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NASA ATOMIC HYDROGEN STANDARDS PROGRAM —AN UPDATE—

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— AN UPDATE —

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Special Acknowledgement

The authors would like to make a special acknowledgement to Harry E. Peters. Harry Peters designed all of the frequency standards discussed in this paper, and until his recent retirement was the principal force behind NASA's hydrogen standards program.

Introduction

Since 1966, at Goddard Space Flight Center, NASA has had a program whose principal task has been to develop and test field operable hydrogen masers. After successful results with an experimental maser (NX-1), the NP series of prototype masers was developed. Figure 1 shows a picture of an NP maser. These masers have been extensively tested in many years of field use around the world. This extensive field use, amounting to over 25 years of accumulated experience with the NP masers, allows us to draw some valuable conclusions as to the reliability and lifetime of the component parts of hydrogen masers under actual field conditions. The latter part of this paper will present reliability data on the NP masers and draw conclusions from this data.

The NASA program did not stop with the development of the NP series. Based on experience with the NP masers, two new experimental masers (NX-2 and NX-3) were built. Figure 2 shows NX-2 as well as the first experimental maser, NX-1. In this paper we will also compare the performance of the NP masers and the new NX masers. Presently, in a joint program with the Applied Physics Laboratory (APL) of Johns Hopkins University a new series of field operable hydrogen masers (NR series) is being developed. Some of the novel features of the NR masers will also be discussed.

Another task of the NASA program has been to develop atomic hydrogen primary frequency standards in order to calibrate our field operable hydrogen masers. Our goal is to develop a primary standard with a fractional accuracy of 10^{-14}. We are developing two such standards: a hydrogen beam frequency standard[2,3] and a Concertina Hydrogen Maser.[4] The hydrogen beam frequency standard is shown in Figure 2. Presently all effort on the beam standard is being directed towards developing a hydrogen detector with high signal to noise ratio. A palladium-silicon MOSFET detector being developed by our microelectronics division is showing promise.

The Concertina Maser is a variable volume hydrogen maser which uses an FEP teflon bellows as the variable volume storage bulb. Figure 3 shows the Concertina storage bulb in various states of elongation. We have achieved oscillation with the Concertina Maser, but haven't obtained a very good tuning factor as yet. Presently we are redesigning the Concertina Maser to remedy this situation.

We have included mention of the two calibrations standards for completeness. There will be no further mention of them in this paper.

NASA Maser Design and Performance

Before discussing NP maser reliability, we would like to discuss some of the noteworthy features of NASA masers and compare the performance of the NP and NX masers. Figure 4 shows the principal elements of a NASA hydrogen maser. Figure 5 shows a picture of some of these elements from an NP maser. The noteworthy features are as follows:

Large Hydrogen Source Bulb. The R.F. dissociator is a cylindrical bulb two inches in diameter by two inches high. The large size of the bulb enables it to run reliably with just convection cooling.

Palladium Purifier. To supply hydrogen to the R.F. Dissociator, a palladium purifier is used. In the NP masers, the purifier consists of a palladium-silver pellet brazed to stainless steel tubing. In order to wet the stainless steel tubing it is necessary to use a high temperature silver solder which sometimes alloys with the palladium pellet. In the NX and NR masers, the stainless steel tubing is nickel plated before brazing. This allows the use of lower temperature eutectic silver solder for the braze, eliminating the alloying problem and producing a more reliable bond.

State Selector. In the NX and NR masers, there is an electromagnetic quadrupole state selector. This state selector configuration has a high focussing efficiency allowing the use of smaller pumps and contributing to long pump life.

Replaceable Pumps. Both the NX and NR masers allow the ion pumps to be replaced without letting the masers up to air. The masers each use two 60 l/sec Varian Associates Noble Vac Ion pumps. Reduced hydrogen consumption should allow 15 to 20 years of pump life before replacement is required.[1]

Small Entrance Stem. The one inch diameter entrance stem reduces the size of holes in the magnetic shielding reducing inhomogeneity effects.

Magnetic Shields. The NP masers use a quadruple layer of Molypermalloy shielding which has a shielding factor of 800. In the NX and NR masers, a fifth shield has been added which consists of a rectangular box that forms part of the maser frame. This increases the shielding factor to 15,000.

Elongated Storage Bulb. The elongated cavity and the large cylindrical storage bulb yield a high filling factor[5], and a reduced magnetic inhomogeneity shift[6,7] as well as high line Q.[5]

Aluminum Cavity. The microwave cavity in NASA masers is aluminum whose high thermal expansion is put to use to tune the cavity by changing the cavity temperature. With use of aged thermistors in the temperature control loop, frequency stability is better than one part in 10^{14} over a one day period.[1]

Presently we are working on a new design for the cavity using a combination of low temperature coefficient materials and aluminum which will greatly reduce the temperature sensitivity of the cavity, but will still allow the cavity to be temperature tuned.

Electronics Package. All of the critical electronics is in a temperature controlled package between the inner and outer magnetic shields to minimize thermal instability effects from either the receiver system or the thermal control system. In the NP and NX masers, the receiver front end is a low noise amplifier to ensure good short term stability. In the NR maser, APL is adding an isolator to reduce coupling between the cavity and the low noise amplifier, and is adding an image reject filter to improve the receiver noise figure by 3db.

Autotuner. Another feature of NASA masers is automatic flux tuning. Figure 6 shows a block diagram of the autotuner. The autotuner is described in detail in reference 5. In the NP masers, the flux tuning information is converted into a sign bit which is averaged and used to control the cavity frequency. In the NX maser, the autotuner also supplies magnitude information to the averager to take advantage of the improved crystal reference oscillators now available. In the NR masers, the autotuner will use a microprocessor which will also control all other key functions in the maser.

When the autotuner changes the maser flux during operation, a phase shift occurs due to amplitude to phase conversion. This phase shift, 10 to 20ps in the NP masers, is large enough to severely degrade short term stability. In the NX maser we have reduced this phase shift to less than 1ps with an amplitude to phase compensator. Figure 7 shows the phase shift with and without compensation. Notice that with compensation there is still a transient phase disturbance even though the net effect is zero. We are presently trying to reduce this disturbance by developing a system to change the flux slowly.

Since changing the maser flux disturbs maser operations, there is a possibility that the phase shift from high to low flux and from low to high flux will not be equal. This means that there may be a cumulative phase shift which would effect the accuracy of an autotuned hydrogen maser used as a primary standard. We performed an experiment to check this possibility, and found that the phase shifts cancelled to: 0.19ps ±0.4ps. For our autotuning system, this would produce a fractional frequency error of less than 1.7×10^{-15}, a negligible error for most applications.

Environmental Performance. Figure 8 summarizes the effects of environmental changes on the fractional frequency stability of NP and NX masers. The NP data was measured at Haystack Observatory[8], the NX data at Goddard Space Flight Center.

Reliability and Operating Life of NASA Masers

Since 1969, NP hydrogen masers have seen extensive field use around the world supporting many programs. Figure 9 shows the locations where NP masers have been in use, and Figure 10 lists some of the programs which were supported. In many instances, NP masers made multiple trips to the locations indicated in the map. Figure 11 lists the total number of trips and the mileage for each NP maser. During the past six years, the average NP maser has made 14 trips and has traveled 28 thousand miles. The point of all these statistics is that the field use of the NP masers in the past six years has been far flung and extensive, so that from the history of the NP masers during this period, we can draw conclusions as to the reliability of the component parts of hydrogen masers of the NASA design under fairly rugged conditions.

Figure 12 indicates the operational history of NASA masers. NX-1 is included because of its long operation (since September, 1967) and as a comparison example of a NASA maser operating under laboratory conditions. Before going on to discuss failures, we would like to describe some of our relevant operating procedures and how we define a failure. NP masers were transported by air cargo or truck and experienced personnel were always sent with the masers to help set them up at remote sites. If travel was less than 8 hours, the masers were sent fully operating on storage battery power. For longer trips (up to 21 days), NP masers were sent with only its pumps under power. On the one trip NX-1 made, it was totally dismantled. After masers were shipped, it was sometimes necessary to replace burnt out display bulbs or tighten loose cables. This will be considered part of normal maintenance required due to handling.

In discussing failures, we shall divide them into two classes: electronic and non-electronic failures. Since standard commercial electrical components are used in NASA masers, and in many cases breadboard electronics, we do not consider our electronics failures relevant to any considerations for future masers. We will therefore not consider electronics failures. For completeness, however, Figure 13 indicates these failures.

Non-electronic failures and major modifications in NX-1 are shown in Figure 14. The length of down time in this chart is not necessarily an indication of the severity of the failure; many times personnel who could repair the masers were not available or were only available on a limited basis. Notice that the failure rate of NP-4 was high compared with the other masers; NP-4 had continual vacuum problems, either from a slow leak or a contaminated system which could not be found. This caused the maser output to decay slowly, indicating that good vacuum conditions are indeed essential to long term maser operation.

Using our operational history we can draw the following conclusions as to the reliability and lifetime of NASA maser components:

Hydrogen Source Bulb. The large diameter pyrex bulb runs reliably for many years if the vacuum and hydrogen supply are clean. In both NP-1 and NP-2, the source bulb has lasted greater than 7 years, and in NP-3, 4-1/2 years until its bulb cracked. In NP-3 after the purifier was repaired, due to some contamination in the hydrogen line and a bad source oscillator, the source ceased to produce atomic hydrogen. The source cleaned itself up, however, after running several days on clean hydrogen.

Storage Bulb. As a matter of procedure, storage bulbs were recoated whenever masers were taken apart, so some of the recoatings shown are not because of lifetime limitations. NP-4 indicates that vacuum leaks degrade storage bulb lifetime. When the storage bulbs of NP-3 and NP-4 were replaced, it was noted that the teflon coating failed the water drop test in a spot opposite the entrance stem. Since the NP masers have a single vacuum system and contamination products from outside the bulb can be exposed to the storage bulb only from near the source region, this bad spot does not necessarily mean that contamination products are coming from the source bulb itself. The NX masers have a double vacuum system, so future results may isolate the cause of this bad spot. In NP-3, when the bulb was replaced there was no indication of a drop in maser power, so this recoating cannot be counted as an indication of the bulb lifetime in a properly operating maser. Even counting this, for NP-1, NP-2, and NP-3, we have an average storage bulb lifetime of greater than 6 years.

Palladium Purifier. Both purifier failures were caused by leaks opening up in the purifiers. As mentioned previously, our new fabrication method should solve this problem. Even with this, the existing design lasted, on the average, for greater than 6.8 years.

Ion Pumps. The ion pumps worked reliably in NP-1 and NP-3 for greater than 6 or 7 years. In NP-2, the failure was a vacuum leak which had nothing to do with the pump itself. Pump pressure in the NP masers is typically 3.6 to 4.8×10^{-7} torr, so at these pressures many years of reliable operation can be expected. In NX-2 and NX-3, operating pressure is 1 to 2×10^{-7} torr. When NX-2 and NX-3 were run at approximately 5 times normal pressure, in six months NX-2 developed a shorted pump element. This indicates that one should run at low pressures to ensure reliable pump operation.

Conclusions

Experience with NASA field operable masers indicates that one can obtain many years of reliable operation with hydrogen masers, even in rugged conditions. Projecting to possible spacecraft use, our data indicate that the technology for reliable space qualified hydrogen masers is already available.

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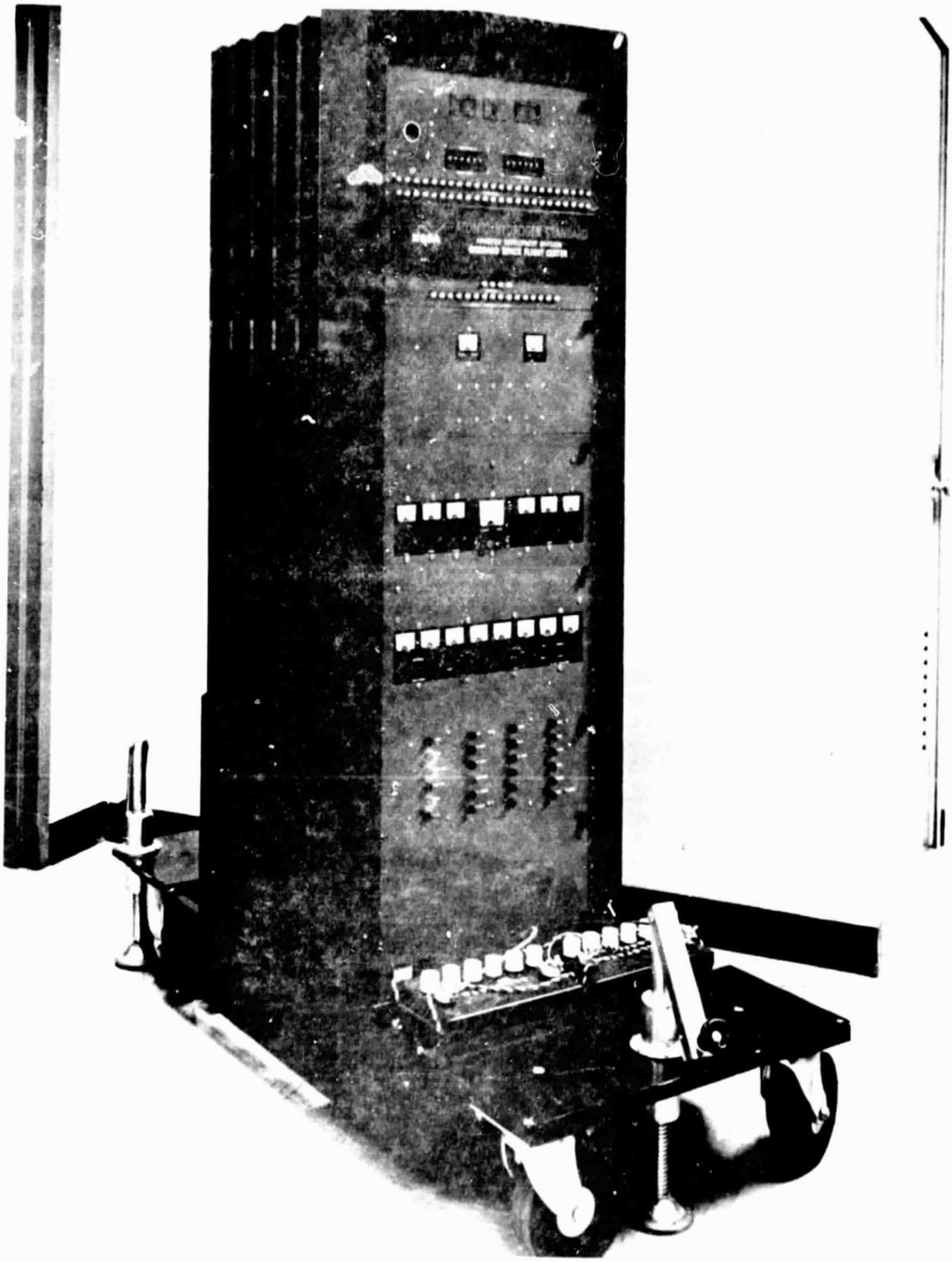

Figure 1. An NP Hydrogen Maser

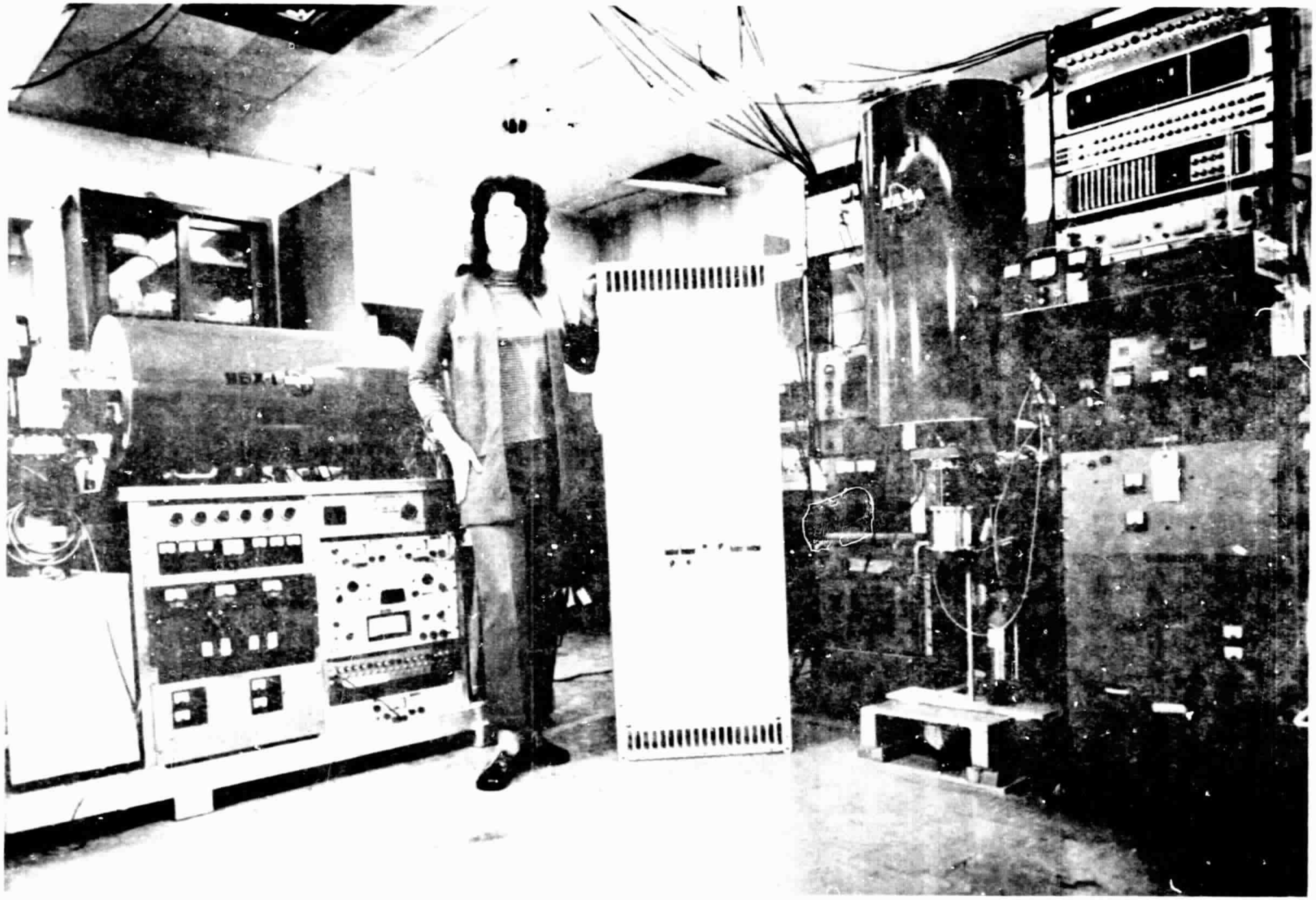

Figure 2. NASA Hydrogen Standards: (from right to left) NX-1, NX-2, and the Hydrogen Beam Standard.

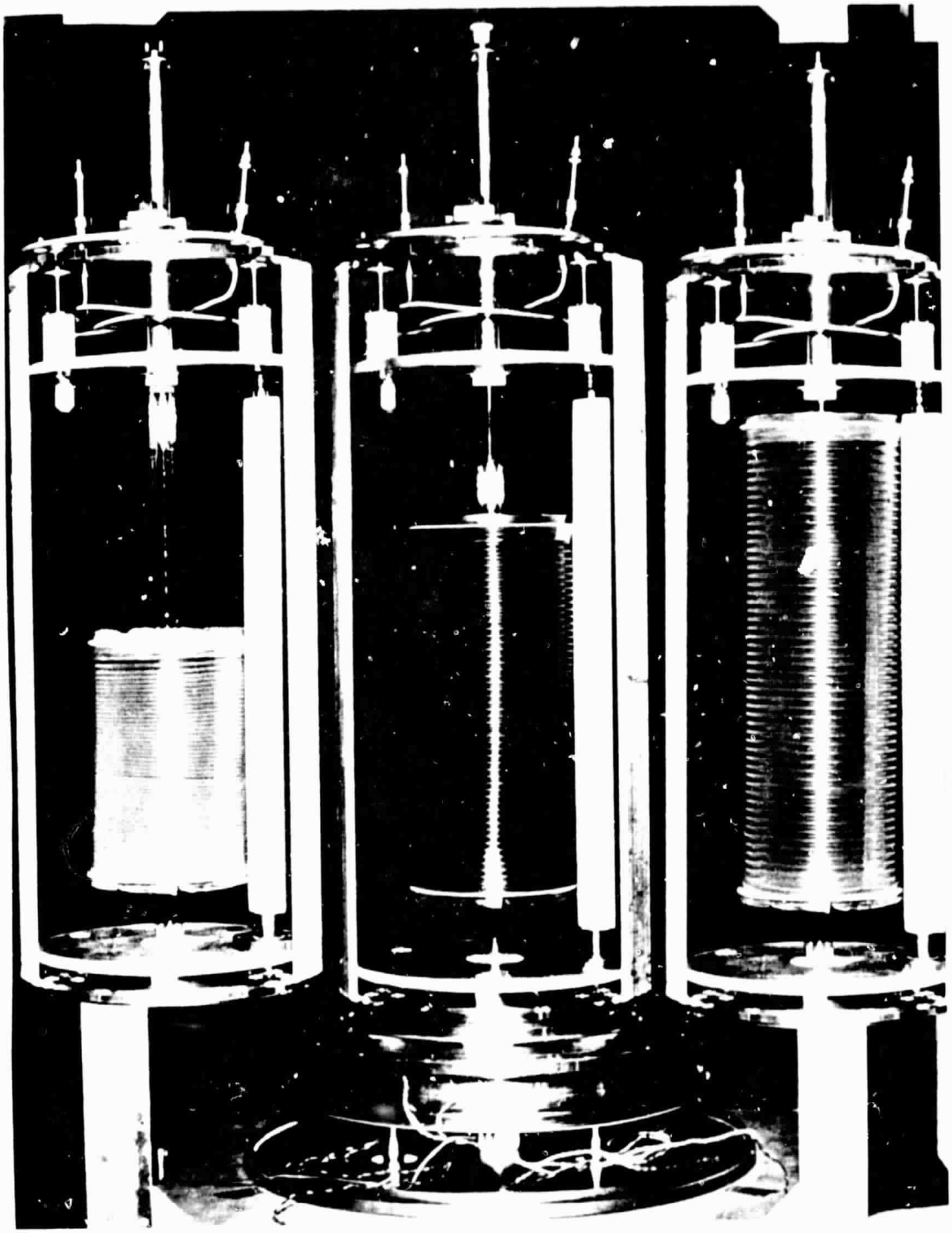

Figure 3. The Concertina Storage Bulb in Various Stages of Elongation.

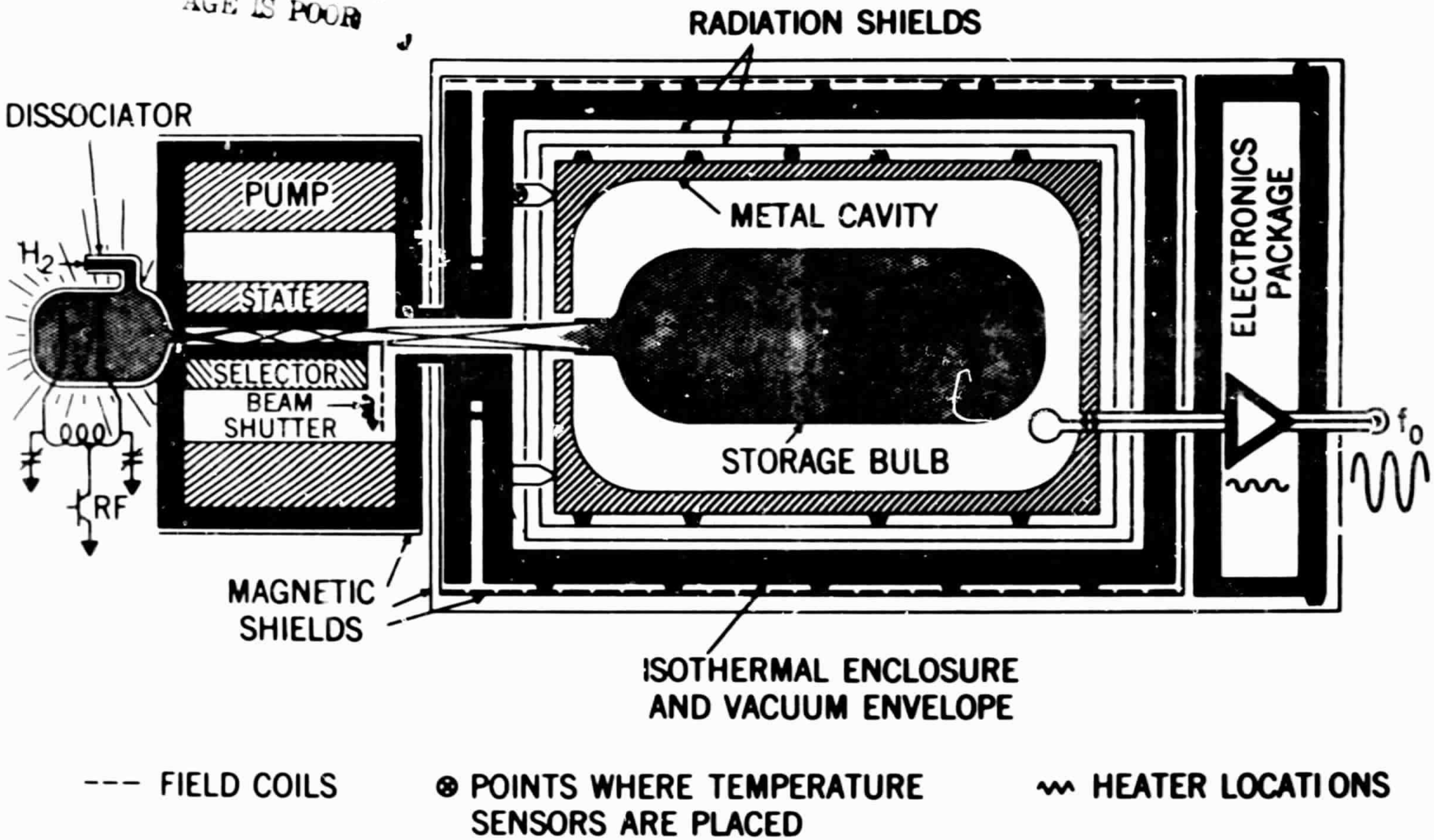

Figure 4. Principal Elements of the NASA Hydrogen Maser.

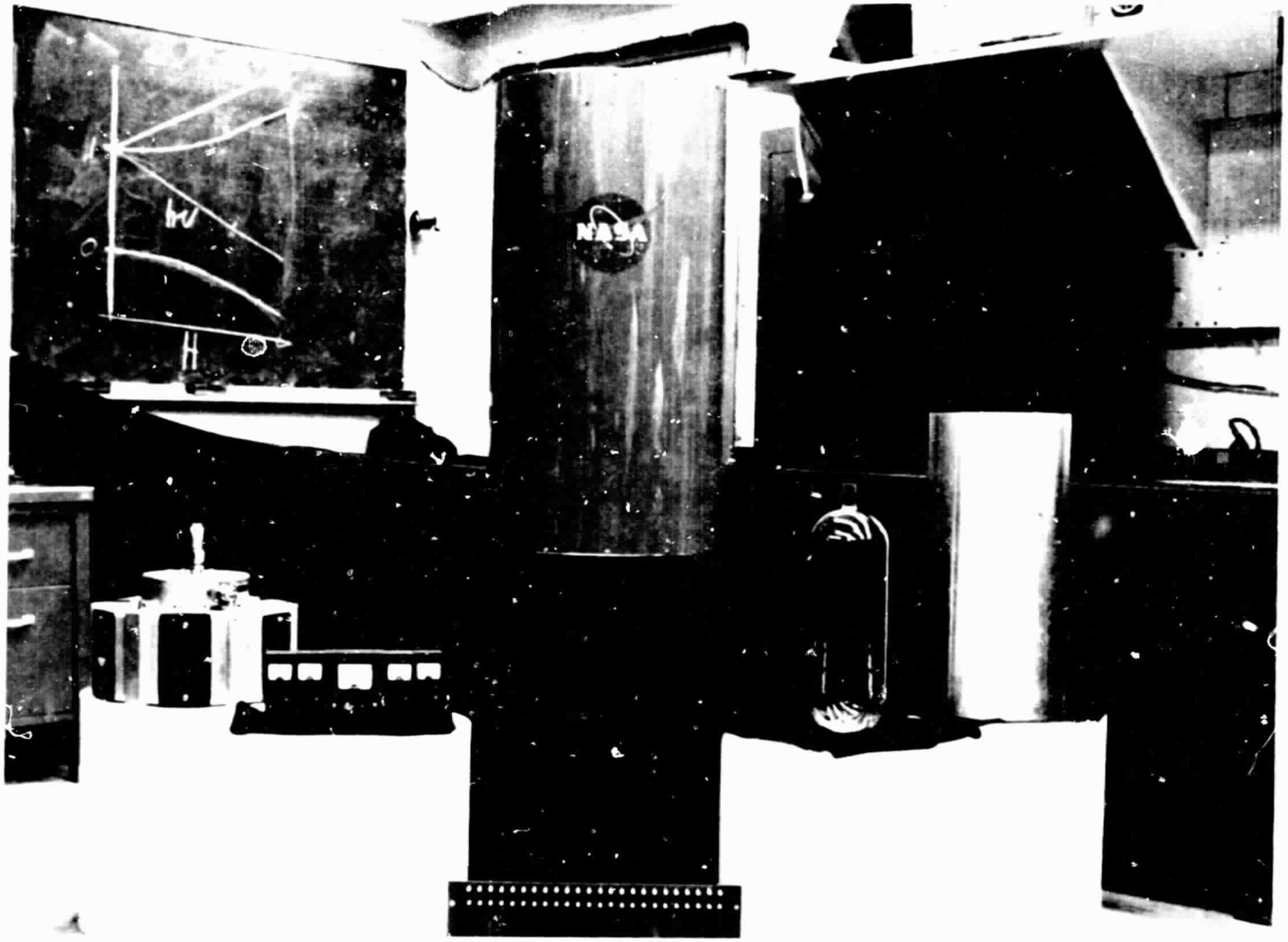

Figure 5. The Parts of an NP Maser.

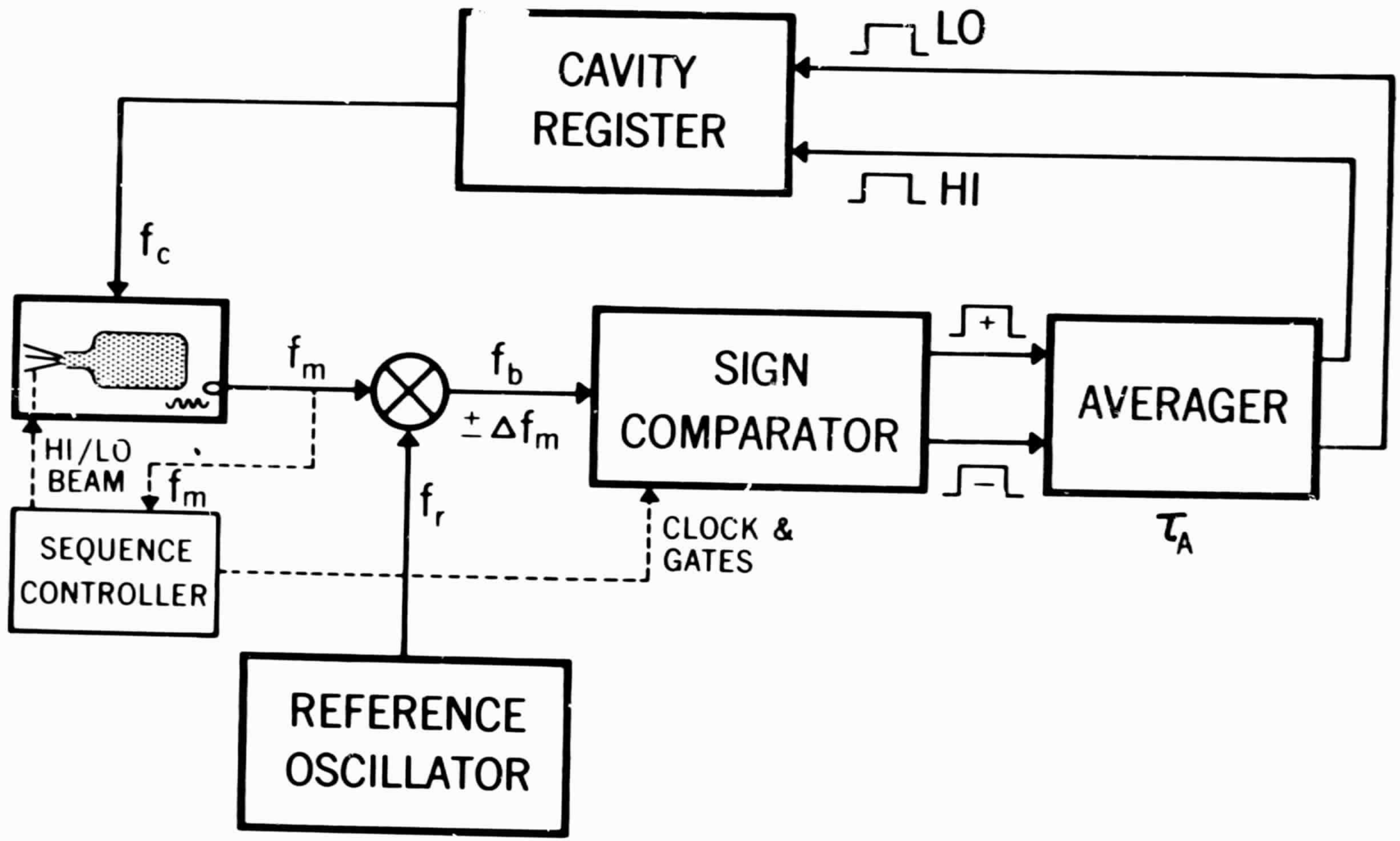

Figure 6. Elementary Autotuner Block Diagram.

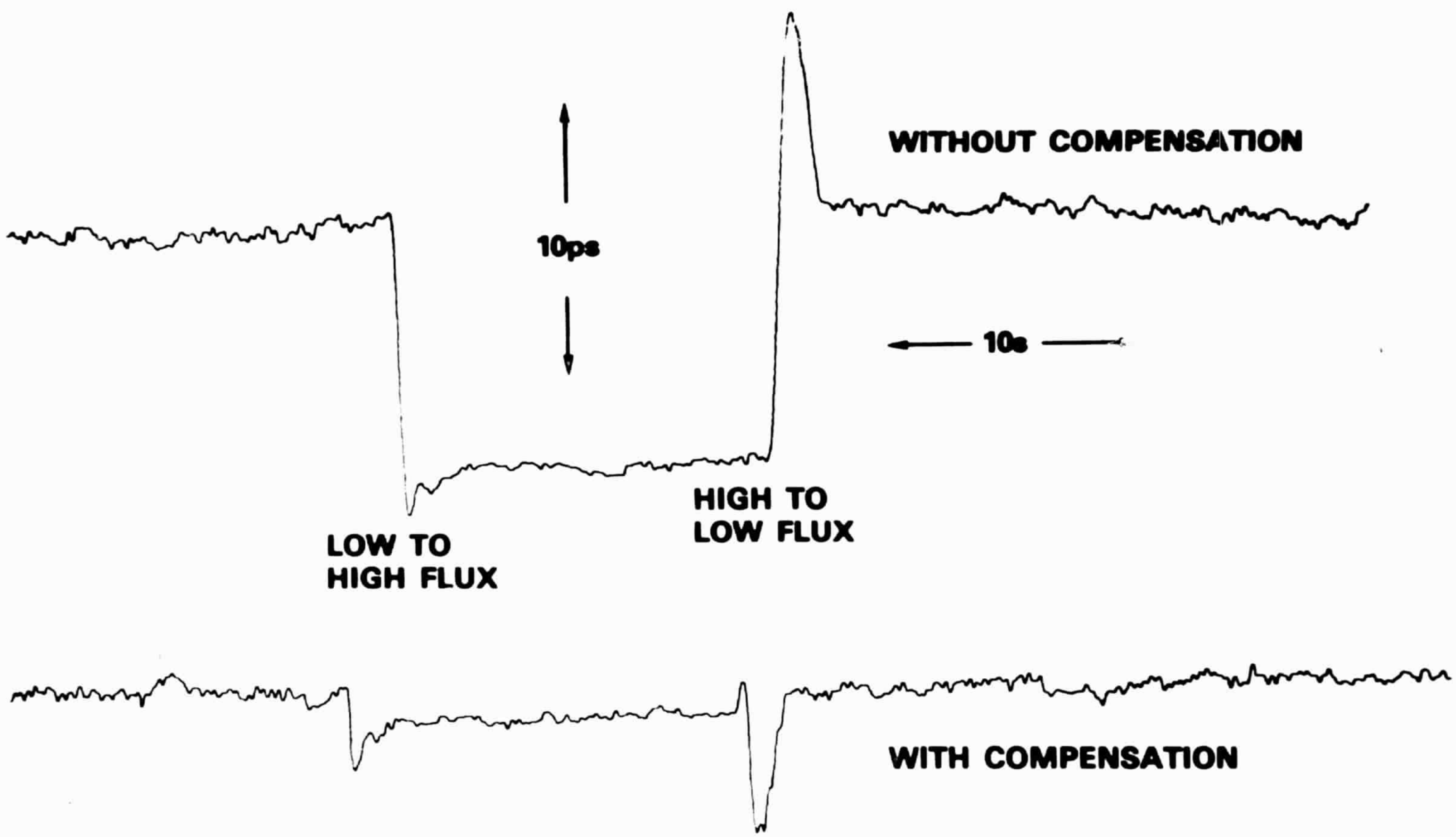

Figure 7. Autotuning Phase Shift With and Without Amplitude to Phase Compensation.

Effect	NP Series	NX Series
Temperature	$2 \times 10^{-14}/°C$	Not Measured
Pressure	$<4 \times 10^{-14}/''Hg$	$5 \times 10^{-15}/''Hg$
Magnetic Field	$5 \times 10^{-12}/G$	$1 \times 10^{-13}/G$

Figure 8. Environmental Sensitivity of NASA Masers

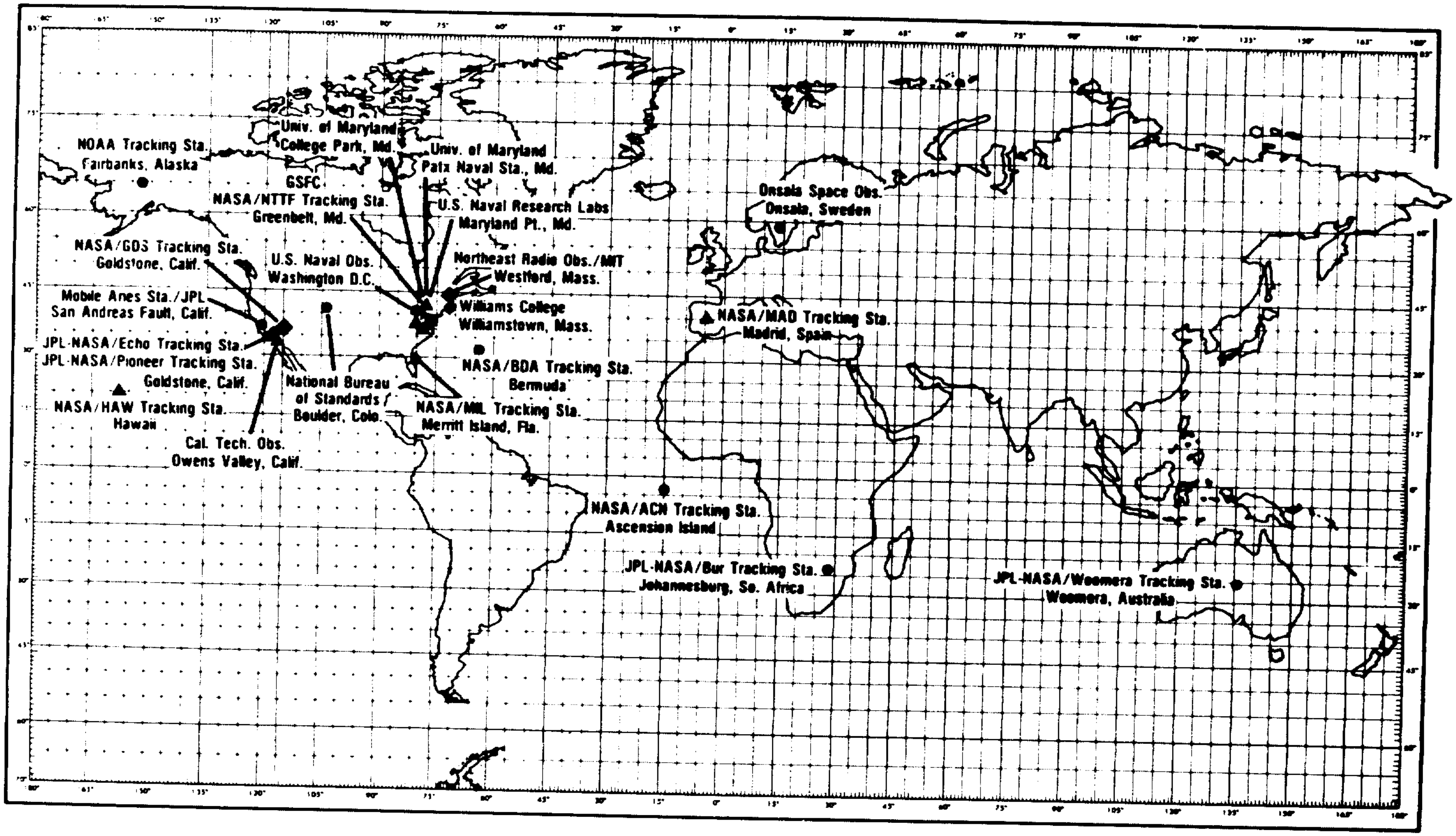

Figure 9. Locations of NP Maser Field Use.

- STUDY OF CELESTIAL WATER SOURCES
- DOUBLE DIFFERENTIAL VERY LONG BASE LINE INTERFEROMETRY (DDVLBI)
- MM-71 TRACKING AND CALIBRATION EXPERIMENT
- ATOMIC CLOCK RELATIVITY EXPERIMENT IN HIGH FLYING AIRCRAFT
- QUASAR PATROL
- POLAR MOTION MEASUREMENTS
- STAR MAPPING
- DETERMINATION OF EARTH'S ROTATIONAL VARIATIONS
- SENSITIVITY OF H-MASERS TO PRESSURE' TEMPERATURE AND MAGNETIC FIELD VARIATIONS.

Figure 10. Programs Supported by NASA Built NP Type Hydrogen Masers.

H-MASER	NO. OF TRIPS	MILEAGE
NX	1	400
NP-1	14	27,400
NP-2	16	50,700
NP-3	16	20,200
NP-4	10	12,600
	57	111,300

Figure 11. Number of Trips and Miles Traveled by NASA Masers.

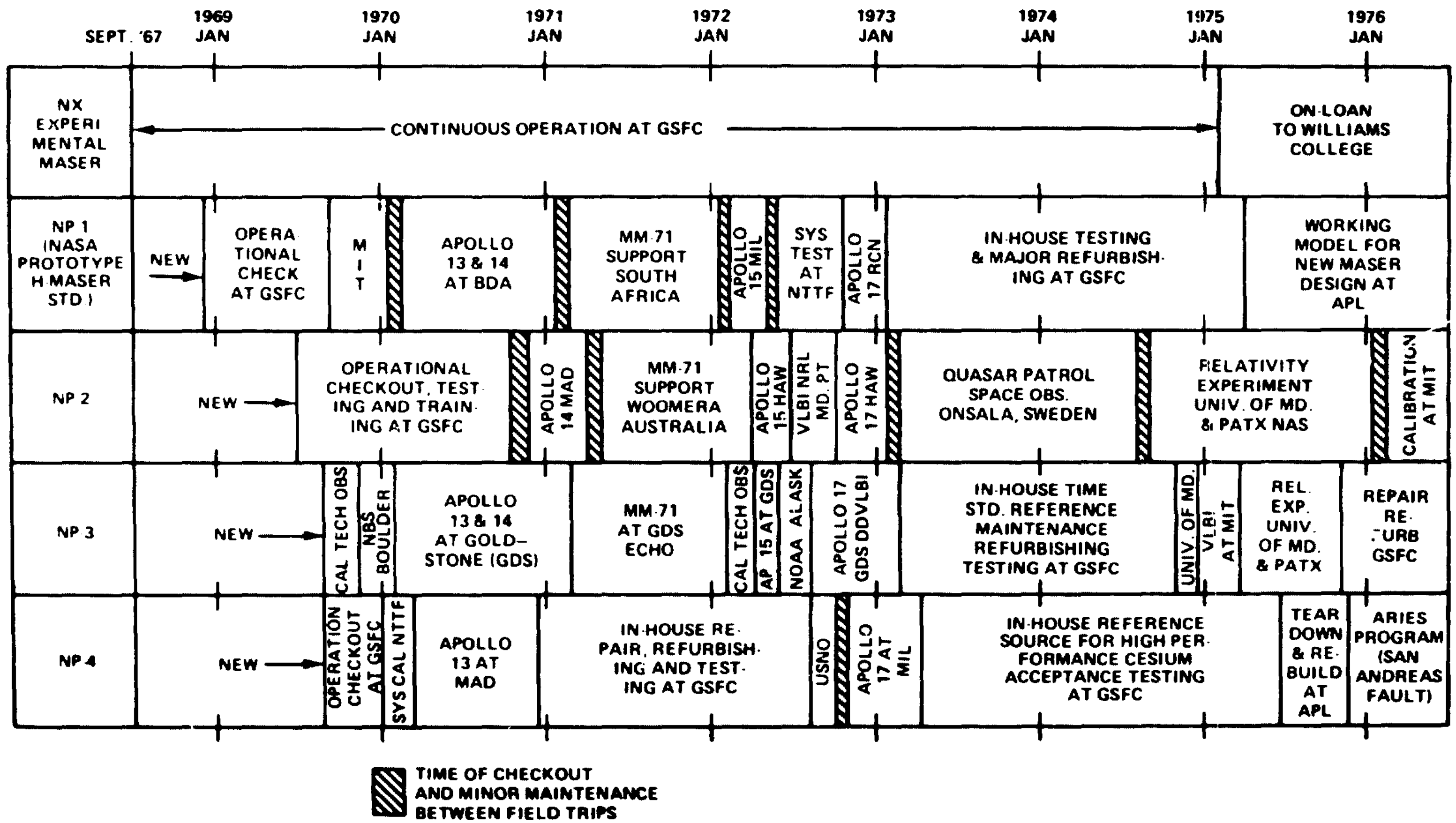

Figure 12. Operational History of NASA Hydrogen Masers.

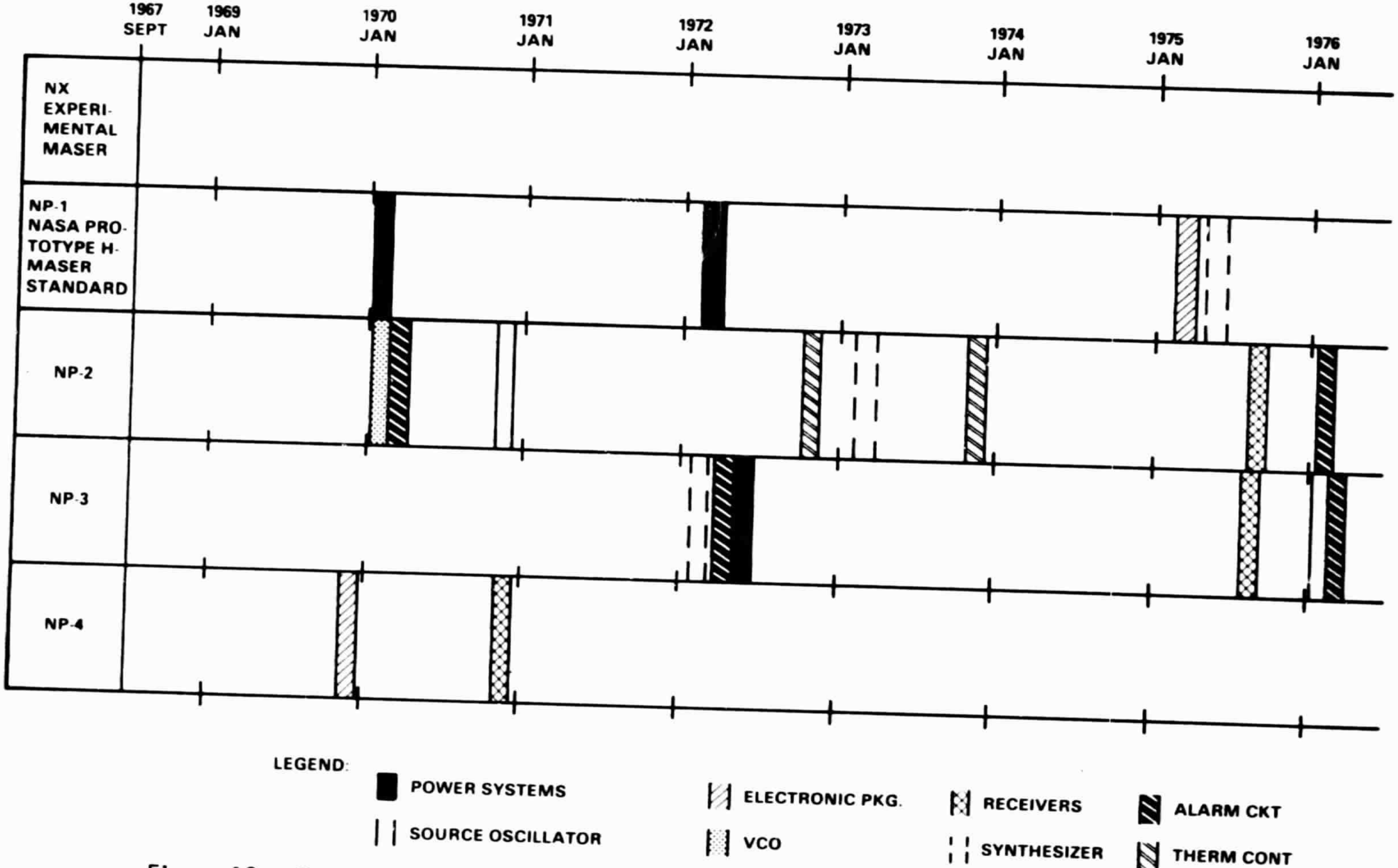

Figure 13. Operational History of NASA Hydrogen Masers - Electrical Systems Failure.

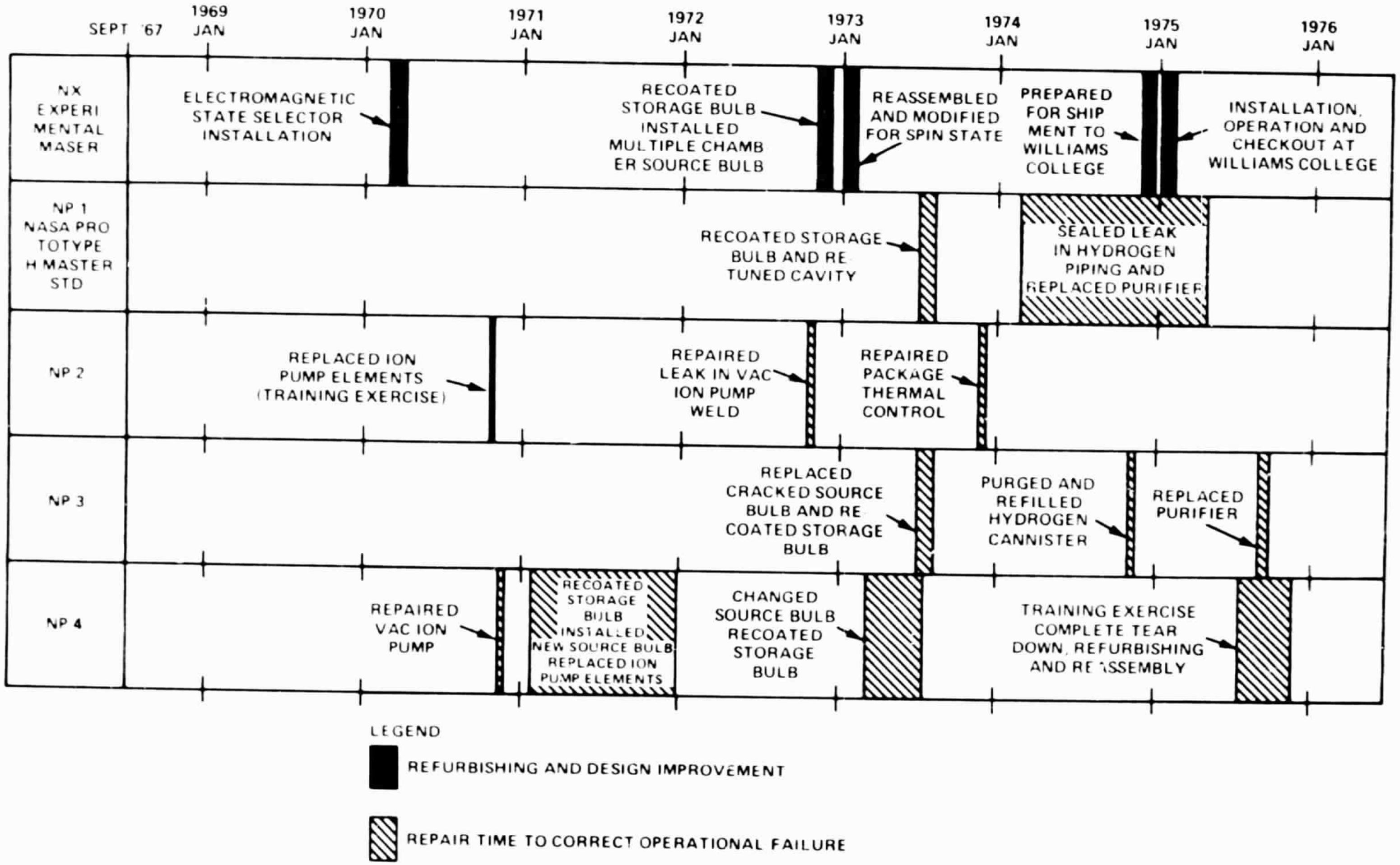

Figure 14. Operational History of NASA Hydrogen Masers - Non-electronic Failure.