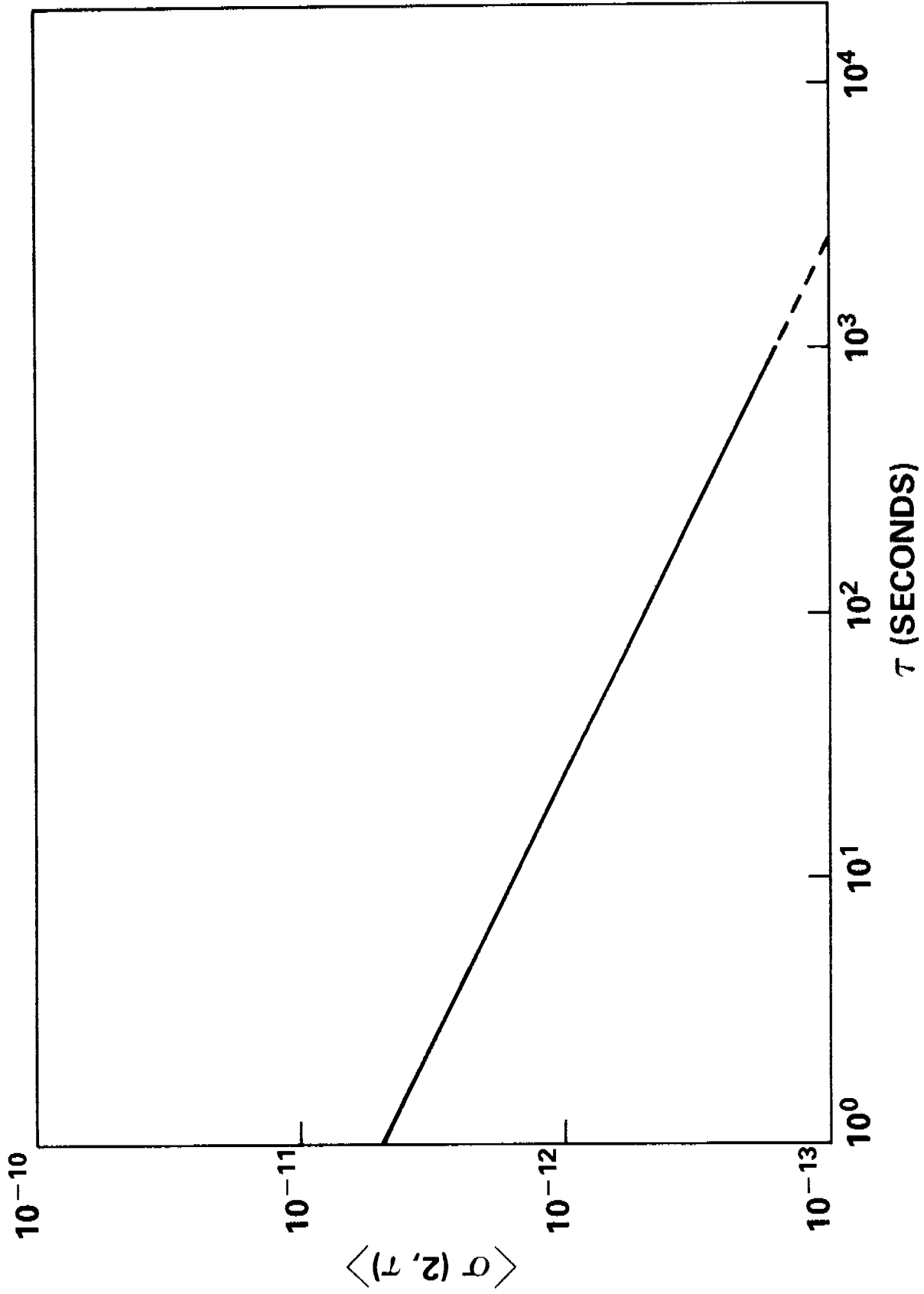
NRL PASSIVE MASER
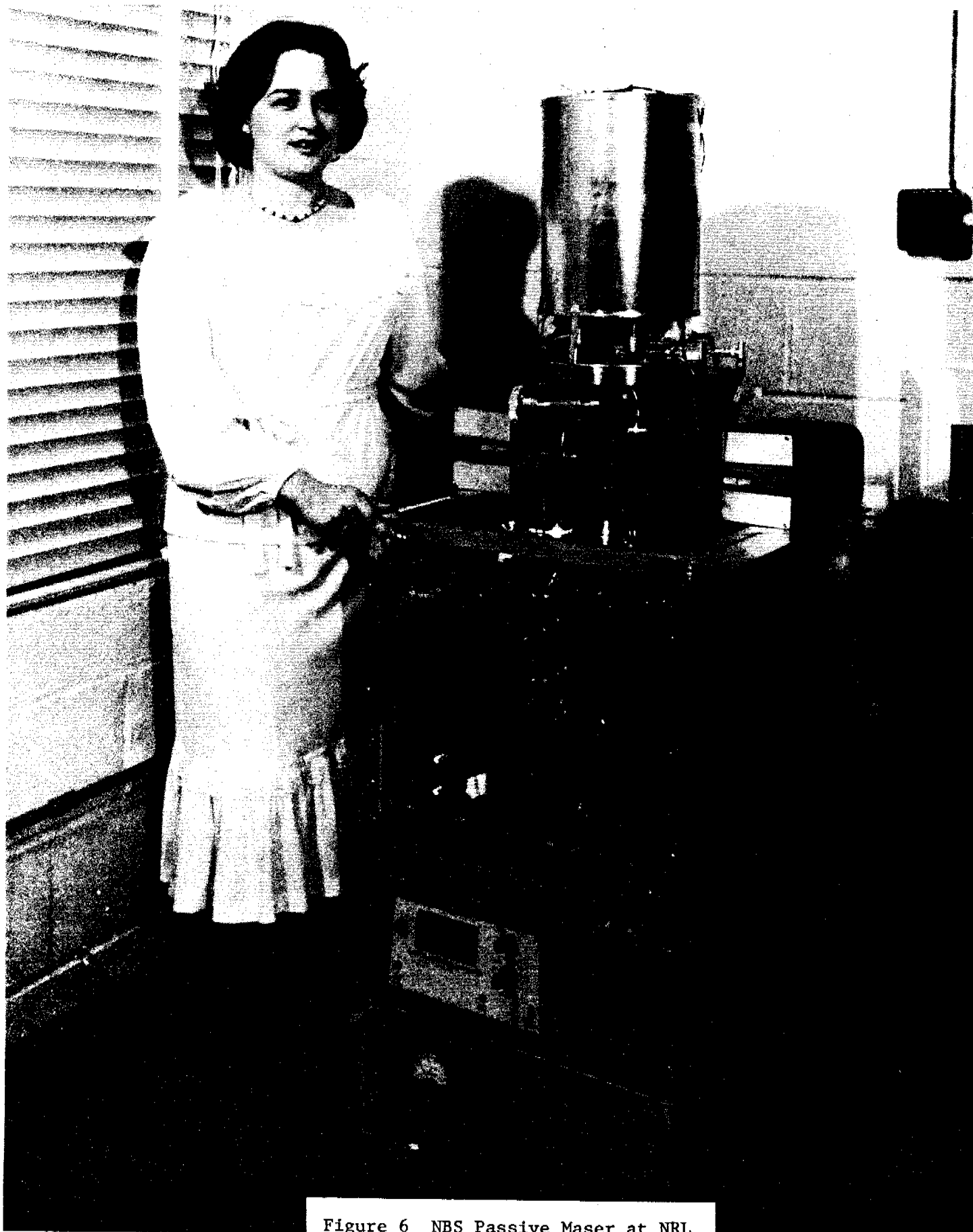

Figure 5   XDM Performance

Figure 6   NBS Passive Maser at NRL

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

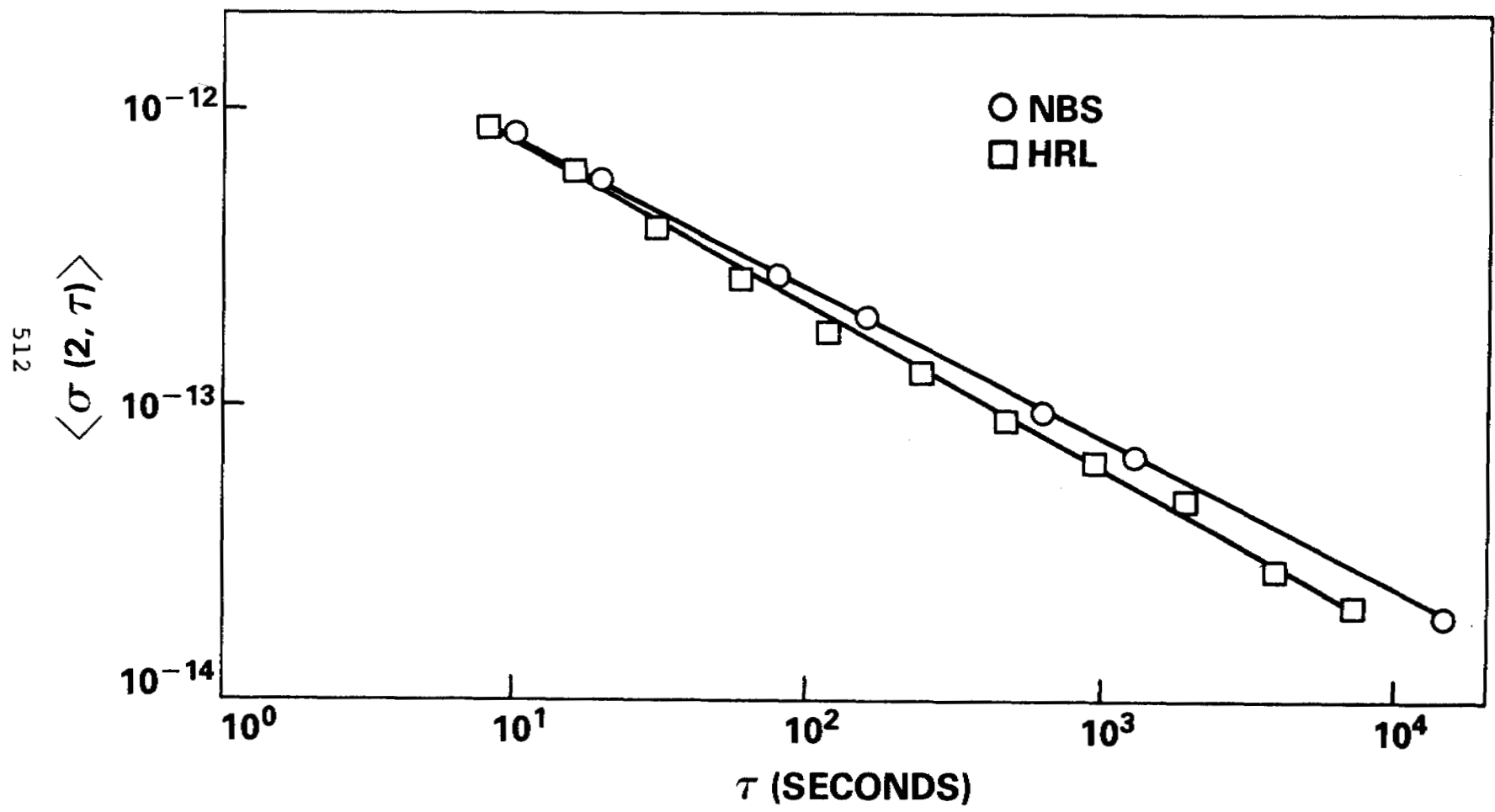**PASSIVE MASER PERFORMANCE**

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.