A SUBCOMPACT Q-ENHANCED ACTIVE HYDROGEN MASER*

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Abstract

A hydrogen maser has been fabricated that is considerably smaller than others developed by Hughes Research Laboratories (HRL) (1,2). The system uses an L-C loading structure to lower the resonant frequency of the microwave cavity, and an electronic cavity stabilization servo to ensure long-term cavity stability. The overall size of the physics unit (microwave cavity, vacuum chamber, dissociator, state selector, hydrogen source, four nested magnetic shields, and front-end electronics) is 5.6 in. by 5.6 in. by 14.5 in. The entire maser, including all power supplies and receiver electronics, is being packaged in a 6 in. by 16 in. by 17 in. envelope suitable for rack mounting.

Preliminary data show a stability of 8×10^{-14} for a τ of 100 s, which is very close to the theoretical limit for this design (3), and significantly better than that for other standards of comparable size. Such a maser should prove very attractive for applications in which high stability, small package size, and low weight are critical requirements.

Introduction

A frequency standard having the intrinsic stability associated with the narrow linewidth of the hydrogen hyperfine resonance and the small size of a commercial cesium standard would be a very desirable addition to the wide spectrum of available atomic standards. Size reduction, however, also means some sacrifice in performance. If reducing the size of a maser to that of a cesium clock reduces the stability to that of said clock, or below, then the desirability of such a maser vanishes. Earlier calculations (3) indicated that such a reduction in size would have a moderate, not severe, effect on overall stability. The data presented herein, although preliminary in nature, show that a moderate effect is indeed the case, and that, in fact, the fractional reduction in performance is an order of magnitude less than the fractional reduction in system volume.

The design for the subcompact maser described here has been discussed in considerable detail in an earlier presentation (3). Therefore, this paper emphasizes the implementation of this design, some of the problems encountered in its realization, and the comparison of the actual maser performance with theoretical predictions and with the performance of other compact masers developed by HRL.

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Physics Package

Figure 1 shows the main features of this maser which, for historical reasons, carries the acronym CHYMNS III(a). The essential elements of the physics package are, from left to right, the dissociator, the dissociator pressure monitor, the hydrogen source and variable leak valve assembly, the plenum chamber (which houses the state selector magnet), the magnetic shields and, within the shields and therefore not visible, the vacuum chamber and microwave cavity. The various boxes at the right end of the maser contain most of the RF and cavity control electronics, and are hereafter referred to as the "front-end electronics." The overall length of this assembly is 14.5 in.; the height is 5.6 in.

The dissociator is a 1.5-in.-diameter quartz bulb mounted on a molybdenum collar. A hemispherical electrode covering one end of the bulb, and a ground plane at the other, are used to induce the 144-MHz electric field that dissociates the molecular hydrogen into atomic hydrogen. The particular geometry used presents a vanishingly small reactive component and a 50-Ω resistive load to the external driver when the dissociator pressure is about 50 mTorr and the incident power 3 W.

Beam collimation was initially effected with a 20-mil-thick capillary array with 10 μm holes. Although this array gave superior collimation, we found that the RF discharge within the dissociator attacked the array, causing a darkening of the array material (Pyrex) and a subsequent increase in the atomic-to-molecular hydrogen recombination rate, which reduced the efficiency of the dissociator. This degradation of the capillary array material seems peculiar to this array size, since other arrays, with considerably larger hole sizes (50 μm) have given satisfactory service in similar applications. The troublesome array was eventually removed and replaced with a Pyrex disc 40 mils thick with a 4-mil-diameter hole in its center. There has been no measurable dissociator degradation since this second collimator was installed.

The quadrupole state selector magnet, designed by Naval Research Laboratory and manufactured by the Electron Dynamics Division of Hughes Aircraft Company, is 1.5 in. in diameter and 1.25 in. long, has a pole separation of about 20 mils, and has an estimated field strength at the pole tips of about 8 kG. The estimated number of atoms in the m=0 excited state reaching the bottle interior for this particular dissociator-quadrupole combination, and for the pressure and RF power listed above, is 6×10^{11}/s.

Figure 2 shows the microwave resonator before assembly. The storage bulb on the left, which was not used in the final version, has three electrodes attached to its surface with a low-loss epoxy. This loading structure (bulb plus electrodes), when installed in the microwave cavity, had an unusually high temperature coefficient of 150 kHz/°C, and for this reason was replaced with a two-electrode version with a coefficient of 48 kHz/°C. The cavity and electrodes were fabricated from OFHC copper, the storage bulb from 50-mil-thick fused quartz. The uncoupled cavity Q of the two-electrode resonator was 5700.

The quartz storage bulb is coated with five layers of Teflon. The wall relaxation time T_{2w} for this coating has been estimated by measuring the radiative lifetime T_2 as a function of dissociator pressure, extrapolating to zero pressure, and then subtracting the computed geometrical storage time. The value for T_{2w} obtained by this technique is

680 ms, which is considerably better than that achieved for earlier coatings, but still somewhat below the design goal of of 1 s (3). The 680 ms wall relaxation, together with a geometrical storage time of 350 ms and a spin-exchange relaxation associated with a beam flux of 6 x 10^{11}/s, gave an effective lifetime T_2 of about 160 ms. The threshold cavity Q for this beam flux has been measured to be 22,000. Maximum stability is theoretically achieved when the system operates with an enhanced Q of about 47,000, a value close to the 44,000 used for the data described below.

The cavity resonator is installed in the all-titanium vacuum chamber using titanium leaf springs and titanium screws. Semirigid 70-mil-diameter coaxial cable is used to feed the microwave signal into and out of the resonator; these cables are brought out through the right-side neck, thus obviating the problems associated with fishing these cables down the beam tube. A proprietary isolated feedthrough is used to bring these cables through the vacuum-atmosphere interface. The cables are thermally shunted to a temperature-controlled surface at one end of the vacuum chamber, so that external temperature variations will not be transmitted through these cables to the microwave cavity.

Thermoelectric currents within the vacuum chamber, which could generate unwanted magnetic fields, have been minimized either by using identical materials at all interfaces, or using high-resistivity materials when this is not possible (e.g., the titanium screws in the copper cavity), or by electrically isolating the different metals at the interfaces. One interface for which none of these solutions is applicable was titanium-indium at the indium O-ring on the vacuum chamber. Although this interface was cause for concern, there has been, to date, no measurable evidence of thermoelectric currents from this seal.

The temperature of the microwave resonator is controlled by two quadrufilar-wound copper heaters, one located at each end of the titanium vacuum chamber. The heaters are driven at 45 kHz, a frequency well above the maser Zeeman frequency (approximately 280 Hz). To expedite assembly, no heaters were used on the cylindrical surface of the vacuum chamber, nor on the magnetic shields or front-end electronics. Such a thermal control system is, by maser standards, woefully inadequate. The stability data, on the other hand, are surprisingly good, which suggests that a good cavity-control system can cure a multitude of ills. The intent, however, was to have the cavity-control system play the role of a roving back, and not of an entire defensive line, and in keeping with this philosophy, version "b" of this maser, currently being assembled, will incorporate, at a very minimum, the missing heaters listed above.

Electronics

A schematic of the receiver, Q-enhancement, and cavity control electronics is shown in Figure 3. The injected signal level and electronic gain of the cavity-control system are such that the overall loop time constant is about 4 s. This value is long enough to filter out most of the electronic noise, yet short enough to allow the system to respond dynamically to short-term variations. The injected sideband signal level is no more than 10 dB higher than the maser signal, and the position of the sidebands is such that no Fourier component of the injected signal falls within 5 Hz of the maser line, thereby minimizing possible frequency-pulling effects. The measured power in the Fourier components closest to the maser line is 42 dB below that of the atomic resonance.

Measurement of Performance

A standard Dual-Mixer-Time-Difference system (4), shown schematically in Figure 4, with a Smithsonian Astrophysical Observatory model VLG-11 maser (5) as the reference, has been used to measure the performance of CHYMNS III(a). Data for a seven-day period are shown in Figures 5-8. The Allan Variance follows a roughly $1/\sqrt{\tau}$ dependence, deviating only for larger values of τ.

The diurnal variations in phase correlate well with the diurnal variations in room temperature (not shown), and are most likely associated with the poor thermal control system. Experience with the other two compact masers developed at HRL has shown that these variations can be essentially eliminated by enclosing the front-end-electronics in a environmentally controlled container – and something like this enclosure will probably be made for CHYMNS III(b). The long-term drift of 1.86×10^{-14}/day, however, cannot be so easily dismissed, since its cause is not understood at present. Since this drift is currently the fundamental limitation to the ultimate long-term stability of the maser, the drift figure is a little troubling. A systematic investigation of the processes that could cause such a drift is now underway.

Table I compares the performance of this mini-maser with the theoretically predicted value and with the performances of two other Hughes Aircraft Company Masers, CHYMNS I and II. The reduction in performance in going from CHYMNS II to CHYMNS III is less than 30%, a very reasonable tradeoff when one considers the threefold reduction in the size of the maser.

Future Plans

The present system uses an externally mounted zirconium- graphite (ST-172) getter and a 2 l/s ion pump to maintain the high vacuum needed for maser operation. The system also uses several commercial power supplies and a number of bulky heater, dissociator, and Palladium valve drivers, all of which take up quite a bit of space. To make the system as compact as possible, version "b" will use a modified plenum chamber that serves both as a quadrupole-dissociator housing and as a chamber for two getter slugs, and in a volume to fit within the existing physics package envelope (5.6 in. by 5.6 in. by 14.5 in.). We are also expending considerable effort on miniaturizing the electronics, particularly the larger items like the heater controllers and power supplies. Figure 9 shows the 100 W switching power supply of version (b): the unit provides partially (1%) regulated voltages of 8, ±19, and 28 V, fully (0.01%) regulated voltages of 5, ±15, and 24 V, and 2000 V for the ion pump. The unit is approximately 70% efficient, and occupies a volume of 5.2 in. by 6.2 in. by 1.75 in. A similar package (4.2 in. by 5.2 in. by 1.8 in.) has been fabricated that will drive the six ac or dc heaters used for temperature control.

The finished maser will be completely self-contained, will operate from a standard 110 V outlet, and will have a package outline of 6 in. by 16 in. by 17 in. The maser will thus be comparable in size to commercially available cesium standards, and will perform significantly better for measurement times up to several days. Better environmental control of the more sensitive electronic components should improve the longer-term stability.

References

1. H.T.M. Wang, "Characteristics of oscillating compact masers," Proc. 36th Ann. Symp. on Freq. Control, (1982) p. 249.

2. H.T.M. Wang, "An oscillating compact hydrogen maser," Proc. 34th Ann. Symp. on Freq. Control, (1980) p. 364.

3. R.R. Hayes and H.T.M. Wang, "Design for a subcompact Q-enhanced active maser," Proc. 38th Ann. Symp. on Freq. Control, (1985) p. 80.

4. D. Allan, "Report on NBS dual mixer time difference system (DMTD)," NBSIR75-827, NBS, Boulder, CO (1976).

5. The Smithsonian Astrophysical Observatory (SAO) Model VLG-11 Hydrogen Maser Frequency Standard is on loan from the Naval Research Laboratory.

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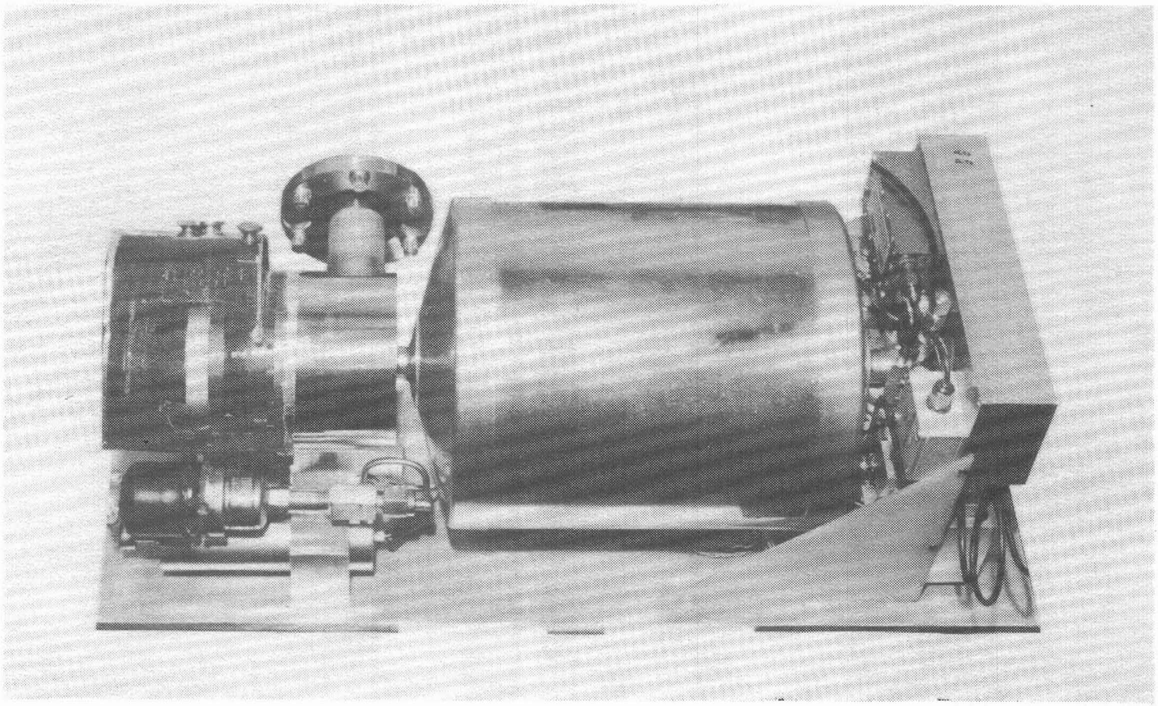

Figure 1. Side view of CHYMNS III(a) physics package.

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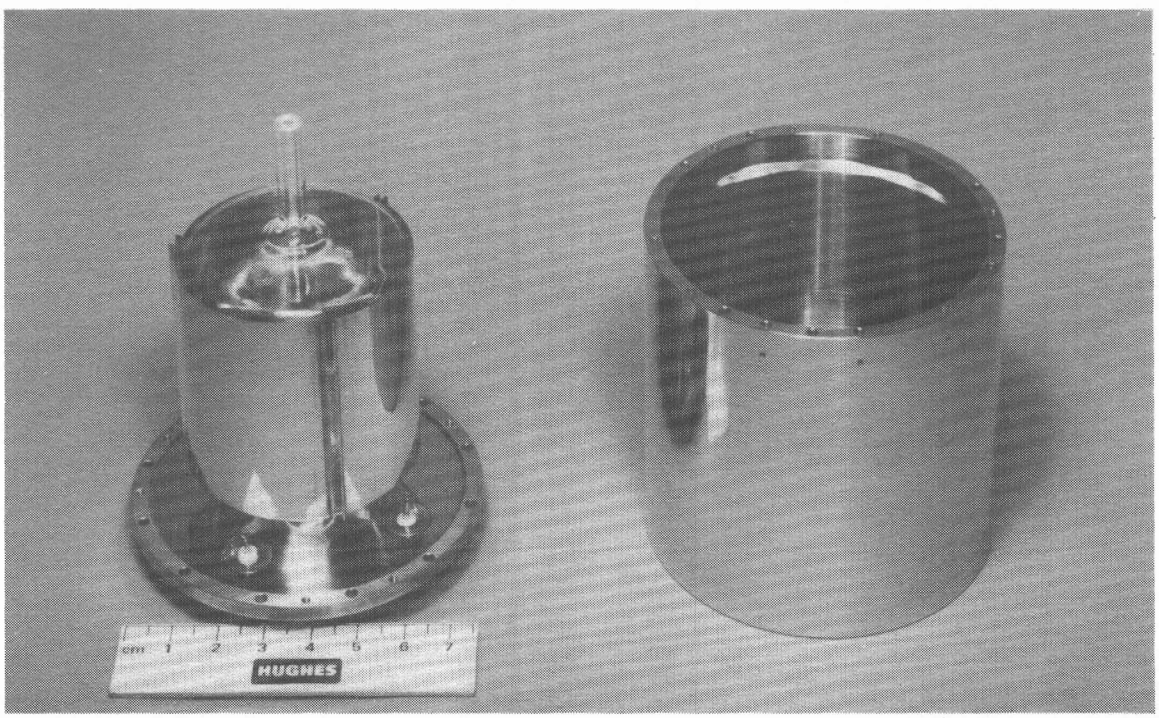

Figure 2. Microwave resonator, showing endplate, storage bottle with loading electrodes, and cavity.

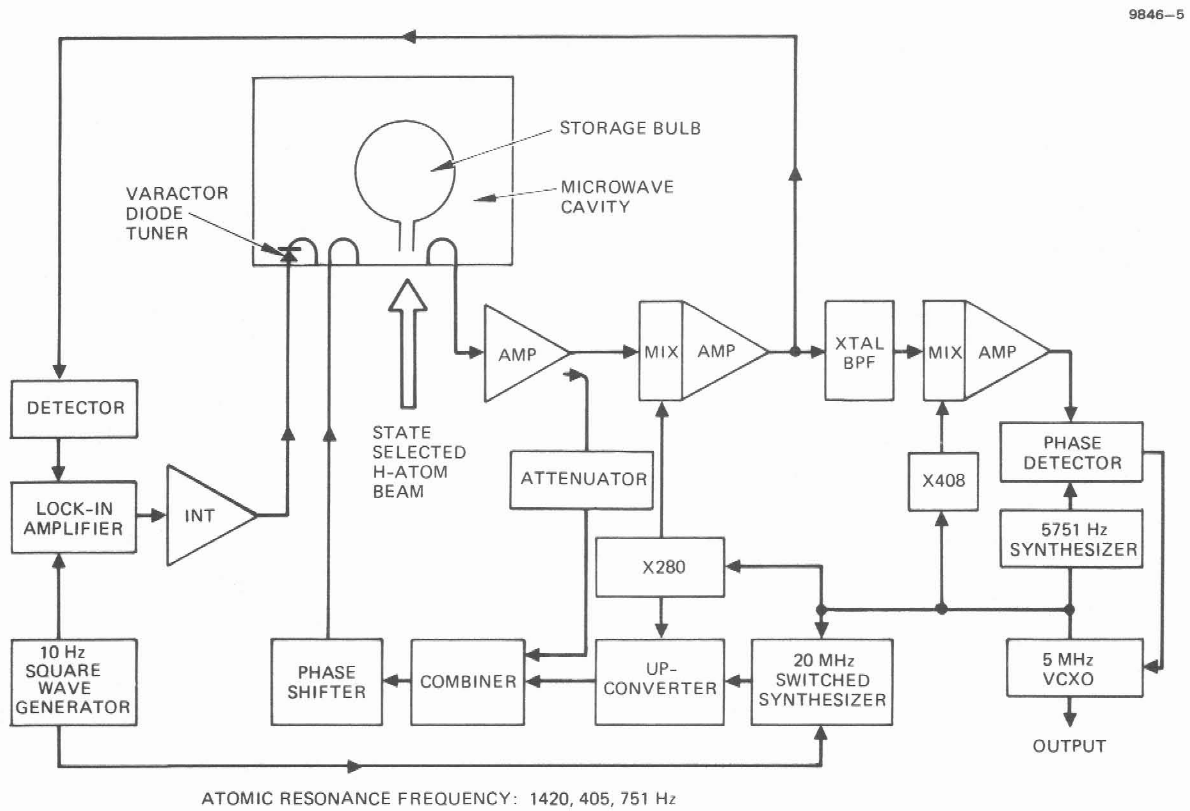

Figure 3. Diagram of system electronics.

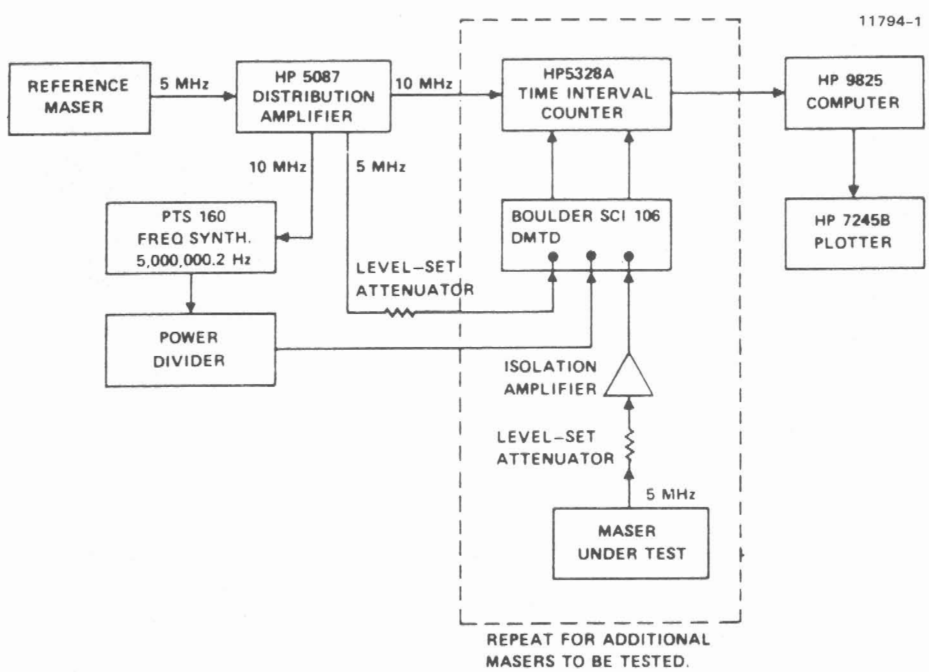

Figure 4. Schematic of measurement system.

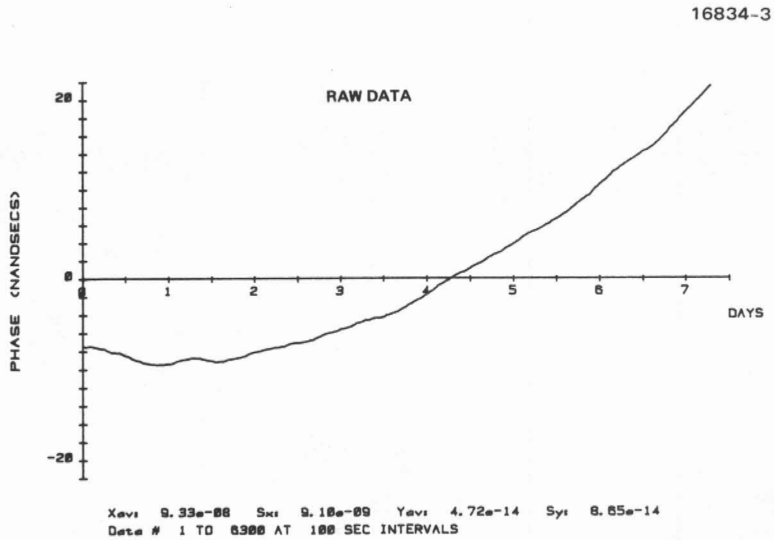

Figure 5. Measured phase difference between the reference maser and CHYMNS III(a) for a seven-day period.

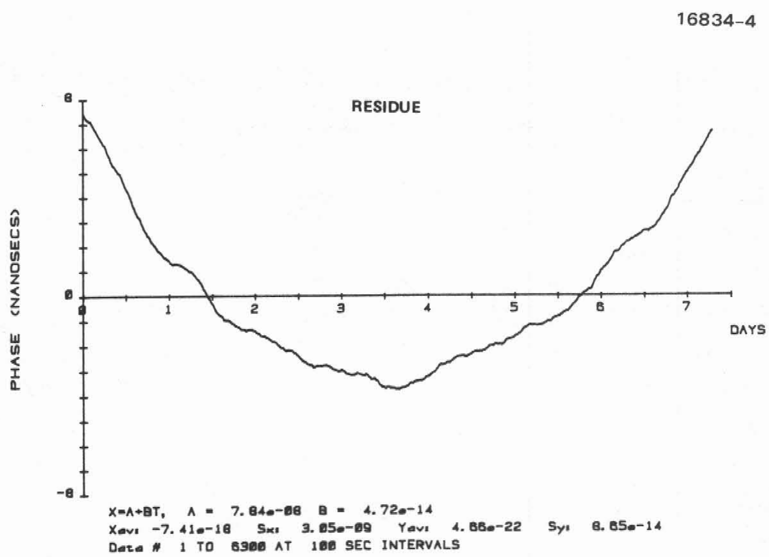

Figure 6. Residue after the constant-frequency component has been subtracted.

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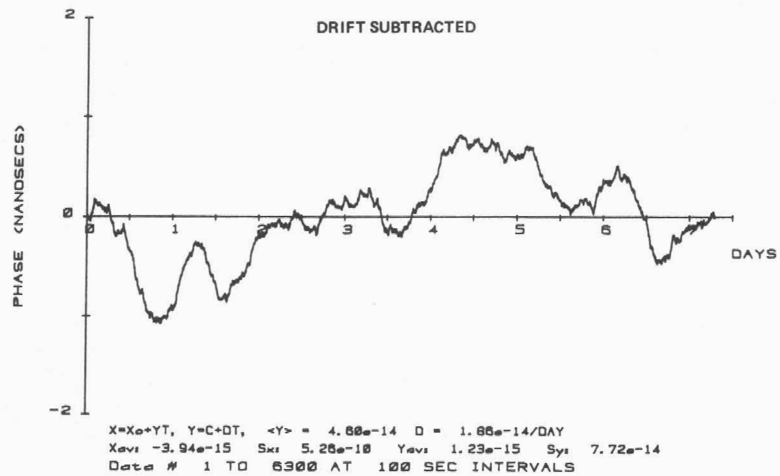

Figure 7. Residue after a linear frequency drift of 1.86 x 10^{-14}/day has been subtracted.

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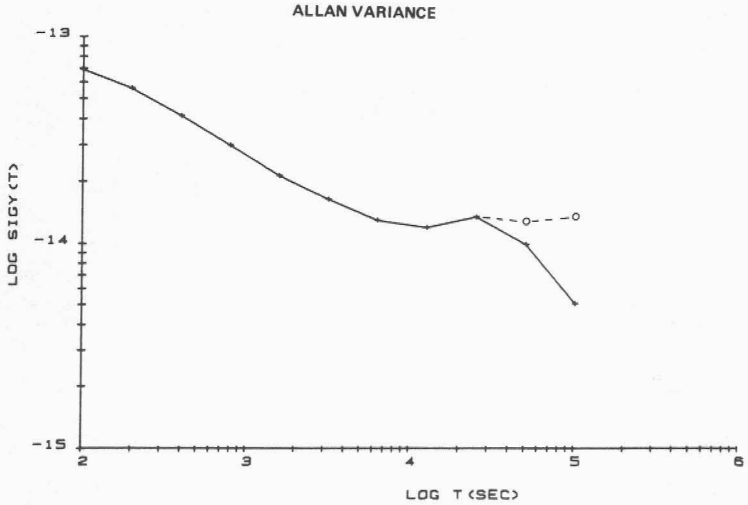

Figure 8. Root Allan Variance. The broken line is for the data of Figure 6, the solid line for that of Figure 7.

Table I. Comparison of CHYMNS III(a) performance with the theoretical prediction and with other Hughes Aircraft Company masers.

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MASER	CHYMNS I	CHYMNS II	CHYMNS III
Cavity Dimensions	6 in. dia by 6 in L	4.1 in. dia by 6 in. L	3 in. dia by 3 in. L
Physics Package Volume	4000 in^3	1350 in^3	450 in^3
$\sigma_{theoretical}$ (400 s)	1.9×10^{-14}	3.1×10^{-14}	3.9×10^{-14}
$\sigma_{measured}$ (400 s)	2.4×10^{-14}	3.0×10^{-14}	4.14×10^{-14}

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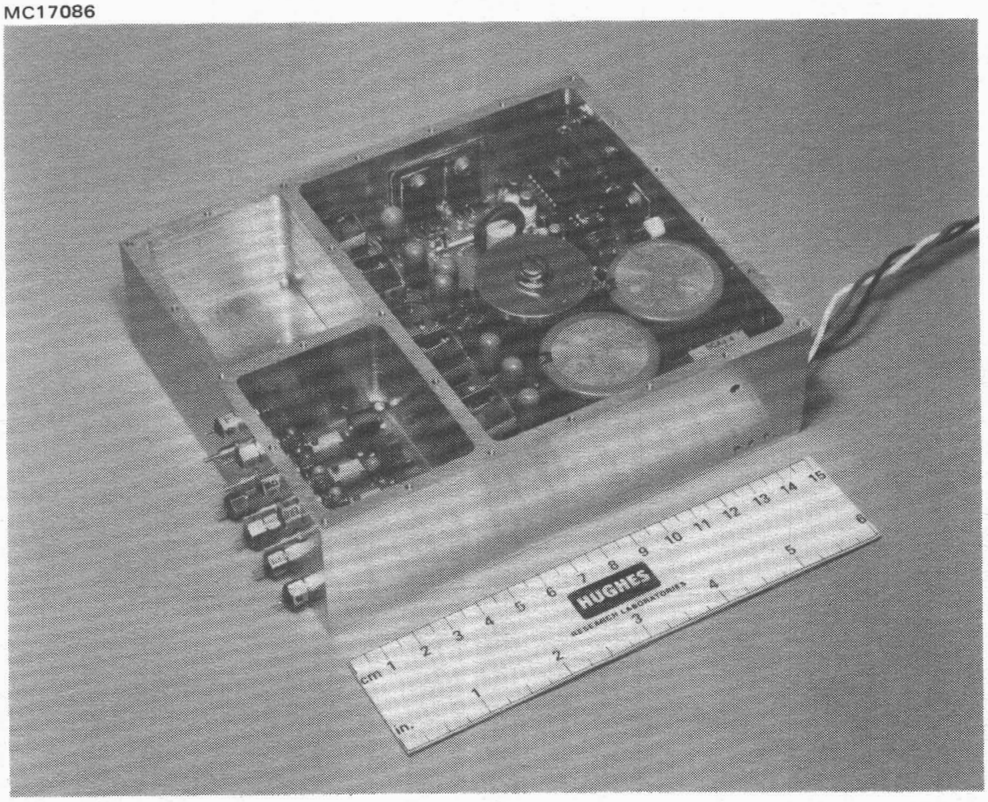

Figure 9. Low-noise multiple-output 100-W switching power supply.