HYDROGEN MASER IMPLEMENTATION IN THE DEEP SPACE NETWORK AT THE JET PROPULSION LABORATORY

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ABSTRACT

Hydrogen masers (H-masers) are the most stable frequency standards in use today within the sampling intervals (τ) from 100 to 10^4 seconds. The Jet Propulsion Laboratory (JPL) employs hydrogen maser frequency standards in a variety of fixed and mobile applications, ranging from the 64-meter Deep Space Network stations to the 9-meter Astronomical Radio Interferometric Earth Surveying (ARIES) stations.

This paper describes the Frequency Standard Test Laboratory (FSTL) developed and implemented by JPL. This test laboratory has the capability to measure the frequency stability of five frequency standards including environmental parameters. Nine frequency standards may be evaluated simultaneously upon completion of the current instrumentation expansion program. Frequency stability measurements and environmental data on five H-masers are presented.

JPL is continuing hydrogen maser implementation plans by evaluating new H-maser designs for use during the 1980s.

INTRODUCTION

JPL supplies hydrogen masers as the prime frequency standard for navigation to the outer planets and for Very Long Baseline Interferometer (VLBI) experiments in both fixed and mobile ground stations. JPL has instrumented a Frequency Standard Test Laboratory to evaluate and test H-masers, other frequency standard types and reference frequency distribution equipment during development and prior to implementation in the user's facility. Selected representative test data recorded during the past two years is included in this report.

Hydrogen Masers at JPL

H-maser users at JPL have been using prototype and experimental H-masers for approximately 10 years for VLBI experiments and selected spacecraft tracking functions. In 1978, JPL formally installed one H-maser at each of the Deep Space Network (DSN) 64-meter tracking stations at Goldstone, California and Madrid, Spain. A JPL DSN-type H-maser had previously been installed and has been in use at the DSN 64-meter tracking station near Canberra, Australia since 1976. In addition, JPL has operating H-masers at one DSN 26-meter tracking station at Goldstone, Owens Valley Radiometric Observatory (OVRO) and the ARIES mobile ground station. Three H-masers are retained at the JPL Pasadena complex. Two of these are reference masers in the test laboratory; the third is used as the DSN spare and by the ARIES geophysical mobile ground station.

Currently JPL has a total of eight H-masers in continuous use. These have been supplied by two well-known manufacturers and JPL. There are three Smithsonian Astrophysical Observatory (SAO) model VLG-10B H-masers which were supplied to JPL by the NASA Marshall Space Flight Center. The NASA Goddard Space Flight Center (GSFC) has loaned JPL one model NX H-maser and has, until recently, supplied JPL with three model NP H-masers.

JPL has three of the DSN type and one prototype H-maser in use at this time. Figure 1 tabulates the location, manufacturer, model and serial number of each H-maser in use by JPL today.

Some Selected Test Data Results to Date

JPL established a Frequency Standard Test Laboratory at the Pasadena, California complex and subsequently tested five H-masers between May 1978 and April 1979. These five are currently in use as shown in Figure 1. The units tested were JPL model DSN, serial numbers 2 and 3 and SAO model VLG-10B, serial numbers P5, P6, and P7.

The tests scheduled were considered to describe fully the necessary operating parameters of each H-maser. Additional parameters were usually recorded to assist in diagnostics or help explain the erroneous behavior of a desired parameter. The desired parameters recorded during these test programs were frequency stability versus sampling time (Allan variance) and frequency shift versus the environmental parameters of temperature, barometric pressure and the Earth's magnetic field.

Temperature tests were conducted on the five H-masers for step frequency shift in the temperature range of 21 to 29°C and then repeated from 29°C to 21°C. A step change in temperature usually causes the frequency to start shifting in less than one hour and it will continue to shift for approximately 40 hours with an exponential decay. The temperature coefficient for each H-maser tested is tabulated in Fig. 2. Of the environmental parameters, temperature presents the greatest frequency stability perturbation. It is not uncommon to experience room temperature fluctuations of 1 to 2°C in a diurnal or longer time period, resulting in a 1-2 x 10^{-13} frequency shift. At the 64-meter tracking stations, the H-masers are in separate temperature-controlled rooms. These rooms are controlled to the nearest 0.1°C, thereby minimizing the problem and reducing the temperature-dependent frequency shift to typically 1 x 10^{-14}.

Response to changes in the local barometric pressure was tested on the same H-masers. The test chamber pressure was increased by 6 inches of water and after approximately one hour decreased to minus 6 inches of water, relative to the starting ambient pressure. Because the frequency shift responses are instantaneous, the pressure differential must only be maintained long enough to determine the resultant frequency shift. The barometric pressure coefficient for the five H-masers is tabulated in Fig. 2. The resultant barometric pressure data shows that four of the five H-masers exhibit approximately the same frequency shift for an incremental pressure change. The exception is model VLG-10B Number P6 which exhibited an excessive frequency stability fluctuation during test. This H-maser at Goldstone has not always responded to storm barometric pressure fluctuations. It is planned to schedule a barometric pressure retest on this unit when sufficient H-masers are available to temporarily remove this unit from the field. A typical barometric pressure shift at Goldstone is approximately 0.3 inch Hg. The resultant frequency shift of the other four H-masers would be approximately 1 x 10^{-14}.

Frequency shift response to static magnetic field disturbances was measured on the five H-masers. The results are tabulated in Fig. 2. The resultant normalized frequency shift per gauss is 1 to 5 x 10^{-12} for four of the five H-masers. Magnetic field perturbations in the test laboratory are typically less than one milligauss under controlled operating conditions of minimal movement of ferrous materials. The measured magnetic field perturbations are typically five milligauss at the H-maser installation location within the 64-meter tracking stations. The resultant predicted frequency shift during these disturbances would be typically a maximum of 1 x 10^{-14}. The fifth unit (JPL-DSN2) was several times more sensitive to magnetic field than the other four H-masers tested. Following these tests, this H-maser was installed in a moly-permalloy magnetic shield box, which improved the shielding factor by a minimum of 100 or a predicted magnetic field coefficient of 1.4 x 10^{-13} per gauss.

A selected sample of Allan variance curves for four of the five H-masers tested since June 1978 is shown in Fig. 3.

The sampling times (τ) of less than approximately 1000 seconds are controlled by the signal-to-noise ratio. Each manufacturer designs H-masers to operate within a desired output power range. The JPL model DSN H-maser's nominal output power is approximately -87 to -89 dBm. The SAO model VLG-10B H-maser output power range is approximately -95 to -100 dBm. Therefore the data between the two SAO H-masers measured in June 1978 is approximately as expected. Later tests have used one SAO H-maser compared against one JPL H-maser.

Measurements at sampling times greater than 1000 seconds depict a degradation of frequency stability. This is due to "systematics," which is a combination of environmental effects and oscillator aging. In this set of specific cases, the curves peak at the sampling time of 20,000 seconds (approximately six hours), the 1/4 diurnal temperature cycle. Note that two of four curves exhibit this effect. The other conclusion is that all of these H-masers, except possibly SAO serial number P6, are aging. Since installation, P6 has been nearly continuously compared against a cesium beam frequency standard bank traceable to NBS. There is no indication versus this bank that this H-maser is aging. The curve between serial numbers P5 and P6 in June 1978 indicates that the aging is considerably less than all the other H-masers tested. JPL H-maser DSN-3 is not shown on this curve, but the approximate same slope is apparent as with all H-masers except P6. Note that the frequency stability curves exhibit a broad "bright line" (degradation hump) on two curves for sampling times between 100 and 800 seconds. This is caused by the cooling cycling rate of the building air conditioner. The lower dotted-line curve was recorded during November 1979 after the FSTL temperature control was improved. This is discussed later in this report.

Figure 4 again shows the Allan variance versus sampling time curve in Fig. 3. This plot has the measurement error bars and number of data samples available written beside each bar. In this case, where the number of samples is not shown, the number is greater than 51. Since all sampling times are simultaneously recorded, the number of samples increases as the sampling time decreases.

Frequency Standard Test Laboratory

A Frequency Standard Test Laboratory (FSTL) installation was initiated in August 1977 at the Pasadena complex to determine the operational performance of H-masers. An isolated building was obtained and is located at one end of the "Mesa" antenna range above and behind the Laboratory. This location was chosen because it is isolated from man-made disturbances of the Earth's magnetic field and has sufficient floor space for five H-masers and all instrumentation required at this time. Figure 5 is a view of this building with the Angeles National Forest in the background. The floor plan of this 700-square-foot building (Fig. 6) depicts the location of H-masers, environmental chamber and instrumentation. This laboratory is now equipped with instrumentation to simultaneously measure 12 channels of Allan variance and 12 continuous recording channels of long-term frequency shift.

Figure 7 is a block diagram of a single channel of this frequency stability measurement equipment. Figure 8 is a block diagram of the test configuration for comparing the frequency of three H-masers using three sets of the instrumentation shown in Fig. 7. Local barometric pressure, room and equipment temperature and Earth's magnetic field disturbances are continuously recorded as ancillary data to the frequency stability measurements. Instrumentation is available to record frequency standard anomalies as required. Several examples are: vacion pump current, oven heater temperatures and cavity tuning bias voltage.

Figure 9 is a photograph of the instrumentation room, which contains nine electronic instrument cabinets. The equipment description is as follows, from left to right: (1) cabinets 1 and 2 are for environmental and anomaly measurements; (2) cabinet 3 is for general spectral and waveform analyses; cabinet 4 contains the RF reference isolation amplifiers, mixers and zero crossing detectors shown in Fig. 7; cabinets 5 through 8 each contain three channels of frequency stability measurement and recording equipment, and cabinet 9 contains general instrumentation, a rubidium frequency standard and two spare H-maser receiver crystal VCO's.

A combined temperature and barometric pressure chamber was designed and fabricated by JPL with non-magnetic materials to prevent distorting and attenuating the Earth's magnetic field around the H-maser. A separate connected heat exchanger preconditions the chamber air temperature for barometric pressure and temperature tests.

A 7-foot-diameter double axially concentric Helmholtz coil is used to generate static perturbations of the Earth's magnetic field. Generally, these coils are mounted around the environmental chamber to expedite the schedule on separately measuring H-maser frequency shift versus temperature and magnetic field. The environmental chamber and Helmholtz coil are shown in the far right corner of Fig. 10.

Standby AC power was installed to prevent power loss to the test laboratory. This equipment consists of a 4.5-kVA uninterruptible power supply (UPS) and a 30-kVA automatic starting generator. All frequency standards and critical instrumentation requiring power without interruption are connected to the UPS. The balance of the instrumentation, UPS input power and most of the air conditioning equipment is connected to the generator during primary power outages.

H-maser test results between May 1978 and April 1979 showed that both the laboratory temperature environment and instrumentation required improvement for future test programs to determine the prospective improved long-term frequency stability performance. These revisions are now completed. Subsequent tests show the new computer floor plenum air temperature to be stable to within 0.1°C peak to peak and the room 5 feet above the floor to 0.5°C peak to peak. The previous air conditioning system controlled the room from 1 to 3°C peak to peak for diurnal and longer time periods, depending on the outside weather conditions. An Allan variance test recorded during November 1979 showed considerable stability improvement using the same two H-masers previously recorded in April 1979. Compare the two curves dated April 1979 and November 1979 in Fig. 3. Note that at the Allan variance at 2×10^4 seconds sampling time

(τ) the "bright line" peak is not evident and the overall noise at sampling times greater than 1000 seconds is much lower. Room temperature control is considered to be the major factor in this improvement.

Additions and improvements to the instrumentation expanded the Allan variance and long-term frequency shift measurement capability to 12 channels. Additional recording instrumentation to continuously measure equipment temperature, magnetic field and room humidity has been added. This is sufficient instrumentation to simultaneously measure the stability of five H-masers as shown in Fig. 11.

Frequency shift versus barometric pressure increments have been difficult to measure in the past. It is expected that newer H-maser designs will exhibit even less barometric pressure sensitivity; therefore the environmental chamber has been strengthened to double the barometric pressure stimulus range to ±12 inches of water relative to the local barometric pressure.

It is intended to further improve the laboratory environment and instrumentation to meet the requirements from development and research of future frequency standards. Instrumentation improvements being considered and studied at this time are computerized automation of the data acquisition on a continuous basis, control of the test chamber humidity during environmental tests, and dual difference detection for frequency stability measurements of non-offsettable frequency standards.

Present Test Programs

JPL plans to continue use of the FSTL in the future to give frequency standard research and support to the JPL-operated Deep Space Tracking Station Network and other JPL-operated fixed and mobile ground stations.

An important task scheduled to start in December 1979 is the NASA-JPL program to evaluate the operating performance characteristics of two recently designed H-masers. These are the SAO Model VLG-11B and the GSFC Model NR.

Maintenance, repair and retest of all H-masers currently in field use by JPL is a continuing high priority project. The FSTL has done and will continue to do requalification after repair and diagnostics on non-obvious failures prior to repair. The FSTL has been and will continue to be scheduled to test other types of frequency standards (e.g., cesium beam), active reference frequency cable stabilizer equipment, frequency multipliers and synthesizers.

Recently the Laboratory scheduled and completed a series of tests on one superconducting cavity stable oscillator (SCSO) manufactured by Stanford University and purchased by Caltech. This was part of the JPL research program to evaluate new types of reference oscillators.

ACKNOWLEDGEMENTS

I wish to thank JPL engineers Albert Kirk and Roland E. Taylor for their participation in this program. Their task has been to operate the FSTL since inception. Both have been very involved in the recent upgrade of this laboratory and continued operation of the FSTL.

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS7-100, sponsored by the National Aeronautics and Space Administration.

LOCATION	MANUFACTURER	MODEL	SERIAL NUMBER
DSS 14 GOLDSTONE, CA	SAO	VLG 10 B	P6
DSS 63 MADRID, SPAIN	SAO	VLG 10 B	P7
DSS 43 CANBERRA, AUSTRALIA	JPL	DSN	1
DSS 13 GOLDSTONE, CA	JPL	PROTOTYPE	P2
OVRO BISHOP, CA	GSFC	NX	2
ARIES JPL	SAO	VLG 10 B	P5
FSTL, JPL	JPL	DSN	2
FSTL, JPL	JPL	DSN	3

MANUFACTURER CODE

GSFC: GODDARD SPACE FLIGHT CENTER

SAO: SMITHSONIAN ASTROPHYSICAL OBSERVATORY

JPL: JET PROPULSION LABORATORY

Fig. 1. JPL H-Maser Deployment

	VLG 10 B P5	VLG 10 B P5	VLG 10 B P6	VLG 10 B P7	DSN 3	DSN 2
TEMPERATURE $\frac{\Delta F}{F}$ /°C	-1.6×10^{-14}	-1.2×10^{-13}	-1.0×10^{-13}	7.0×10^{-14}	2.5×10^{-13}	-6.3×10^{-14}
BAROMETRIC PRESSURE $\frac{\Delta F}{F}$ / "$_{HG}$	2.6×10^{-14}	2.6×10^{-14}	-3.4×10^{-13}	2.3×10^{-14}	-3.8×10^{-14}	-4.8×10^{-14}
MAGNETIC FIELD $\frac{\Delta F}{F}$ /GAUSS	1.6×16^{-12}	3.0×10^{-12}	5.0×10^{-12}	2.8×10^{-12}	4.8×10^{-12}	1.4×10^{-11}

Fig. 2. H-Maser Environmental Parameters

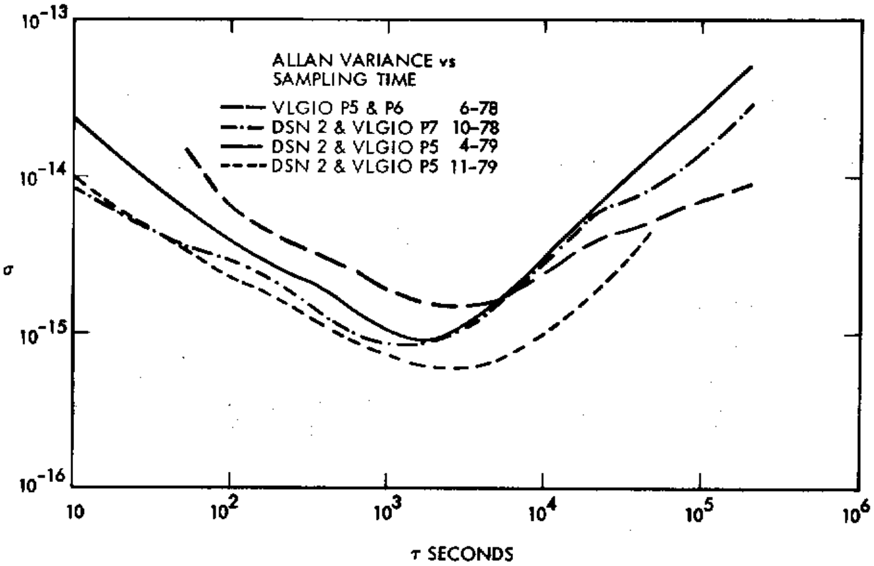

Fig. 3. Allan Variance vs. Sampling Time

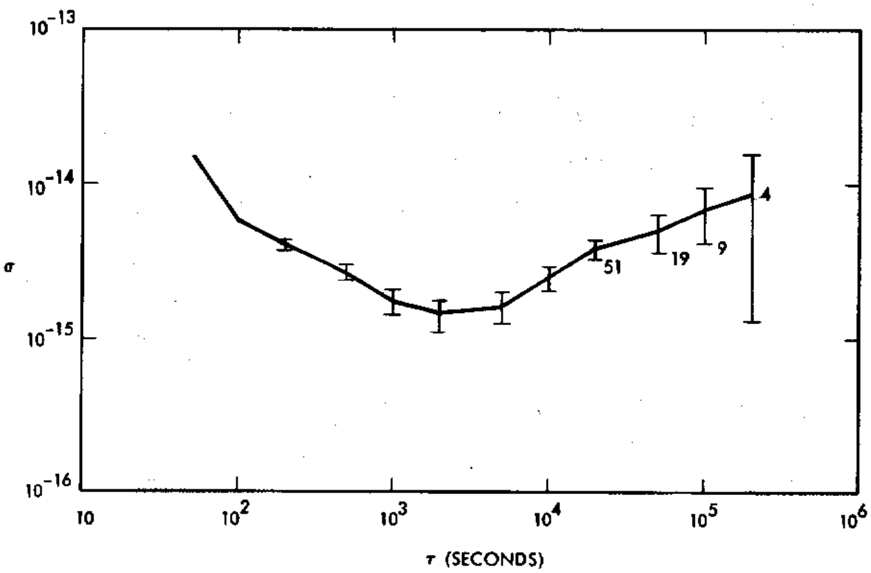

Fig. 4. Allan Variance vs. Sampling Time, with Error Bars

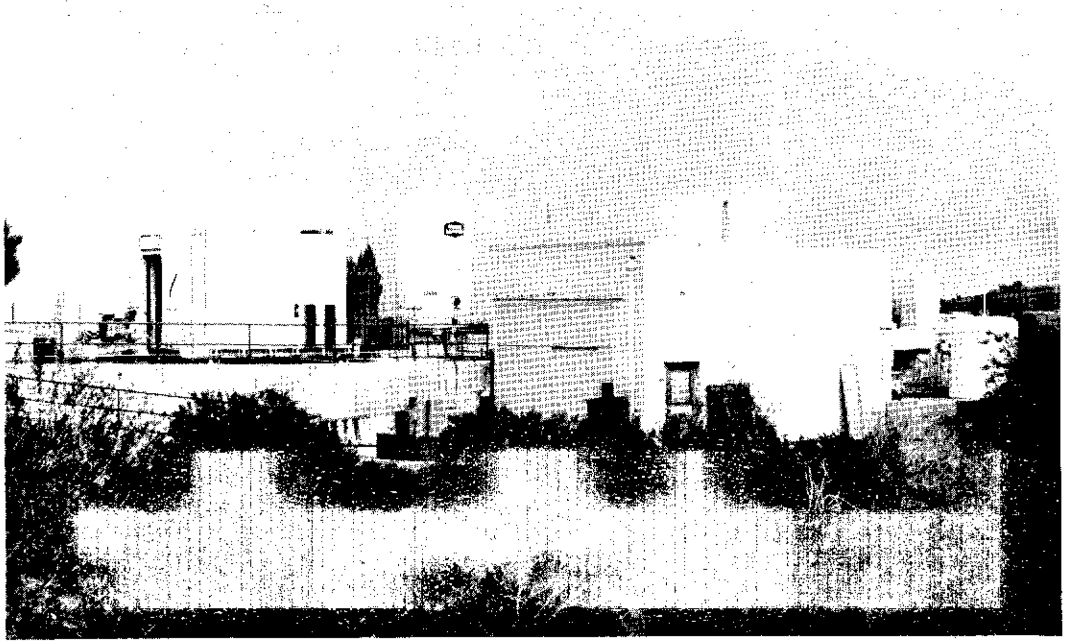

Fig. 5. JPL Frequency Standard Test Laboratory

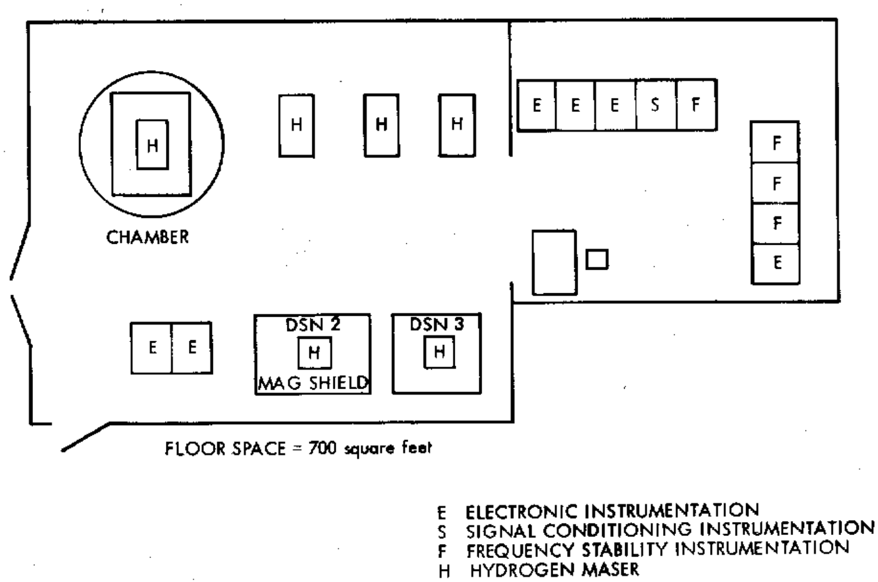

Fig. 6. Frequency Standard Test Laboratory Floor Plan

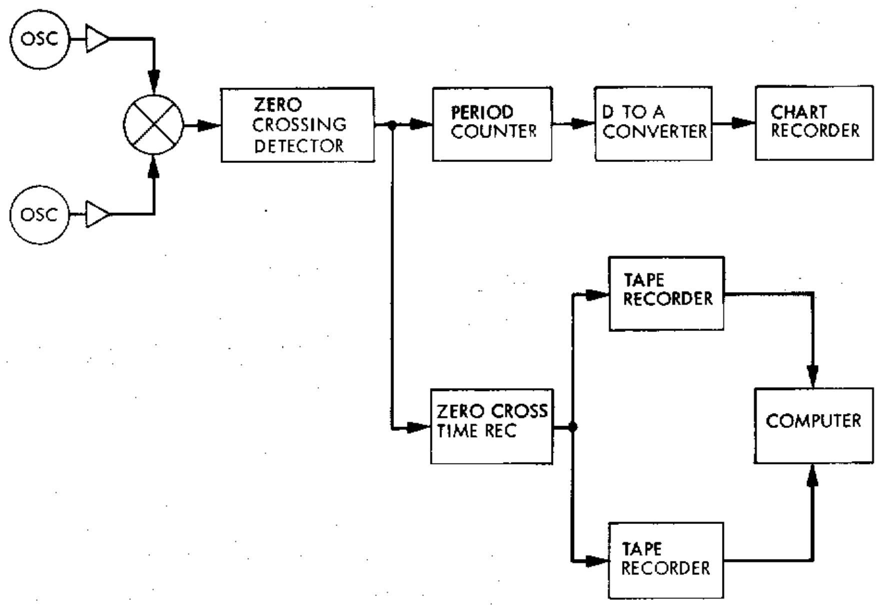

Fig. 7. Frequency Stability Instrumentation Block Diagram

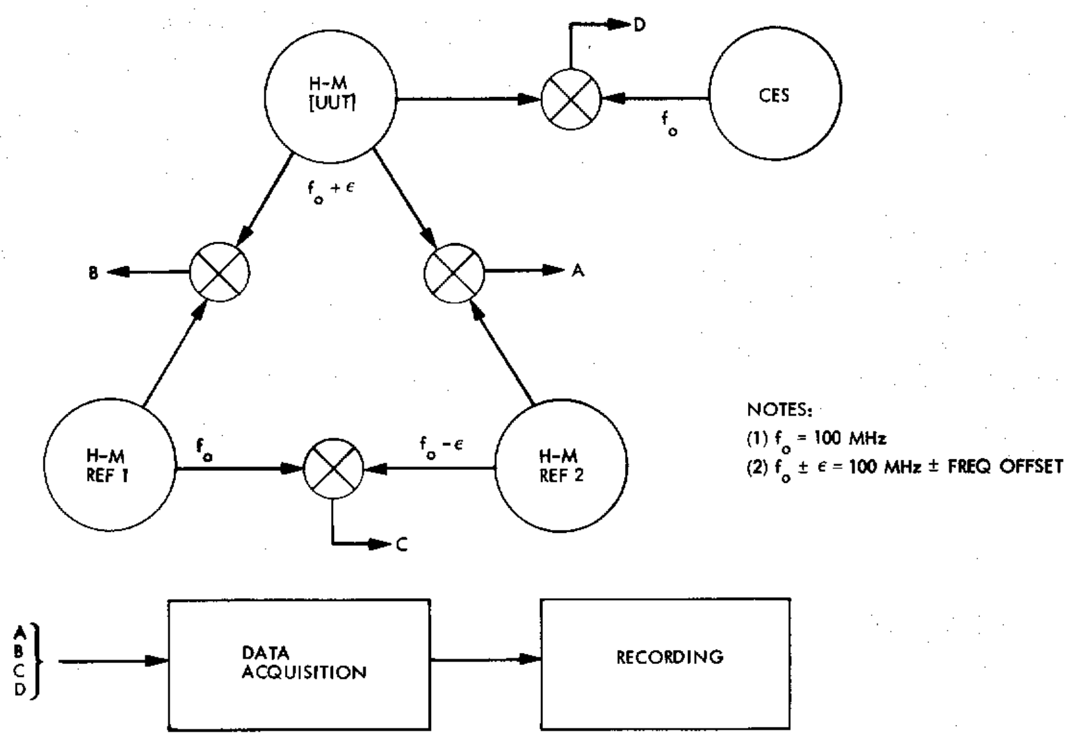

Fig. 8. Test Configuration for Stability Comparison of Three H-Masers

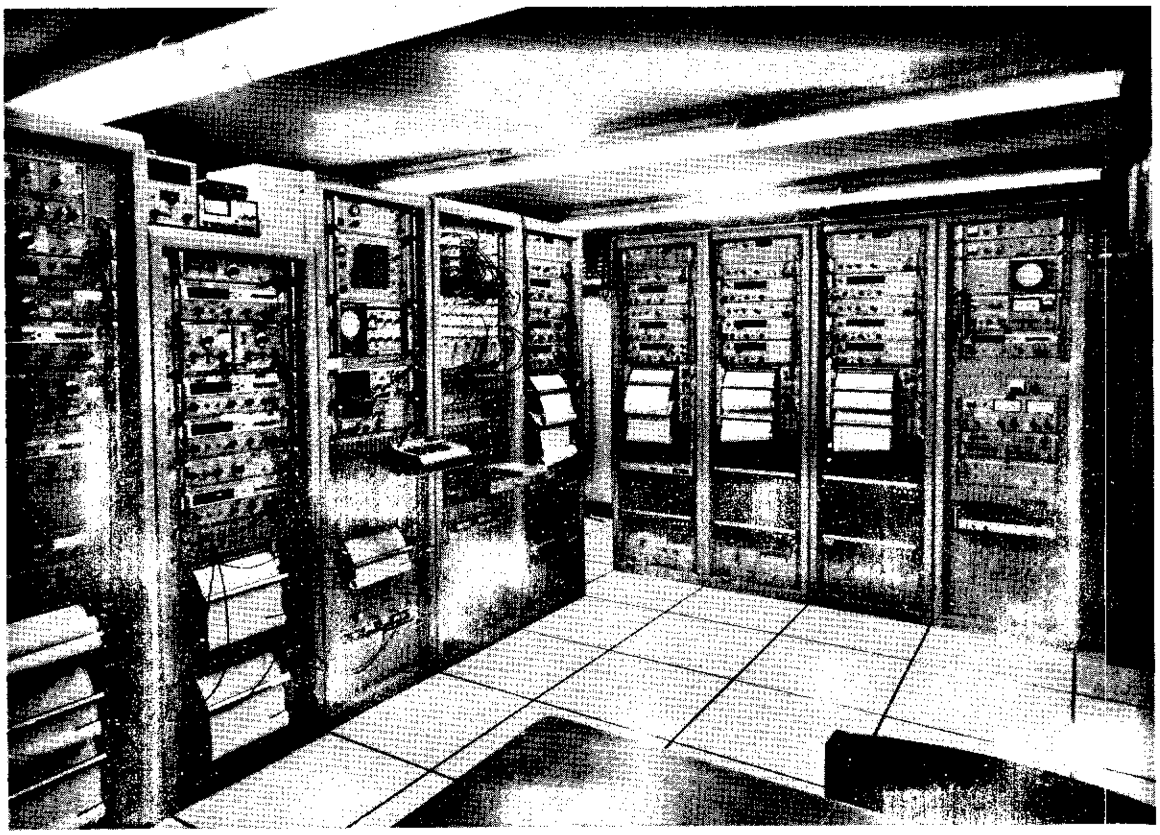

Fig. 9. Instrumentation Room Containing All Measurement Instrumentation

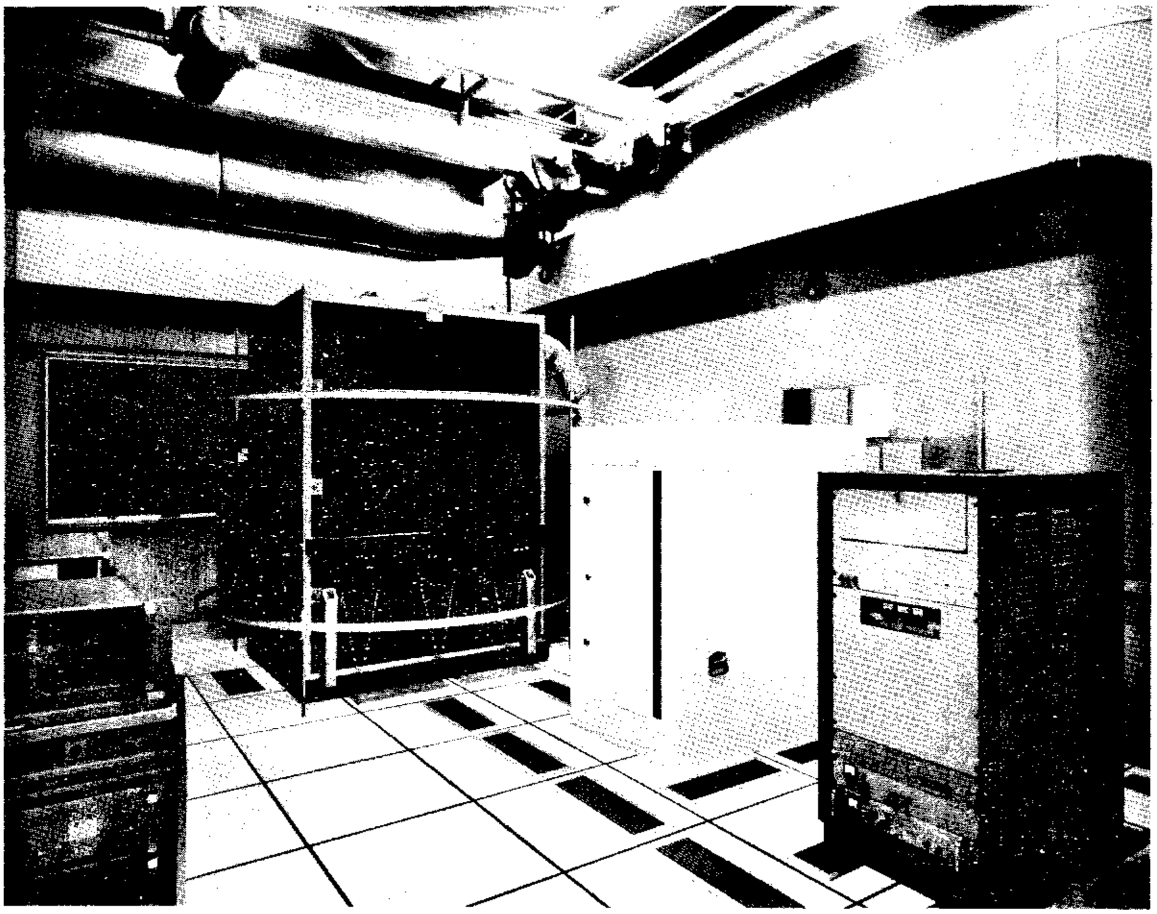

Fig. 10. Frequency Standard Room with Space on Right Side for H-Masers in Test and Environmental Chamber at Far Right

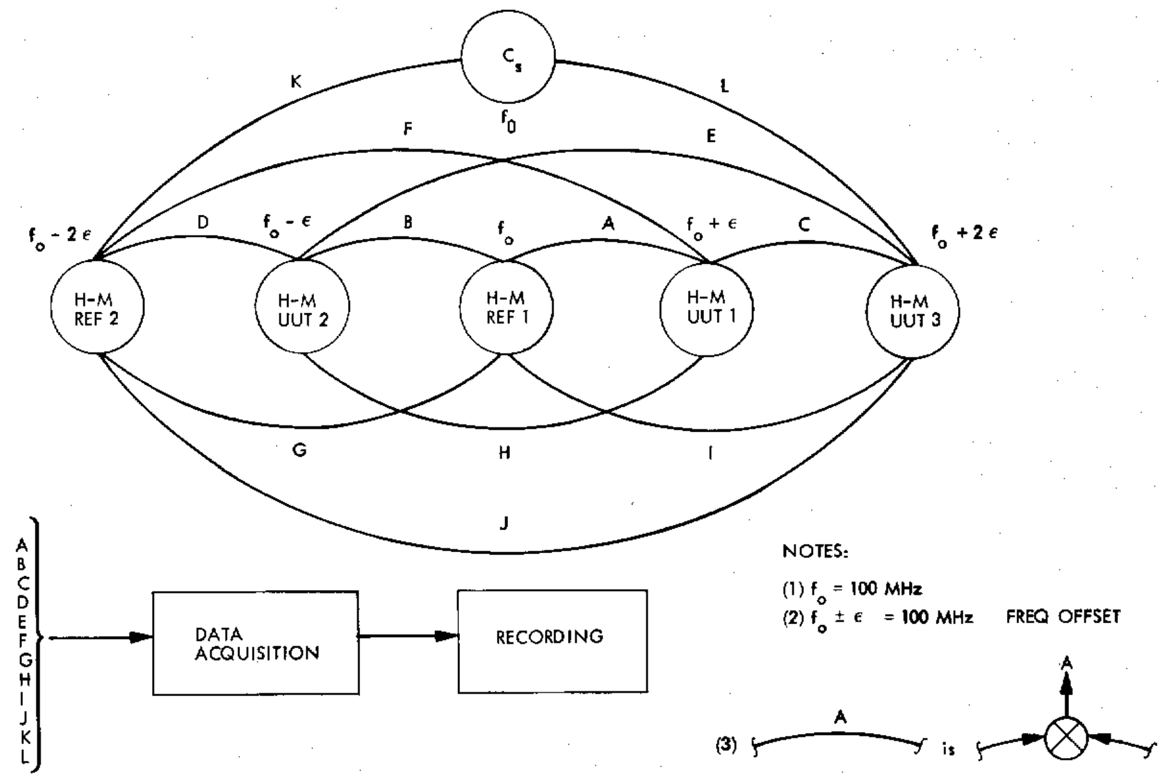

Fig. 11. Test Configuration for Stability Comparison of Five H-Masers