THE NASA/GSFC HYDROGEN MASER PROGRAM: A REVIEW OF RECENT DATA

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ABSTRACT

The NASA/Goddard Space Flight Center Hydrogen Maser Program has had as goals for many years the development of improved field operable hydrogen masers, the improvement of existing field operable hydrogen masers and the development of novel hydrogen maser frequency standards. This paper presents a review of recent data, taken both in the laboratory and in the field, in these areas. Data is presented on the phase and frequency stability, over time periods extending to one week, of the new NR field operable hydrogen masers developed by the Applied Physics Laboratory (APL) and the older NX and NP field operable hydrogen masers developed by Goddard Space Flight Center and maintained and upgraded by Bendix Field Engineering Corporation (BFEC). Data is presented on the NR masers in the laboratory showing frequency stabilities well into the 10^{-15} range and phase stabilities well into the 100 ps range for periods of up to one day. Data is presented on upgraded NP masers in the laboratory showing that the frequency stability has been improved substantially to virtually the NR level. VLBI data is presented on the phase difference between NX-2 at Owens Valley, California and NR-2 at Fort Davis, Texas for a one week period showing, after removal of a constant frequency drift, a 350 ps RMS phase stability. The role of a temperature control chamber for hydrogen masers developed by BFEC in improving the long term stability of hydrogen masers is discussed.

Extensive development work is being performed by both APL and BFEC to improve the performance of hydrogen masers beyond their current levels. A quartz cavity liner designed to retrofit into existing NR, NP, and NX microwave cavity structures has been developed by BFEC and APL in a cooperative effort. This liner has been installed in an NR maser and has been shown to reduce the cavity temperature coefficient by a factor of 8. Data is presented showing the stability of this maser against other NR masers. A completely quartz cavity and storage bulb

ABSTRACT (cont)

structure, called the integral cavity, which will also retrofit into the NR, NX, and NP masers is being developed by BFEC and APL in another cooperative effort. This structure should reduce the cavity temperature coefficient by a factor of 25 or more and should improve the maser's frequency stability under mechanical shock. Data is presented on the recent progress in the development of an external bulb variable volume hydrogen maser primary frequency standard.

INTRODUCTION

The NASA/Goddard Space Flight Center Hydrogen Maser Program has had as its goals for many years the development of improved field operable hydrogen masers, the improvement of existing hydrogen masers, and the development of novel hydrogen maser frequency standards. This paper represents a review of recent data taken both in the laboratory and in the field in these areas. The paper is broken into two basic sections reporting on data taken by Bendix Field Engineering Corporation and the Applied Physics Laboratory of Johns Hopkins University, the two main contractors to the NASA Hydrogen Maser Program.

BENDIX FIELD ENGINEERING

The Bendix Field Engineering Corporation (BFEC) has supported the NASA Goddard Space Flight Center hydrogen maser program for the past ten years. Recently, BFEC has expanded its support in response to the increasing demands of the NASA Crustal Dynamics Project and the NASA research program. Both hydrogen maser maintenance and operations and hydrogen maser research and development are now performed at BFEC's new 4500 square foot Hydrogen Maser Facility located at BFEC Headquarters in Columbia, Maryland.

Thermal Chamber for Hydrogen Masers

Figure 1 shows a thermal chamber developed by BFEC to improve the long term frequency stability of hydrogen masers by improving their thermal environment. These chambers typically reduce room temperature fluctuations by a factor of about 100 and typically keep the temperature of the hydrogen maser from fluctuating no more than 10-20mC in a laboratory environment (1C room temperature fluctuations). Figure 2 shows the thermal chamber with a side panel removed. This shows some of the main features of the thermal chamber:

1. Completely field dismantlable so the unit can be brought into a room through a 30 inch door.
2. Uses thermoelectric coolers for high reliability.

3. Has 18 Rotron fans to create an 1800cfm air flow in the chamber to reduce the effects of temperature gradient changes. (The thermal conductivity of the moving air is equivalent to that of aluminum.)
4. Shock mounts on the chamber and the fans to eliminate 60Hz vibration problems.
5. A failsafe thermostat to prevent accidental overheat of the maser in case of chamber failure.
6. Separate fuses for the thermoelectric coolers and the fans so individual failures in these devices will not keep the chamber from operating.
7. Remote and local alarm outputs.

The chamber has also been successfully used to improve the long term stability of Hewlett Packard high performance cesium standards.

Figure 3 shows typical thermal chamber performance in a good laboratory environment. The figure shows NR-1's upper cabinet temperature and the corresponding air temperature outside the box(smoothed with a 1.5hr time constant temperature probe). In station environments where the temperature has varied as much as 10K, the temperature in the chamber has varied less than 0.1K.

VLBI Data

Figures 4 and 5 show a 7 day phase(group delay) intercomparison between NR-2 at Fort Davis, Texas and NX-2 at Owens Valley, California by very long baseline interferometery(VLBI)(ref1). Figure 4 shows the phase difference in seconds with only a frequency offset term removed from the data(as well as nonclock VLBI terms such as earth rotation). Notice that the data has the quadratic behavior associated with uniform frequency drift. Figure 5 shows the same data with a uniform frequency drift term also removed. The least squares fit used to generate this figure produced clock parameters as follows:

x_o=5686.83(10)ns
y_o=-236.26(04)E-14
D_o=-1.16(01)E-14/Day

The RMS phase(group delay) deviation from the fit was 347ps.

Repair and Upgrade of Hydrogen Masers

Figure 6 shows several NASA NP and NX hydrogen masers being repaired and upgraded in BFEC's Hydrogen Maser Facility. The upgraded NP and NX masers have received new cavity thermal controls, synthesizers, VXCO's, receiver components, and distribution amplifiers and have had the physics packages rebuilt. Figure 7 shows the before upgrade and the after upgrade frequency stabilities of NP-2 measured against NR-6 from 1 to 1000 seconds averaging time. Notice the almost one order of magnitude improvement in performance. Figure 8 shows the frequency stability of the upgraded NP-2 and the non-upgraded NP-3 measured against NX-3 from 10^3 to 10^5 seconds averaging time. NP-2 and NX-3 were in thermal chambers and NP-3 was not. Thus the factor of ten or more long term stability improvement shown is due both to the maser upgrade and the use of the hydrogen maser thermal chambers.

Quartz Cavity Retrofits for NP, NX, and NR Hydrogen Masers

BFEC and APL have a joint effort to improve the temperature coefficient and the mechanical stability of NP, NX, and NR hydrogen masers with retrofitable quartz cavities. There are 2 retrofitable designs being developed. The Hybrid Cavity shown in Figure 9 uses a quartz cylinder coated on the outside with silver as an internal liner in the microwave cavity. This reduces the temperature coefficient of the microwave cavity by about a factor of 5, but still allows the microwave cavity's frequency to be set with tunable end plates and allows one to use temperature tuning of the cavity as with the conventional aluminum cavity. The Hybrid Cavity is being tested in NRB by APL and is reported on in the APL section. The temperature coefficient of NRB with the Hybrid Cavity has been measured by APL as $6.9(9) \times 10^{-15}$/C.

The second retrofitable design being developed is the Integral Cavity whose main components(storage bulb not shown) are shown in Figure 10. In the integral cavity all the parts making up the microwave cavity are made of quartz. After trimming the cavity to the proper frequency, all the pieces (including the storage bulb) will be fused or cemented together. This design will have a cavity temperature coefficient a factor of 25 smaller than a conventional aluminum cavity and should achieve greater mechanical stability because of the fusing of the pieces. An integral cavity has already been fabricated and will be tested in NRX. It has not been determined yet whether temperature or varactor tuning will be used.

External Bulb Hydrogen Maser

The External Bulb Hydrogen Maser is a variable volume hydrogen maser being developed by BFEC for NASA. The purpose of the maser is to provide a primary hydrogen maser frequency standard which will eliminate teflon wall frequency shifts and other accuracy limiting frequency shifts to the 1×10^{-14} level(ref2). As part of the development effort, the maser has been tested with a 1/2 mil thick teflon film bulb and a long time constant collimator(without the external bulb). The results of that test demonstrating an operating line Q of 6.5E9 are shown in Figure 11. The maser has also successfully operated at 90C. Currently the maser is being rebuilt to overcome magnetic problems.

NR MASER STABILITY DATA

The NR maser, shown in Fig.12, has several advantages over the earlier NX and NP masers. Their biggest advantage is an internal 64-channel microprocessor. This microprocessor provides diagnostic and monitoring information on many maser operations, and provides automated control for cavity tuning. Cavity tuning can be accomplished by autotuning against another maser or the crystal oscillator internal to the maser; or by programming the microprocessor to adjust the cavity for a predicted drift. Stability data on several NR masers are presented. These data were measured in the Time and Frequency facility of The Johns Hopkins University Applied Physics Laboratory.

Maser Intercomparisons

Stability measurements between two or more masers are accomplished by offsetting the frequency of one of our masers, NR-6, by -5×10^{-8}. The signal from NR-6 can then be mixed with the signal from a second maser at 200 MHz to obtain a 10 Hz beat. An HP 5300 time interval counter is then used to measure the phase difference between NR-6 and a second maser. This measurement technique using an offset maser provides a 20 million multiplication factor for the time interval measurement; one millisecond on the counter corresponds to 50 picoseconds of phase difference at 200 MHz.

During all the data runs to be presented, NR-6 was located in an environmental control chamber; and was programmed to compensate for a predicted cavity drift. At regular intervals, but not during any of the data runs presented here, NR-6 was tuned.

Recently we began using an automated system for recording phase difference measurements between three maser pairs (all referencing NR-6) at intervals of 100 seconds, onto floppy disks. This system allows continuous phase difference information over long periods of time. Temperature data for the room and the maser environmental chambers are also recorded at hourly intervals.

Figure 13 shows the residuals to a least squares fit of the phase difference between NR-3 and NR-6 over a seven day span. (This treatment of the data is consistant with that of the VLBI users). NR-3 was located in an environmental chamber; NR-3 was not autotuning during this time. Over the majority of the data span, the residuals remained within ± .5 ns, with extremes of ± 1.0 ns. Within this data are two relatively large phase jumps of approximately .5 ns. These jumps are artifacts of our measurement system, which we are working on eliminating. Even with these jumps, the RMS deviation of the week long data was 0.316 ns.

The Allan Variance of the (NR-3) - (NR-6) data shown in Fig.13, removing the two discontinuities, is shown in Fig.14. The Allan Variance of both the raw data and the residuals (i.e. drift removed data) are shown.

Error bars are given for the drift rate removed data but similar error bars apply for the raw data. These error bars were estimated by

$$\text{Error} = \pm \, {}^{1}/\sqrt{(N-2)}\ \%$$

where N is the number of adjacent time intervals of length tau (τ). The factor of two is required because the raw data is in phase rather than frequency. Both masers were assumed to contribute equally to the noise, and hence a factor of $2^{-\frac{1}{2}}$ was included in the calculations.

Figure 14 shows that NR-3's stability at 100,000 seconds is 4×10^{-15} for the drift rate removed data.

Figure 15 again shows the residuals to a least squares fit of the phase difference between NR-B and NR-6. NR-B has the integral cavity liner with the improved temperature coefficient, approximately $7 \times 10^{-15}/^{o}C$. A week long data span is shown. NR-B was not autotuning, and was located in an environmental control chamber. However, NR-B's chamber was operating near its upper temperature control limit, causing larger variations as shown in the temperature plot in Fig. 15. One would not expect temperature variation as large a factor in NR-B's performance as other NR masers without a quartz liner and, in fact, the residuals plotted in Fig. 15 show a peak-to-peak variation of only ± .5 ns. The RMS deviation of the data over the seven days was only 0.251 ns. (Again there appeared a single discontinuity resulting from the measurement system.)

The Allan Variances with the drift rates removed of NR-5, NR-B, and NR-2 whose residuals were not shown, are plotted in Fig. 16. Shorter term data was measured only on NR-2. All masers were measured relative to NR-6 and the variances and error bars were calculated in the same manner as that described earlier for NR-3. NR-5 and NR-2 were autotuning while NR-B was not.

Figure 16 coupled with Fig. 14 on NR-3's stability, illustrates the range of performance in the hydrogen masers APL has completed. Their stabilities are seen to be well into the 10^{-15} range for taus (τ's) of 500 - 100,000 seconds when drift is removed.

NR-1 Long Term Stability

NR-1 maser resides at APL on a long term basis and serves as our laboratory standard. Taking advantage of NR-1's availability, we investigated the performance of a hydrogen maser being operated as a clock relative to our laboratory's cesium option 004 Hewlett-Packard frequency standards.

For ten months, from September 1981 through June 1982, we maintained a continuous record of the phase difference between NR-1* and our Cesium 793. The phase difference was measured at 5 MHz using a dual balance time delay mixer with a beat frequency of about .25 Hz relative to each standard. In our Time and Frequency Laboratory within APL we maintain three cesium standards. Timing information is reported to BIH (Bureau International de l'Heure) on these three cesiums relative to our paper clock, and the USNO (United States Naval Observatory) Master Clock #1, with whom we transfer time using portable cesium clocks. BIH, in turn, calculates and publishes bimonthly, the rates of the reporting clocks relative to UTC (Universal Time Coordinated). Figure 17 shows both the bimonthly clock rates of our three cesium standards published by BIH, and the derived clock rate of NR-1.

Figure 17 shows that, as a clock, NR-1 performed as good or better than the best ten month data span of any of the three cesiums. In fact, the actual performance of the NR-1 maser is most probably masked by the limited resolution in the BIH published data, given only to ± 10 ns; and by the performance of the cesium transfer standard.

Another advantage of the NR-1 hydrogen maser operating as a clock is the ability to set the frequency without adversly affecting the inherent stability of the device. This is not true of present cesiums.

After our ten month data run comparing NR-1 to Cesium 793, the maser operating conditions were changed; NR-1 was placed in a continuous autotune mode. This operating mode allows the cavity bit register to automatically adjust to compensate for the cavity frequency drift. The cavity register value was printed out at four hour intervals and later converted to the frequency shift through a measured value of the frequency shift per cavity register bit**. Figure 18 shows these cavity register drift corrections plotted over a four month interval.

A rather significant piece of data on the maser's performance was obtained quite unintentionally. During the four month time period, our room air conditioner suffered a failure over a weekend when no one was present to immediately correct the situation. NR-1 was in an environmental control chamber, but the room temperature rose above the box's control limit. The spike in the data of Fig. 18 is the cavity register trying to compensate for the temperature control failure. The behavior of NR-1 after temperature control was restored is worthy of note; the cavity came back to the same frequency as that just before the temperature control failed. This behavior

* During this time period, NR-1 was in an environmental control box for temperature control. NR-1 was not autotuning during this time.

** The frequency shift per bit for NR-1 during this time period was 2.03×10^{-16}/bit.

following a failure is a great advantage for our masers operating in remote areas where short term failures, such as the one just described, are more likely to occur.

Ignoring the temperature control failure, the drift corrections to the cavity shown in Fig. 18 appear to increase in a nearly linear manner with time. A quadratic least squares fit of the data was calculated, which gives the linear daily drift of the cavity as:

$$-4.90 \times 10^{-15}/\text{day}.$$

Higher order terms of cavity drift as a function of time are insignificant relative to the linear term. The data in Fig. 18 are frequency corrections made to cavity to compensate for its drift, therefore, the increasing frequency compensates for a cavity frequency that is drifting downward in frequency.

In addition to the cavity register data shown in Fig. 18, two determinations of the NR-1 cavity drift were made; one in early August 1981, and the other in late February 1982. The total change in NR-1's cavity register value over a period of 78 days, was obtained in each case and an average daily drift rate was calculated. These calculations agreed to within 10% of the daily cavity drift calculated for the four month data shown in Fig. 18.

Linear Daily Drift (averaged over 78 days):

-4.4×10^{-15}/day	period ending 4 August 1981
-5.1×10^{-15}/day	period ending 24 February 1982

The cavity drift rate of NR-1 has remained essentially constant over a time period of greater than one year with an uncertainty of $\pm 5 \times 10^{-16}$/day.

ACKNOWLEDGEMENTS

The authors would like to acknowledge C. Knight of Interferometrics Incorporated for reducing the VLBI data shown.

REFERENCES

1. A. R. Whitney, et. al., "A Very Long Baseline Interferometer for Geodetic Applications", Radio Science, Vol. 11, Number 5, pp 421-432(May 1976)

2. V. S. Reinhardt, "Variable Volume Maser Techniques", Proceedings of the 8th Annual NASA/DOD Precise Time and Time Interval Planning Meeting (Washington, DC, 1976)

FIGURES

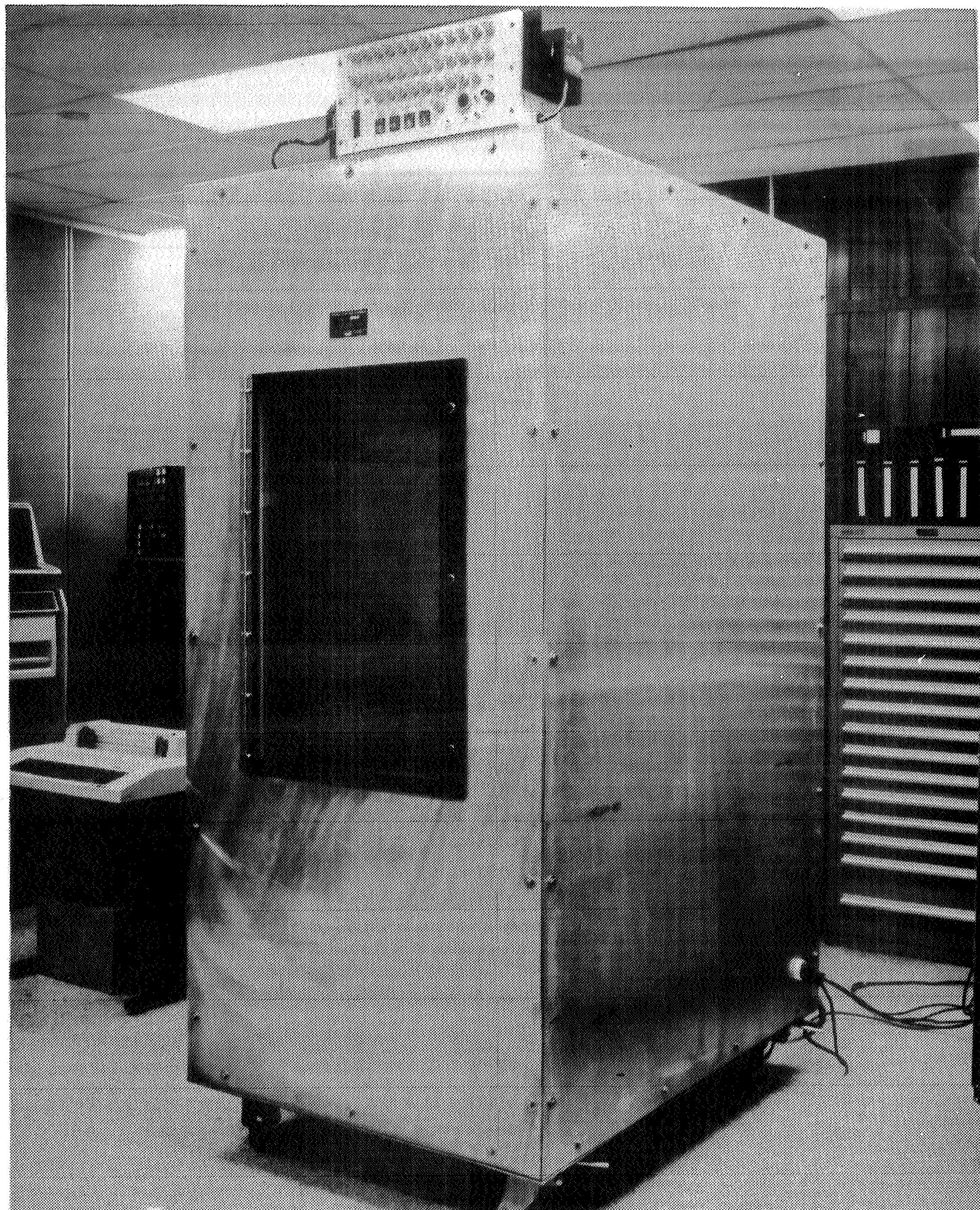


Figure 1. Hydrogen Maser Thermal Control Chamber

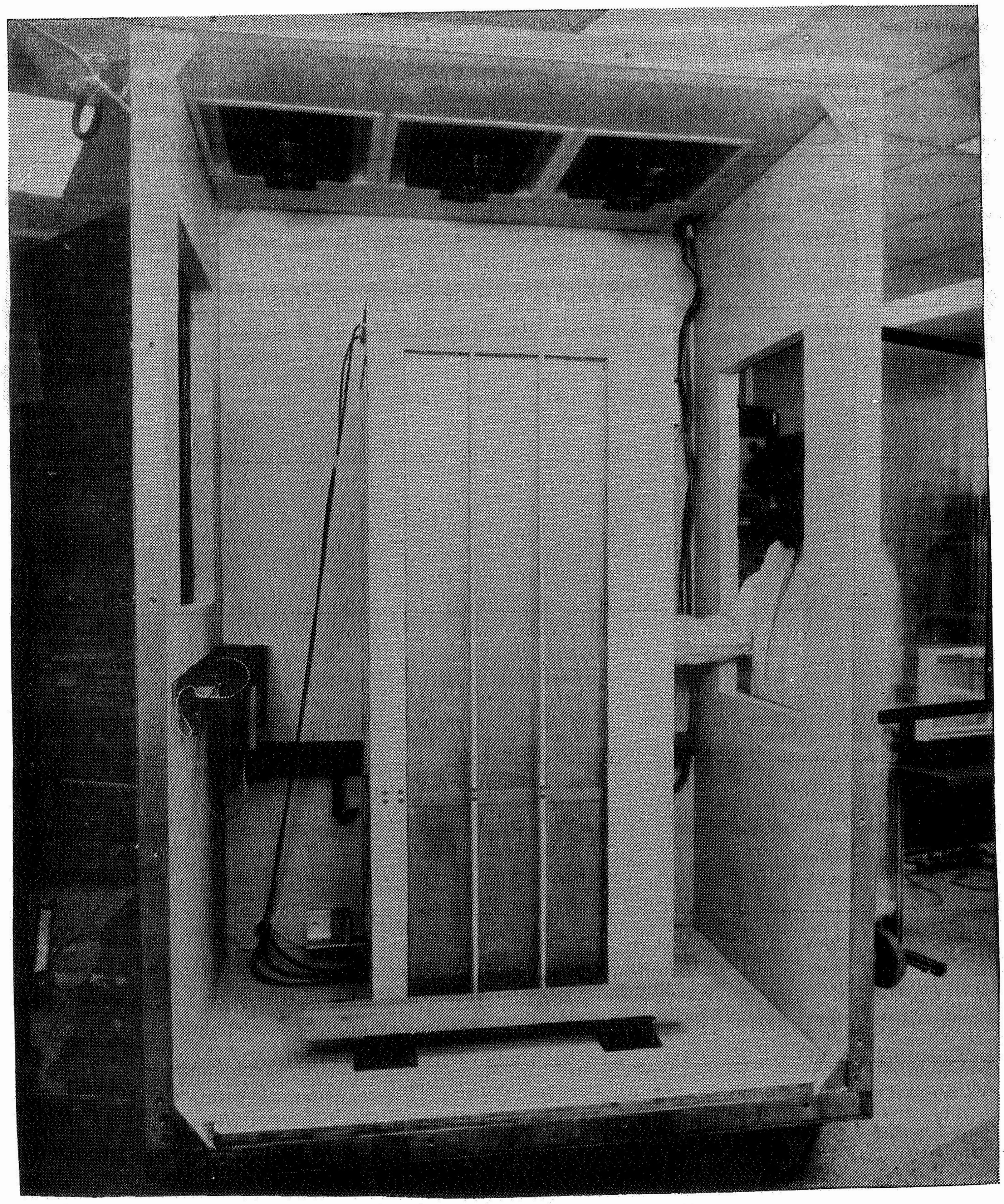
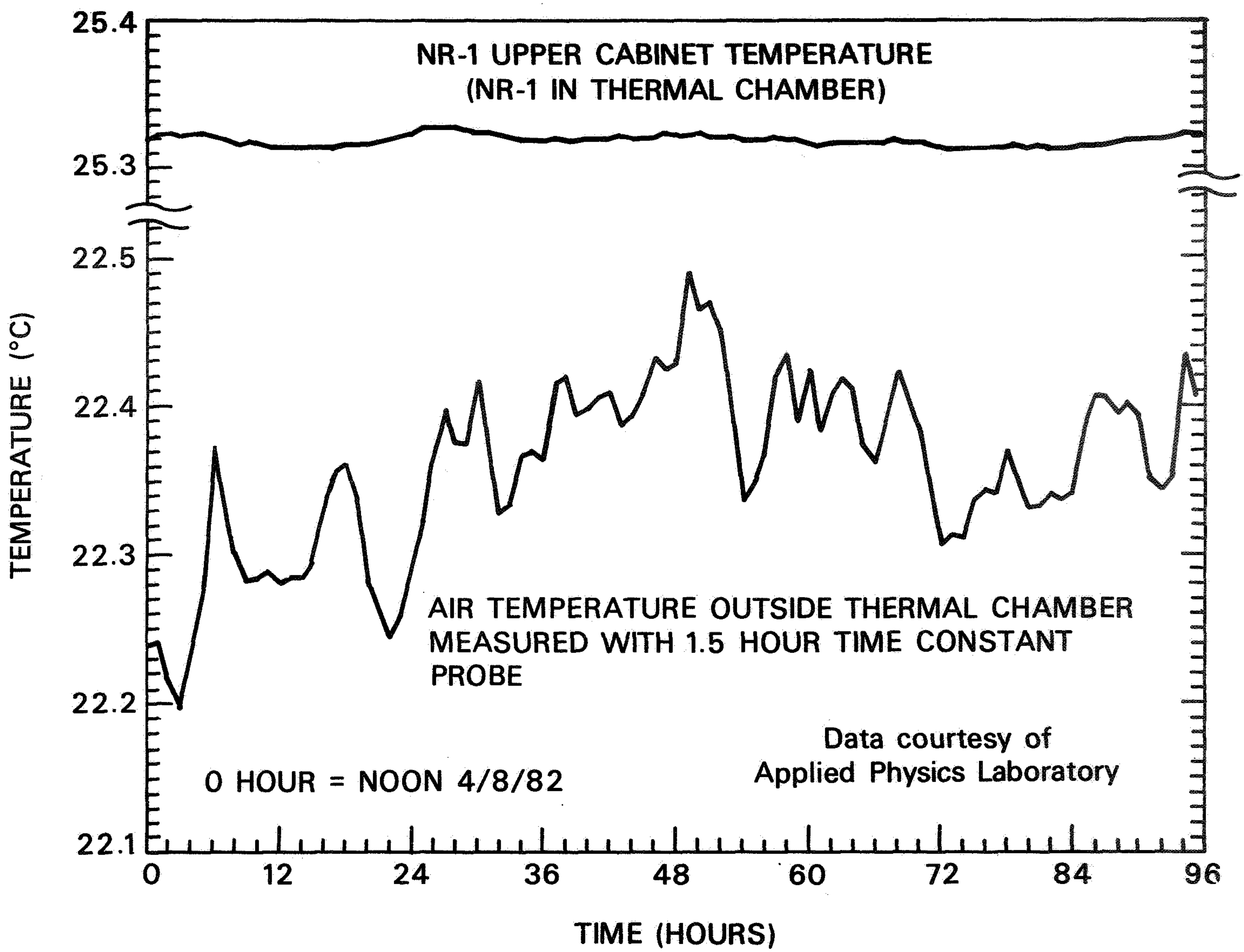


Figure 2. Thermal Chamber with Side Panel Removed



Simultaneous Temperature Data Taken at Applied Physics Laboratory Inside and Outside Thermal Chamber

Figure 3. Thermal Chamber Performance in a Laboratory Environment

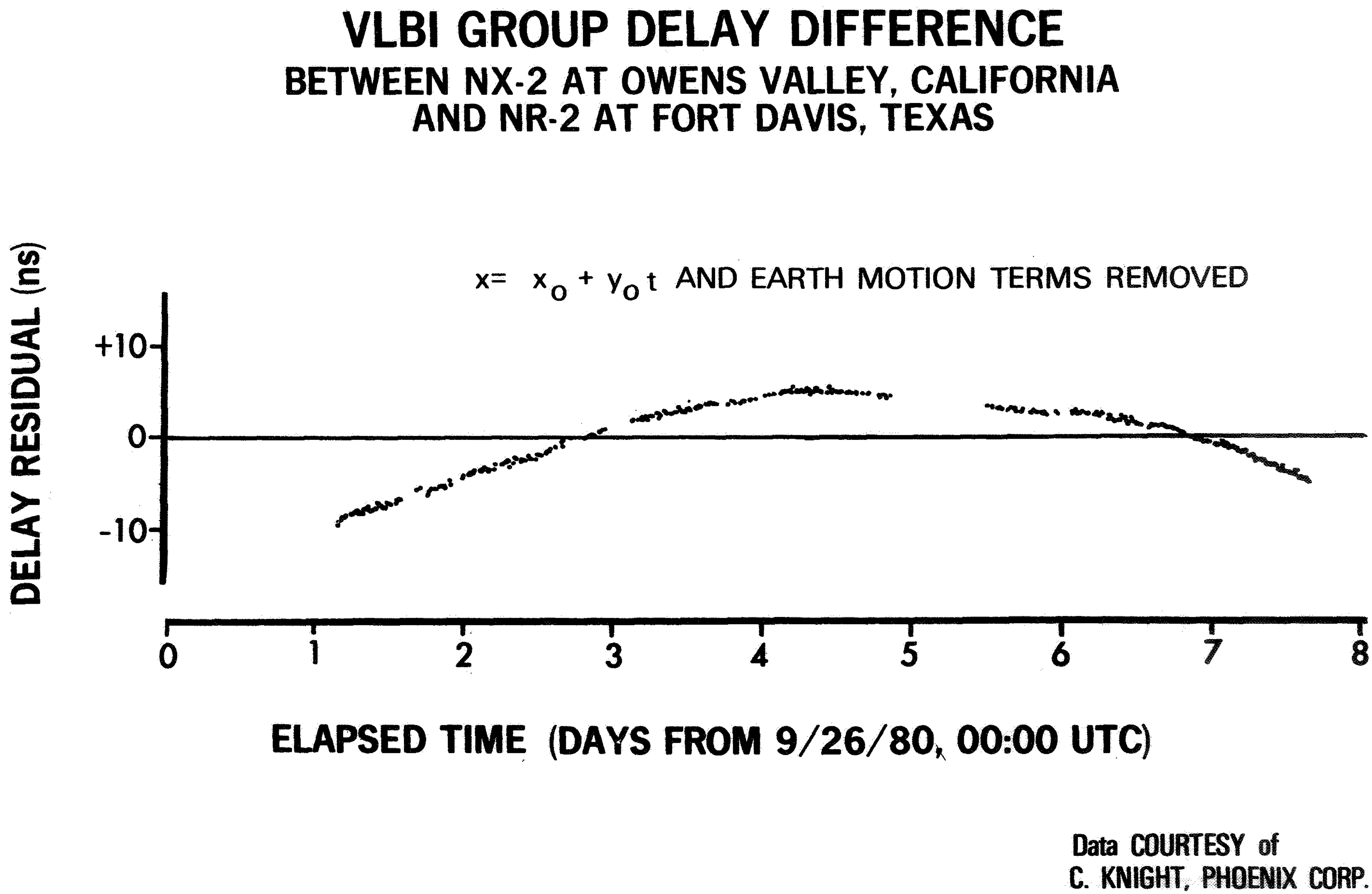


Figure 4. VLBI Phase Comparison Between NR-2 and NX-2 - Frequency Offset Removed

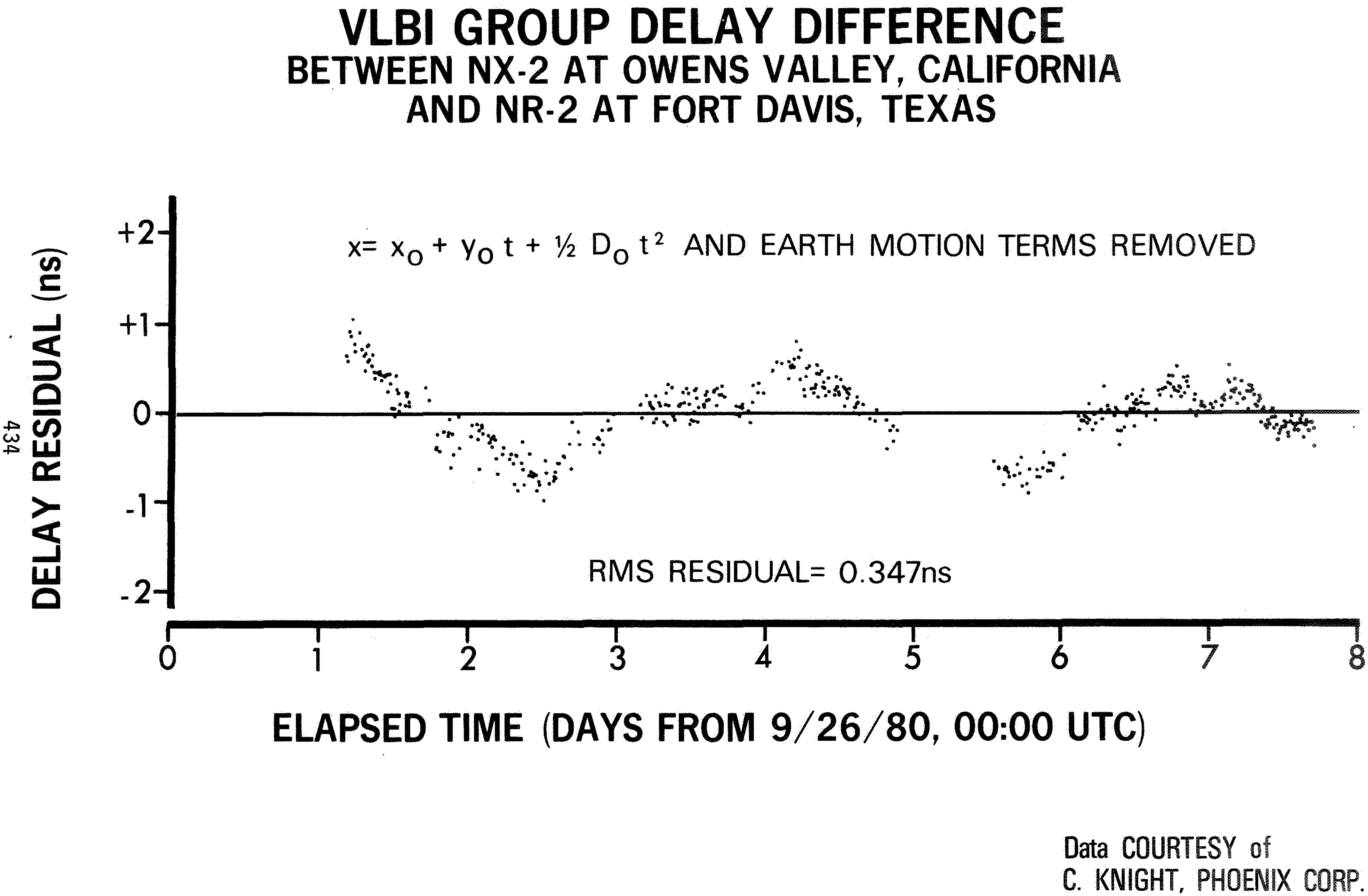
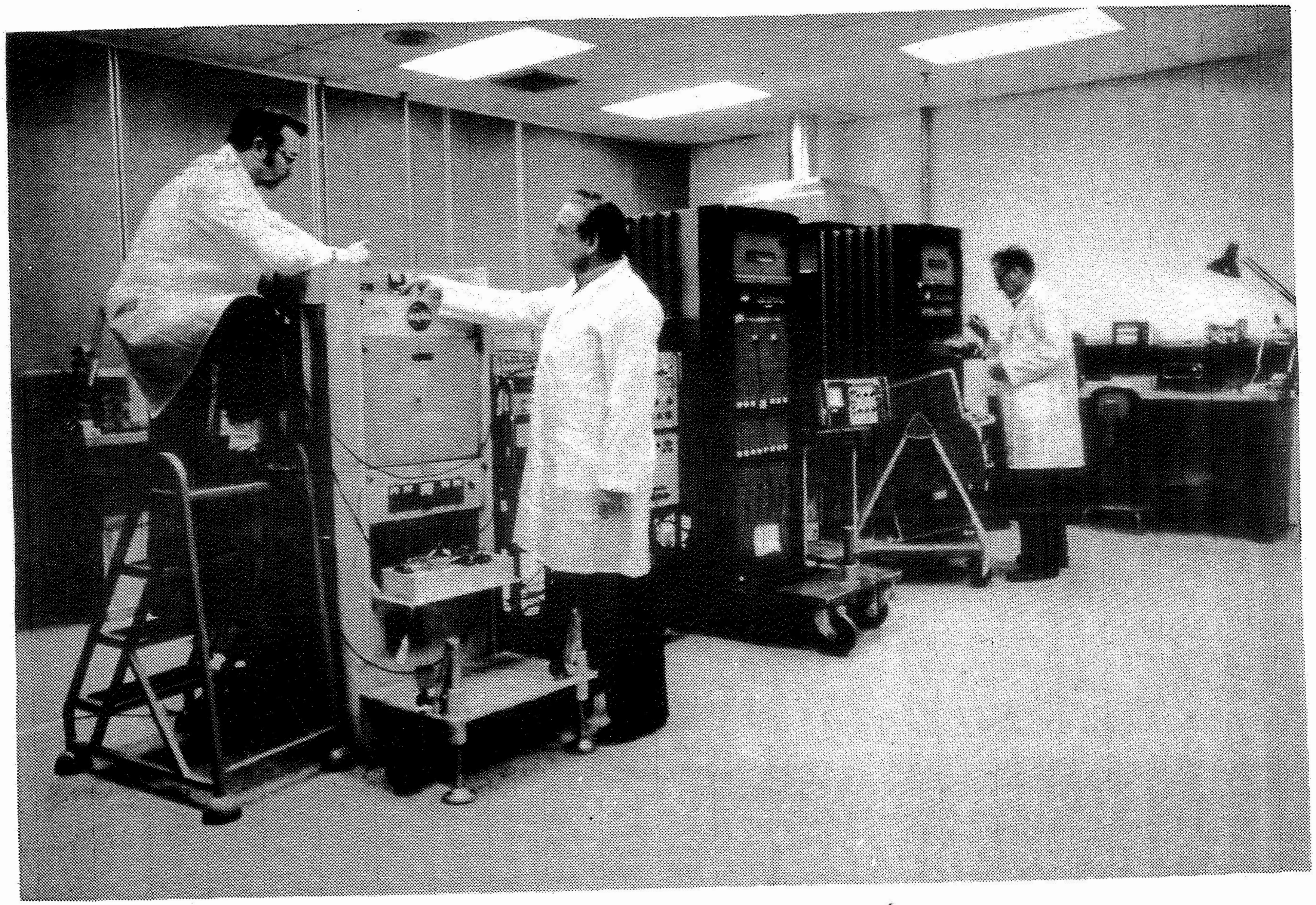


Figure 5. VLBI Phase Comparison Between NR-2 and NX-2 - Frequency Drift Removed

Figure 6. Hydrogen Masers Being Repaired and Upgraded at the BFEC Hydrogen Maser Facility



BENDIX LABORATORY/RETROFIT AREA FOR NP AND NX MASERS

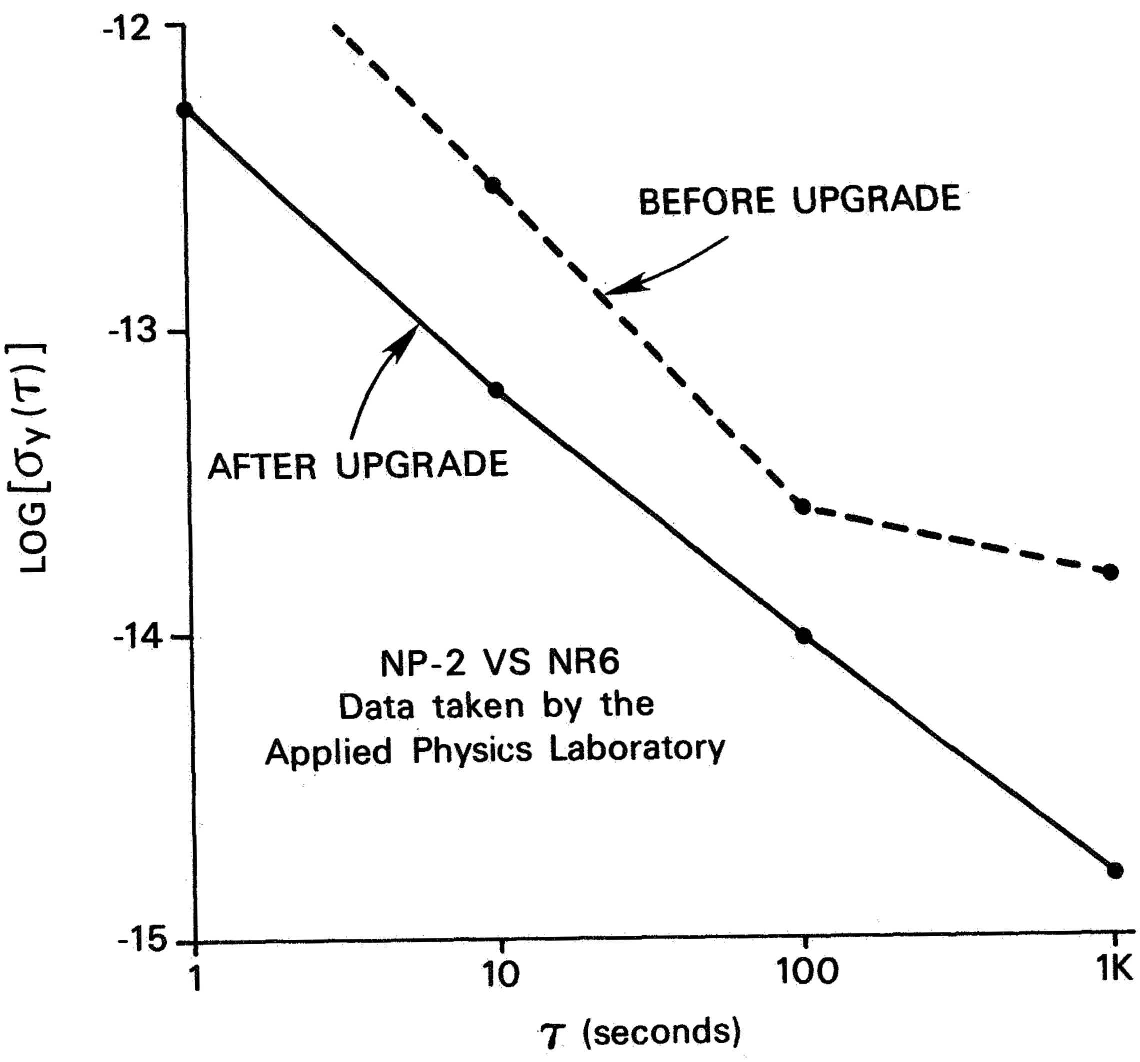


Figure 7. NP-2 Short Term Frequency Stability Before and After Upgrade

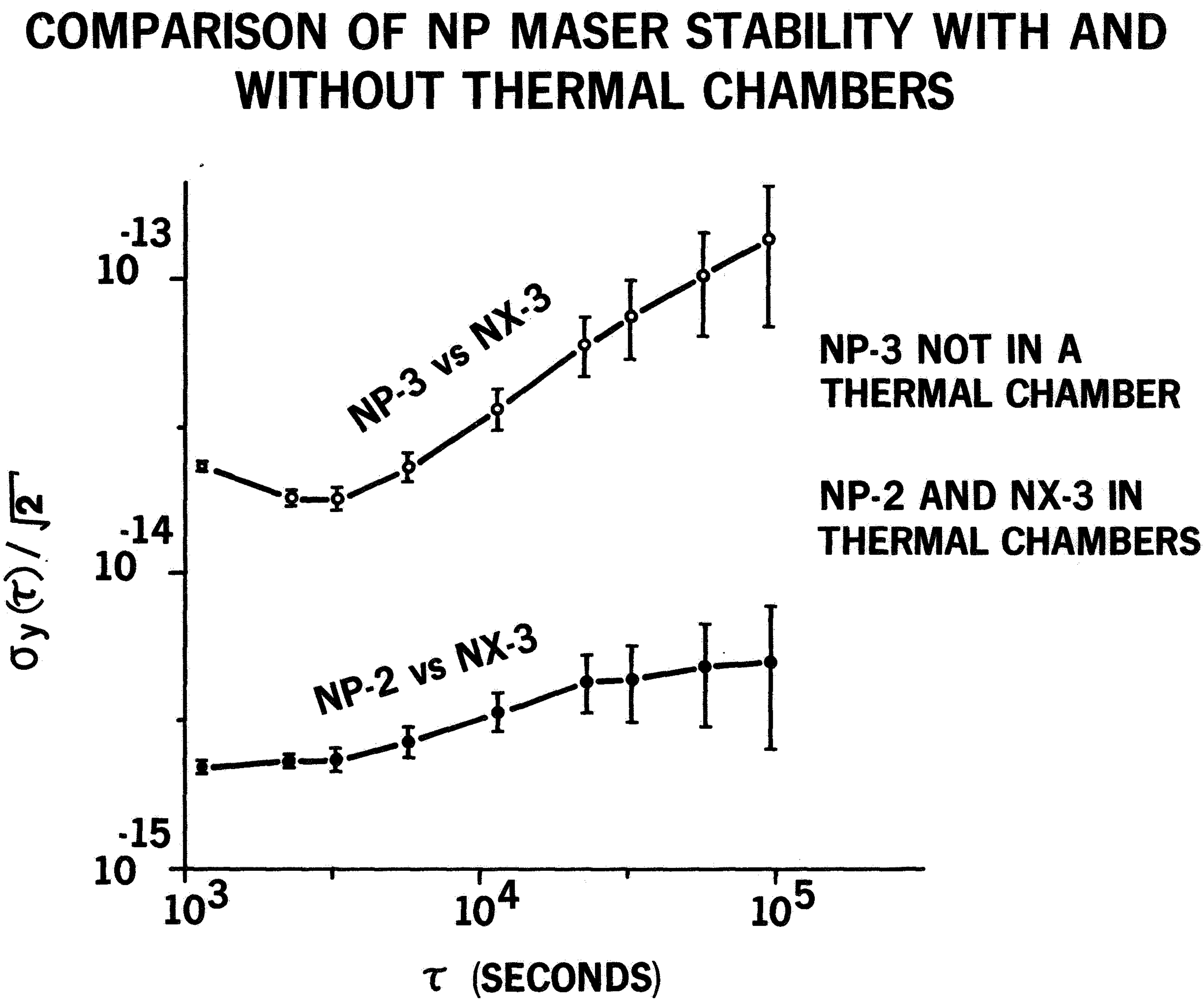


Figure 8. NP Maser Long Term Stability Before and After Upgrade

INTEGRAL FUSED QUARTZ CAVITY-STORAGE BULB

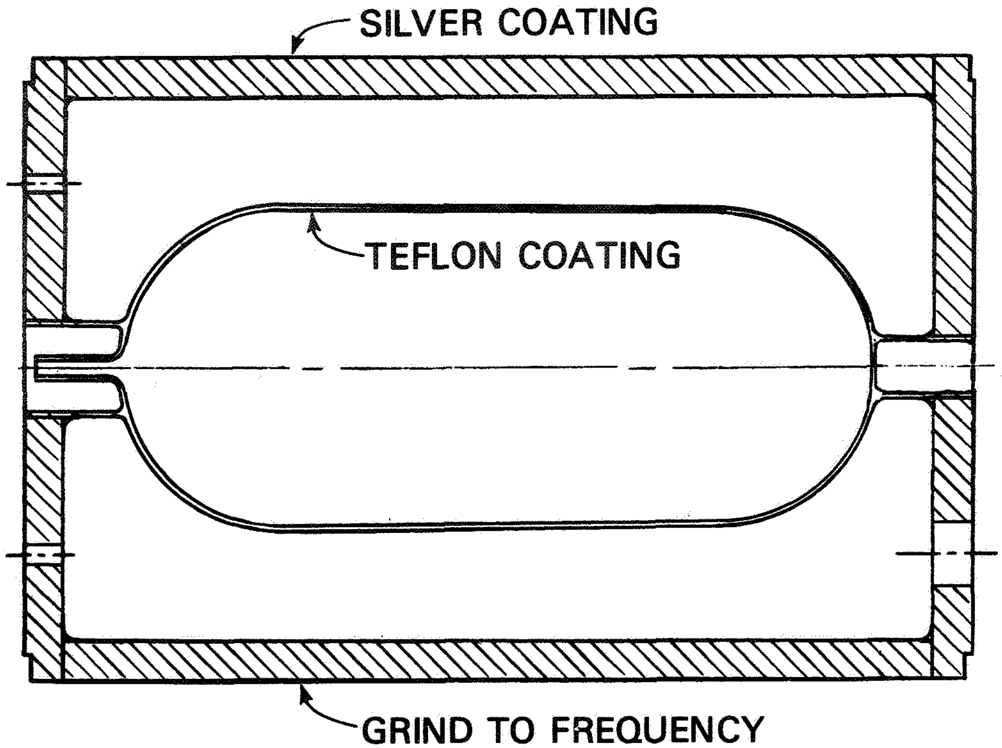


Figure 9. Hybrid Cavity Design

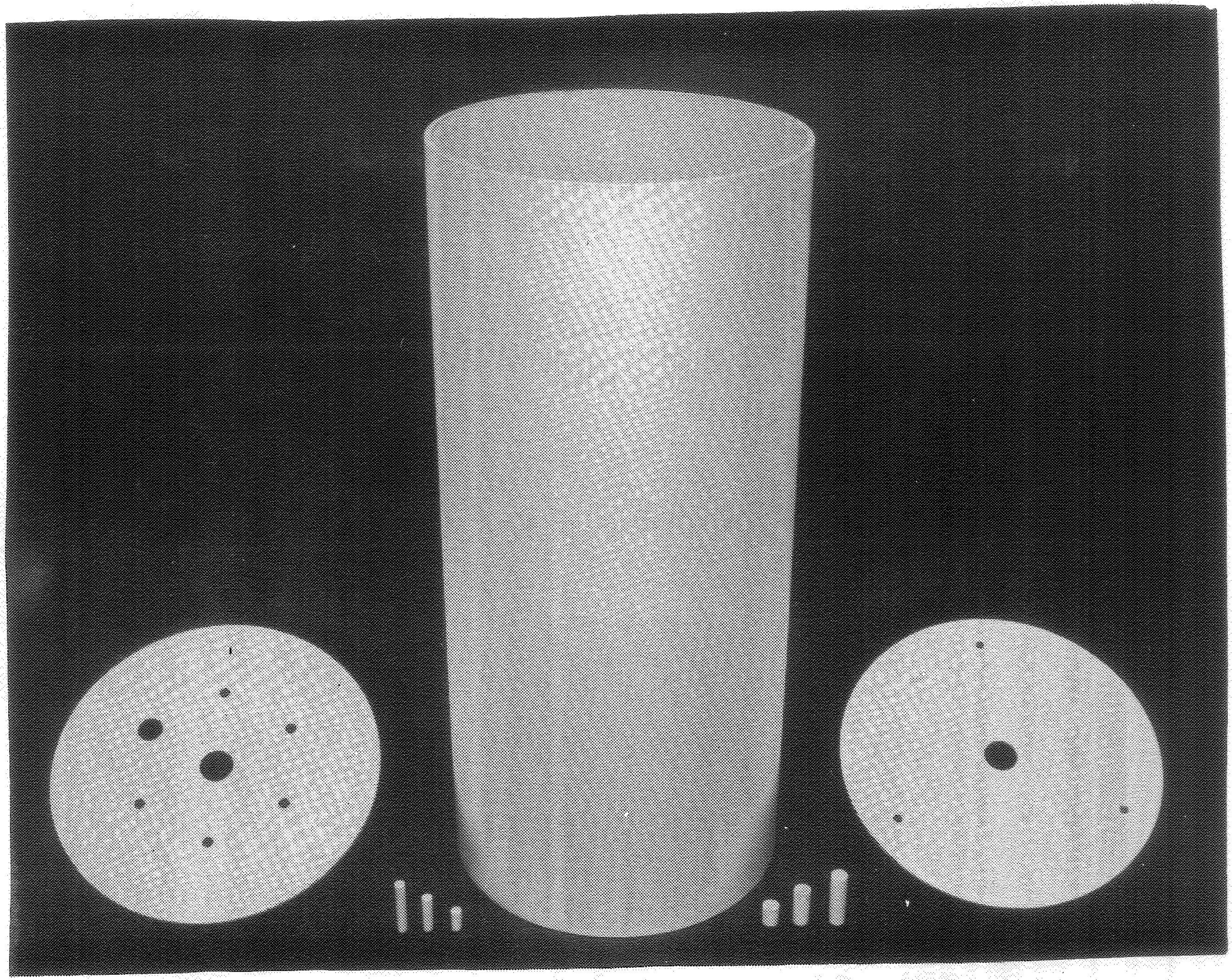


Figure 10. Integral Cavity for NP, NX, and NR Retrofit

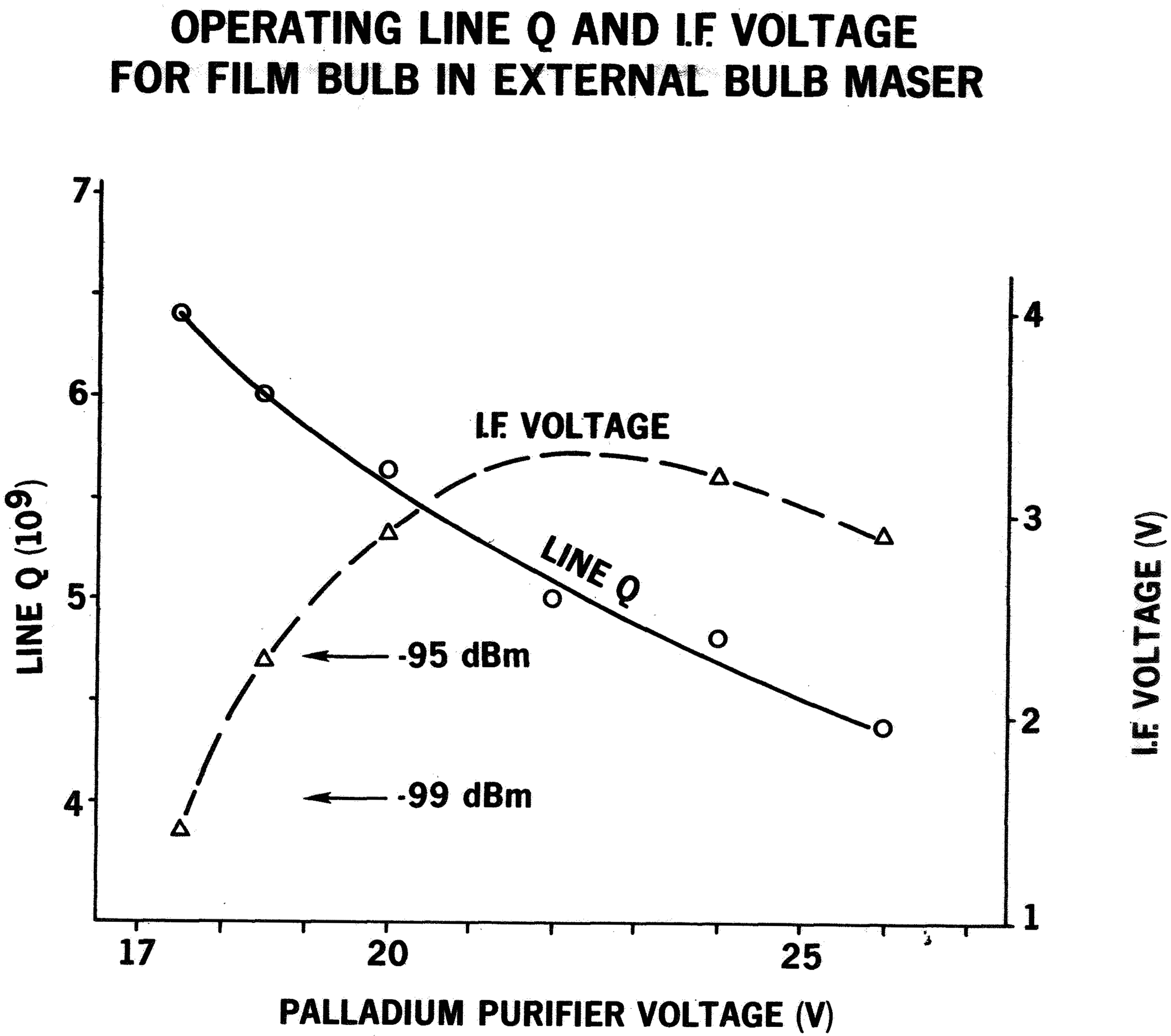


Figure 11. Line Q of External Bulb Maser with Film Storage Bulb Versus Hydrogen Flux

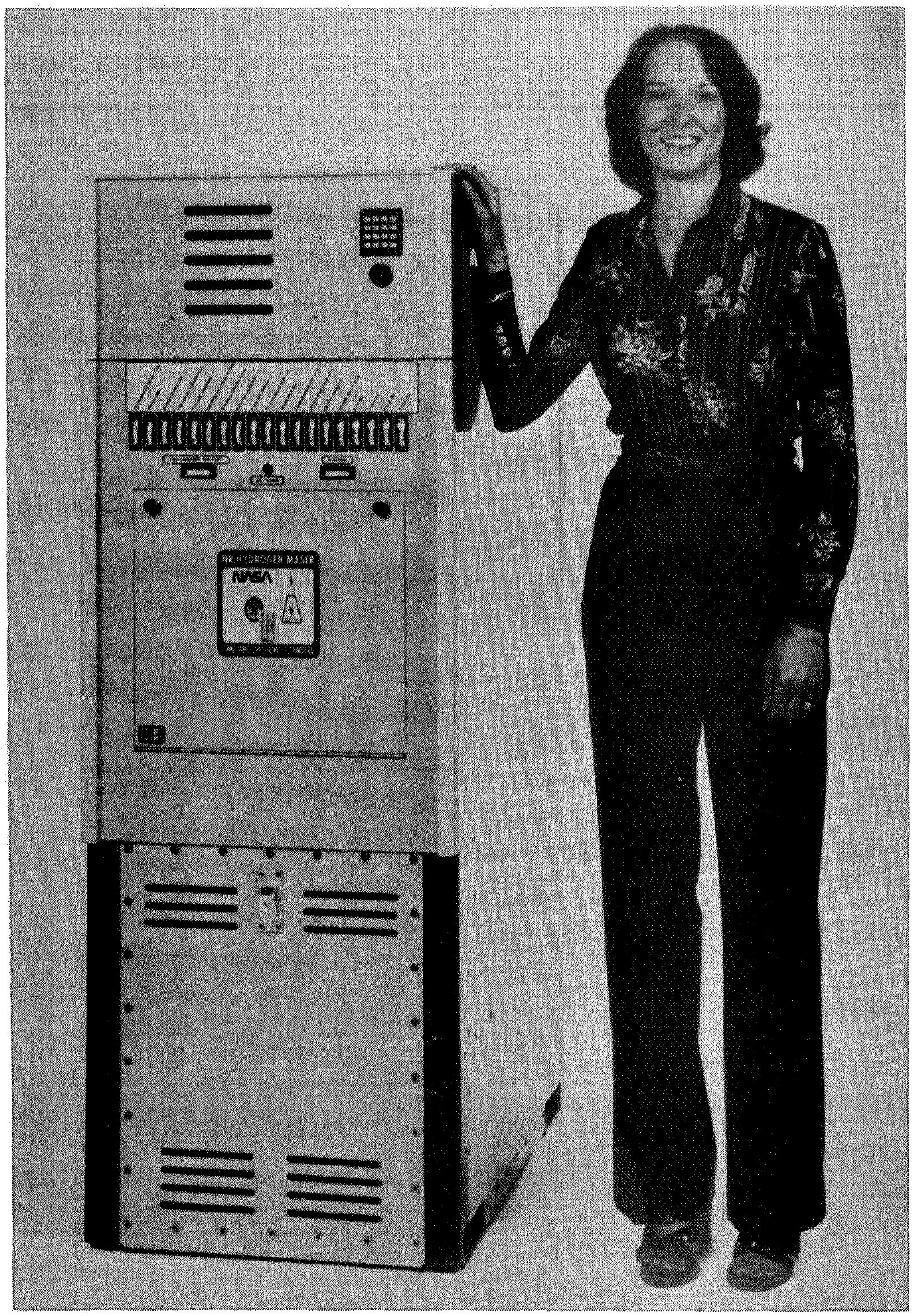


Figure 12. NR Maser

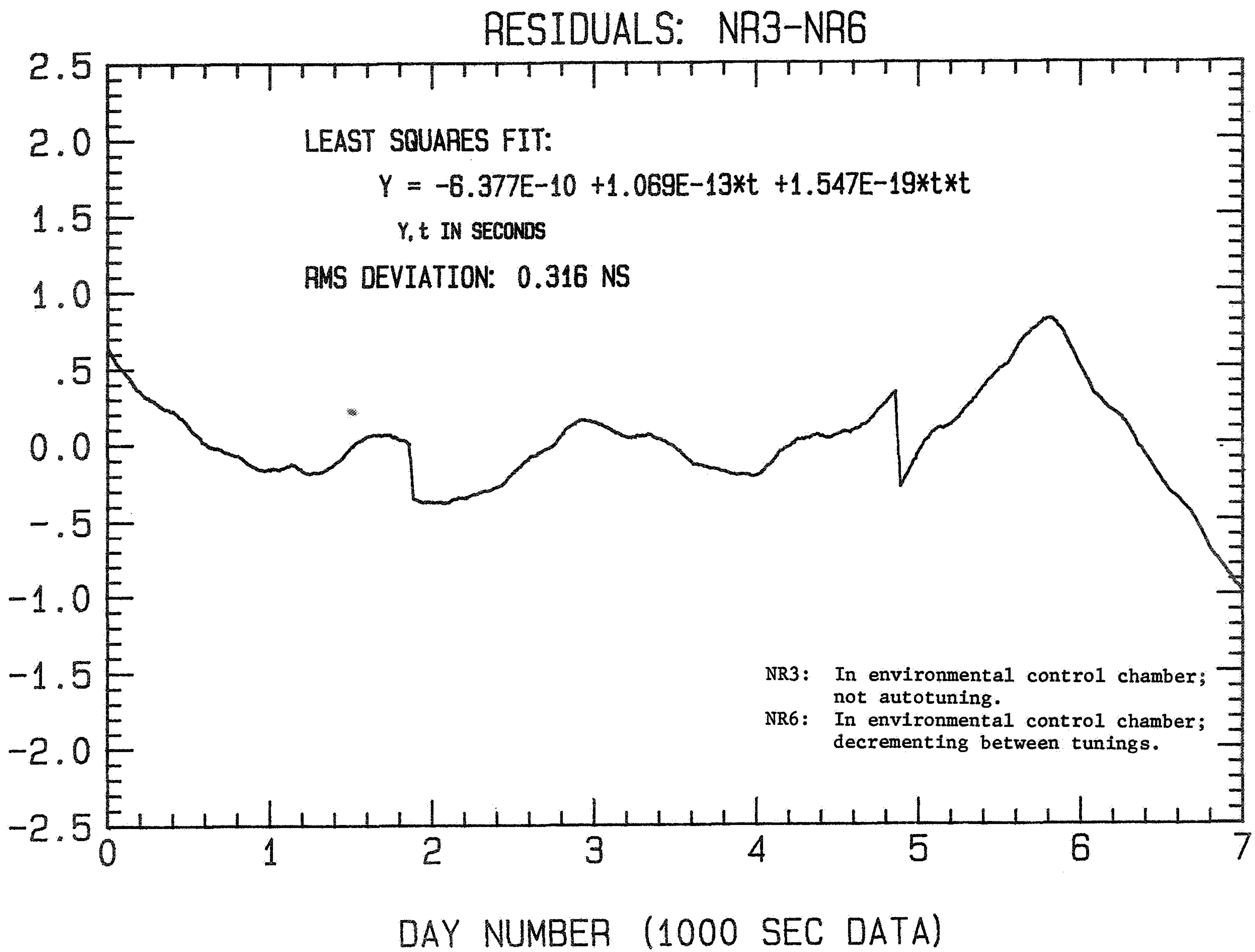


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Figure 13. Residuals to Least Squares Fit of Phase Difference Between NR-3 and NR-6, Over Seven Day Span

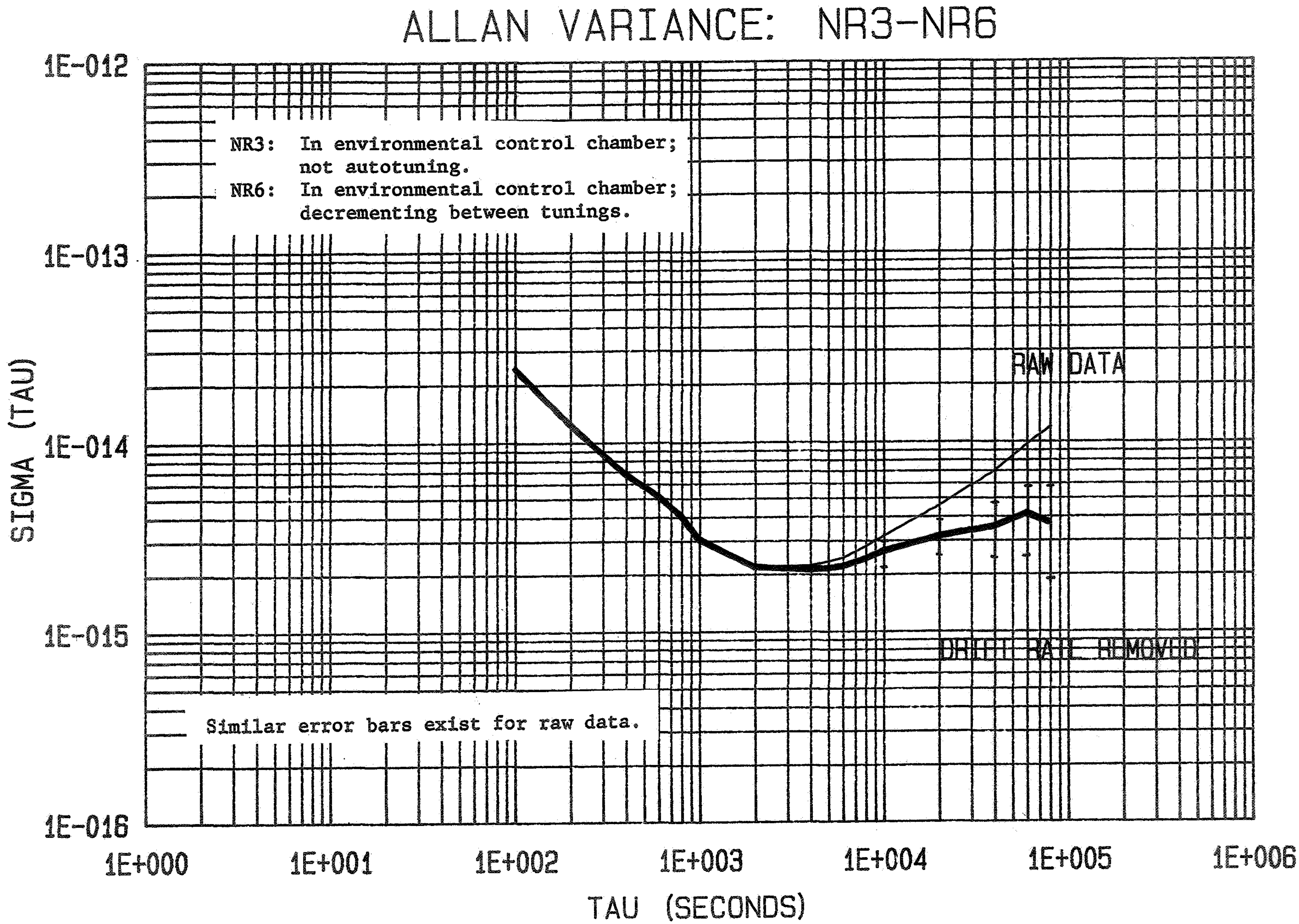

Figure 14. Allan Variance of (NR-3)-(NR-6), Removing the Two Discontinuities

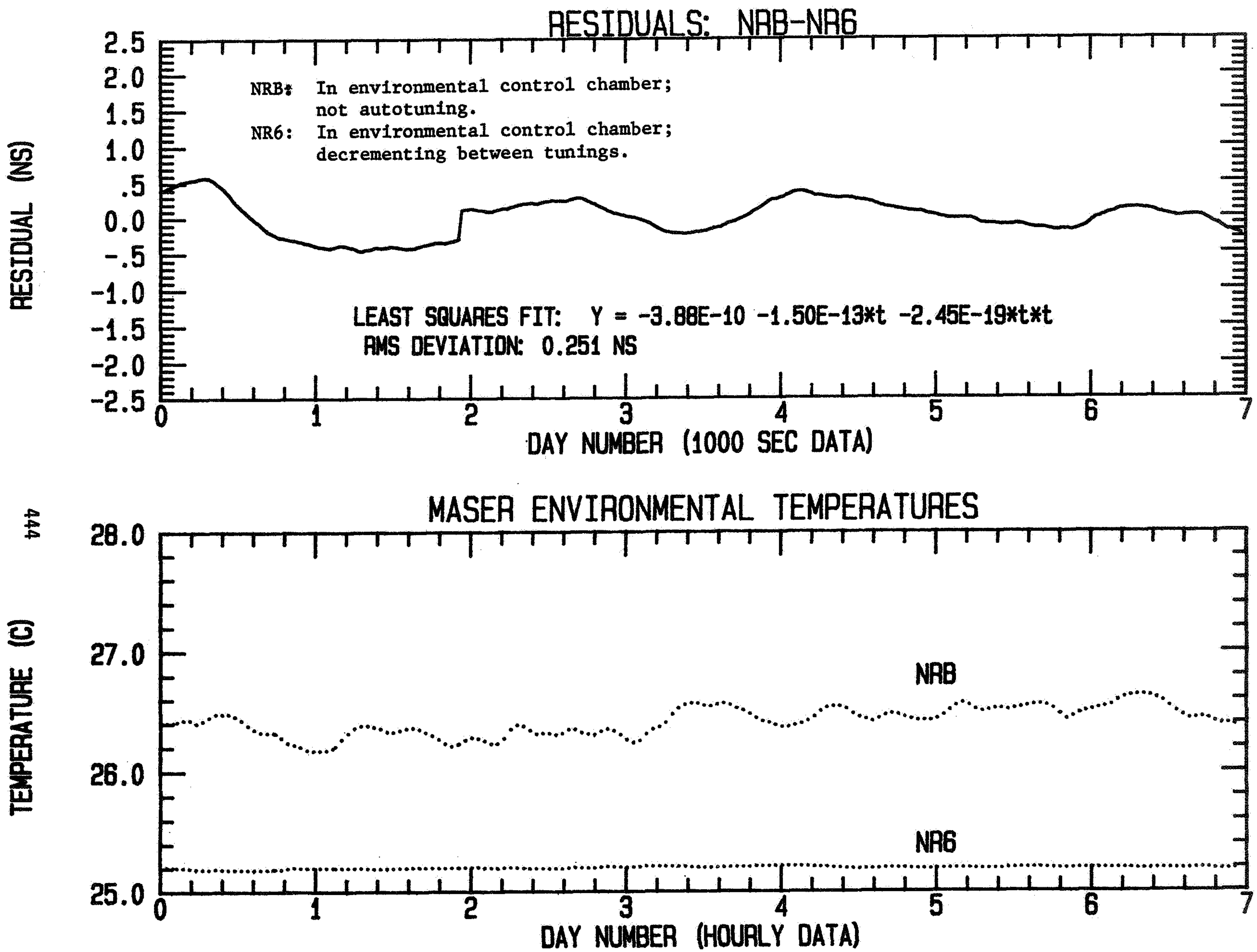

Figure 15. Residuals to Least Squares Fit of Phase Differences Between NR-B and NR-6

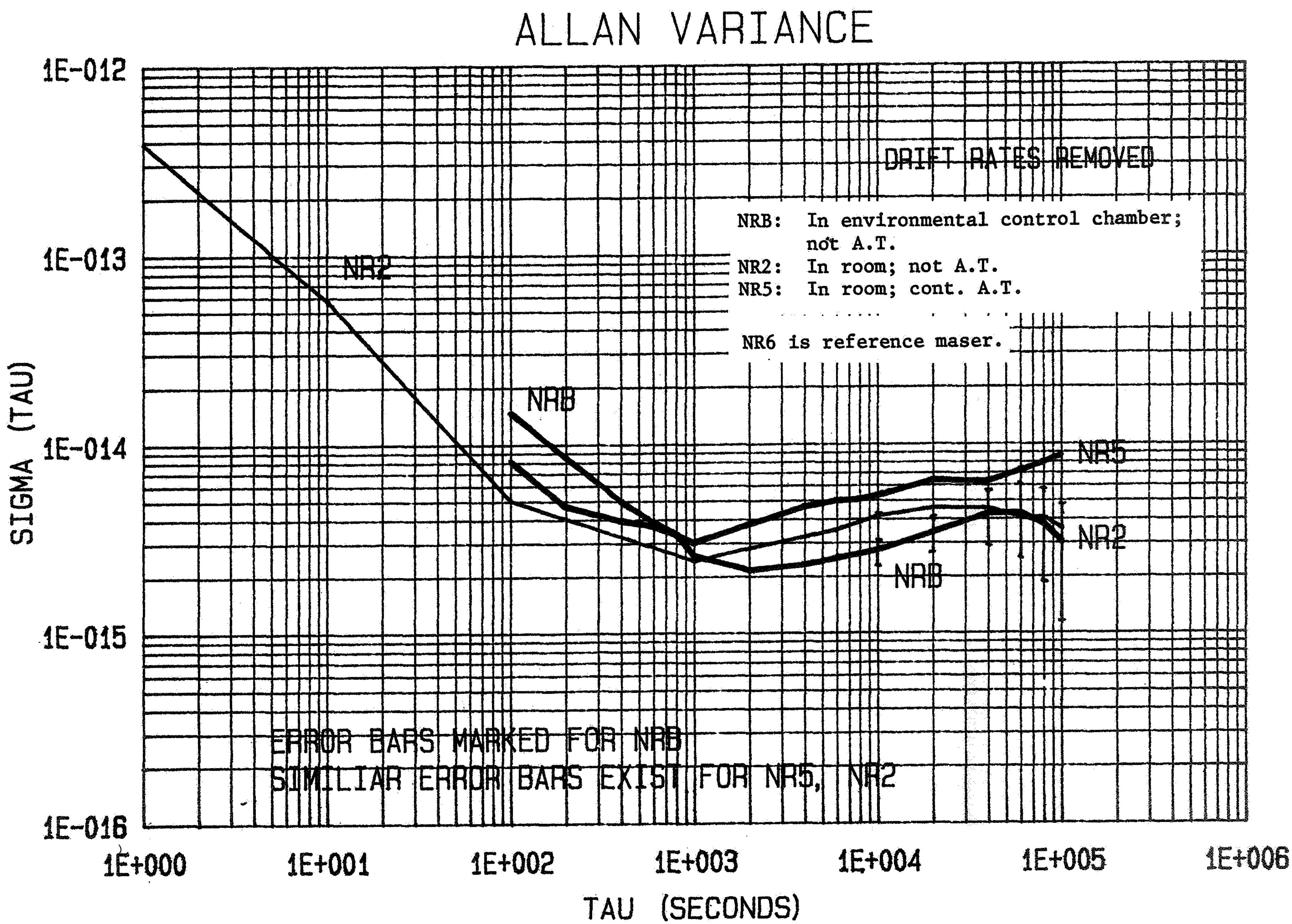

Figure 16. Range of Performance in Hydrogen Maser APL Has Completed

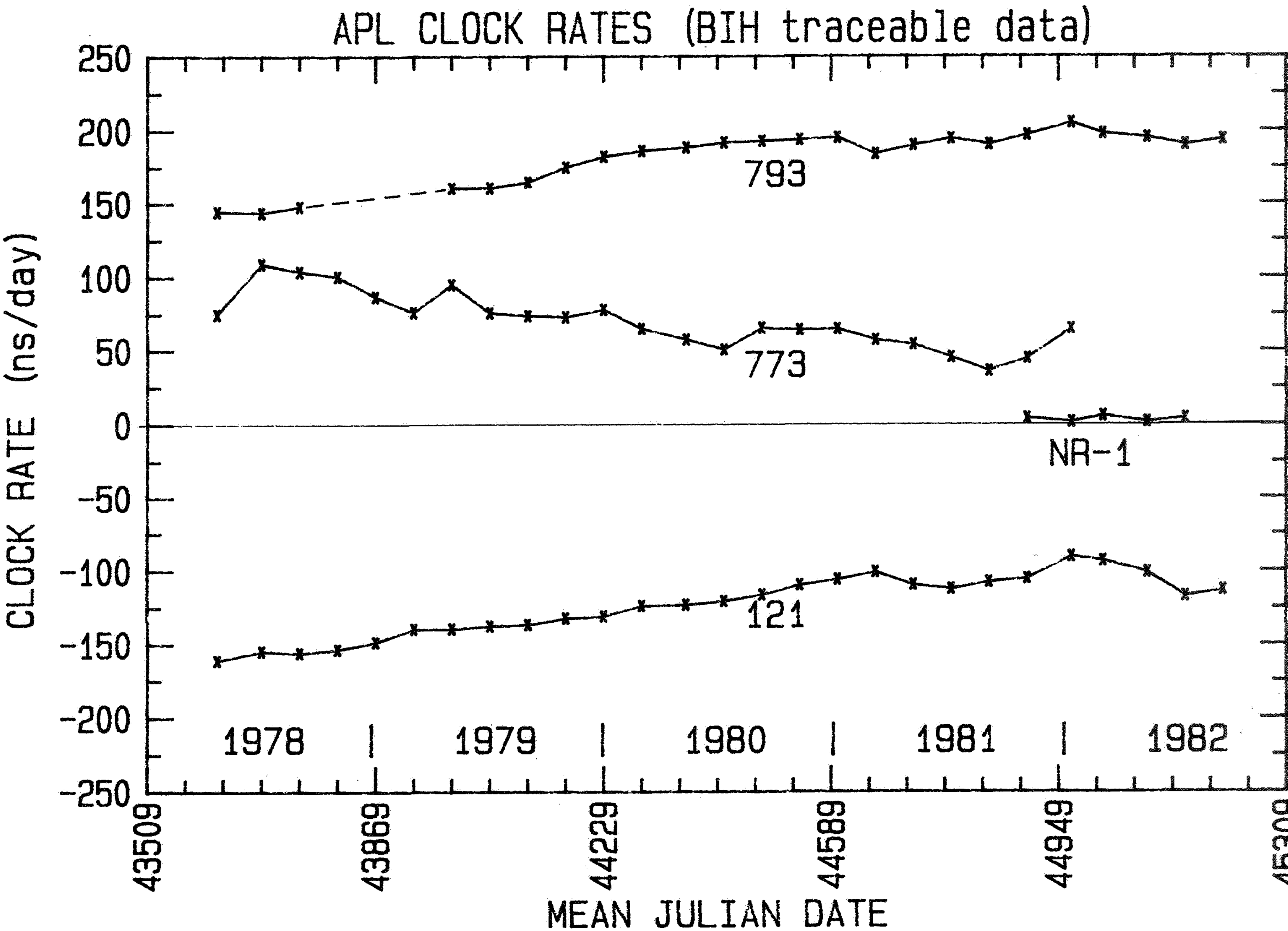

Figure 17. APL Clock Rates

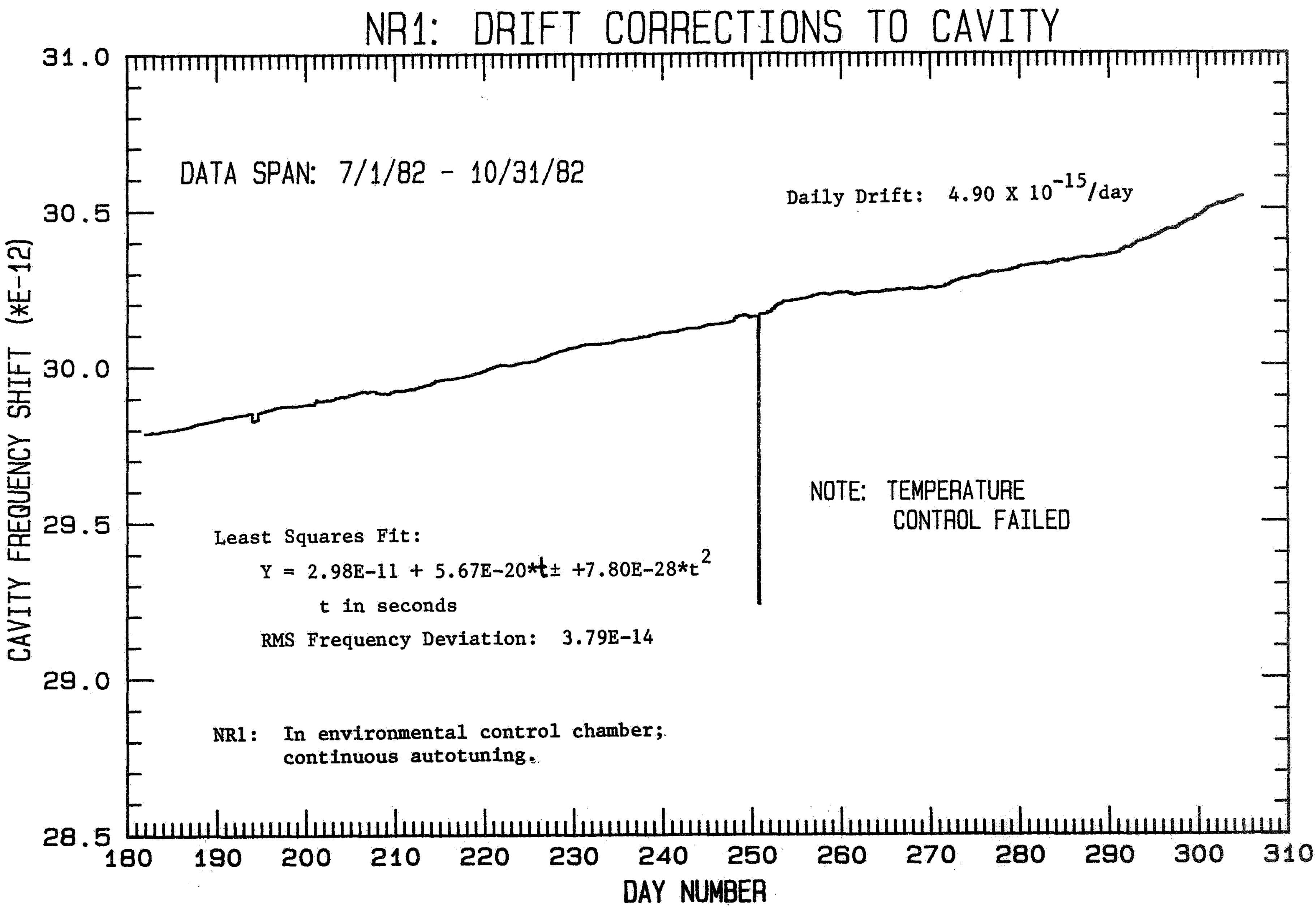

Figure 18. NR-1 Cavity Register Drift Corrections, Plotted Over Four Months

QUESTIONS AND ANSWERS

None for Paper #19

DR. COATES:

Earlier this afternoon, we were talking about frequency standards and clocks. From here on, we're talking about networks for synchronizing various clocks and, of course, you really have to have both in order to have viable precision time and time interval systems.

The first paper in this session is entitled, "Timing Subsystems Development/Network Synchronization Experiments" by Ken Backe.