STABILITY TEST RESULTS FOR GPS RUBIDIUM CLOCKS

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ABSTRACT

This paper presents the results of further long-term stability tests on two prototype GPS rubidium frequency standards. These tests, currently underway at the U.S. Naval Research Laboratory, have resulted in the highest stabilities yet reported for such devices. Both units have smooth, highly modelable drift under 2×10^{-14}/day and a stability of about 1×10^{-14} at 10^5 to 10^6 seconds.

INTRODUCTION

EG&G, Inc., began the development of a high-performance rubidium frequency standard (RFS) for the Global Positioning System (GPS) satellites in early 1980. The design of that unit was described at this conference in 1981[1] and the results of stability, performance, and environmental tests on two prototypes were presented at this conference in 1983[2] and 1985[3]. This paper presents the results of further stability tests currently underway at the Naval Research Laboratory (NRL).

The active work at EG&G on these GPS Rb clocks ended in July 1985, when the units were transferred to NRL. Since that time they have been running nearly continuously. Both of these units have now accumulated a failure-free operating time comparable to their 7.5-year design life, mostly under thermovac conditions.

TEST SETUP

The Rb frequency standards under test were installed together in a thermovac chamber[4] in the NRL Space Applications atomic clock laboratory. For the long-term stability tests, these clocks were operated at a constant +28° C baseplate temperature free of any deliberate environmental disturbances.

Phase and frequency measurements were made with an averaging time of 1 hour using a computer-controlled dual-mixer time difference measuring system[5]. The frequency reference for these measurements was an active hydrogen maser (N1)[6].

A photograph of the test setup is shown in Figure 1.

STABILITY TEST RESULTS

Figures 2-7 show the phase and frequency records for the two Rb clocks (EG&G1 and EG&G2) versus the NRL active H-maser reference (N1). The phase records (Figures 2 and 5) have the parabolic shape characteristic of a source having linear frequency drift, which is also visible in the frequency records (Figures 4 and 7). The drifts are very smooth and uniform and have least-squares fit values of -1.8 and -0.8×10^{-14}/day. Most of the largest frequency excursions (short spikes of about 2×10^{-13} peak) occur simultaneously on both records, and are therefore likely to be from the test setup. The largest drift-corrected phase excursions (about 20 nsec) are associated with small steps (under 1×10^{-13}) in the frequency record. Since there is no deterministic cause for such disturbances, these are the largest nonmodelable clock errors.

The stability of these GPS Rb clocks is also shown in the Allan variance plots of Figures 8-11. The nondrift-corrected plots (Figures 8 and 10) show a $\tau^{-1/2}$ white frequency noise characteristic (at a level of about $3 \times 10^{-12}\tau^{-1/2}$) and a τ^{+1} frequency drift characteristic, with a $\sigma_y(\tau = 10^5)$ seconds) of 1-2 x 10^{-14}, well below the GPS specification shown as the solid line. With the drift removed, this value of stability extends to 10^6 seconds, which, we believe, is the highest level of stability yet reported for a Rb clock. Both units have demonstrated this performance after many years of operation, and one (EG&G2) after two exposures to qualification levels of shock, vibration, and temperature cycling.

A summary of the stability test results is shown in Table I.

TEMPERATURE TEST RESULTS

The two Rb frequency standards were also subjected to a temperature stability test over their operating temperature range of +20 to +45°C. Both units showed excellent temperature insensitivity ($<1 \times 10^{-13}/°C$) over the low-temperature portion of this range, but both had anomalies at the high-temperature end. For EG&G1, this anomaly is due to a secondary loop crystal oscillator that loses oven control above +35°C. For EG&G2, the high-temperature problems seem to be caused by internal temperature rise due to poor thermal transfer between the internal RFS chassis and the thermovac baseplate. Previous tests on this unit showed a temperature sensitivity of $-1 \times 10^{-13}/°C$ over its entire operating temperature range.

DESIGN FACTORS

The very high performance of the EG&G GPS RFS is an expected result of its design, which is carefully implemented using classical RFS principles. The low level of white frequency noise is directly related to the high signal-to-noise ratio of the discriminator signal. The low environmental sensitivity is a result of careful error budget analysis relating to the physics package and electronic sensitivities (such as C-field stability and Rb cell temperature coefficients). The low drift is primarily a result of careful control of such physics package parameters as light and rf power shifts. For example, the lamp exciter is both voltage and current regulated; the lamp is well heat-sunk and temperature-controlled; and the discrete filter cell is adjusted to achieve a very close-to-zero light shift coefficient.

Lamp life tests are continuing at both EG&G and Aerospace Corporation using differential scanning calorimetry to measure their Rb consumption.[7] Over a 6-year test period these lamps have consistently shown a low Rb consumption rate ($0.2\ \mu\text{gram}/\sqrt{\text{hour}}$) without random failures, thus allowing a relatively low fill (100 μgram) for low noise while assuring a long life ($\geq$ 20 years).

The RFS is specifically designed and adjusted for best performance under vacuum, where the light and signal parameters are optimized, the ovens have their highest stabilization factors, and the unit is freest of such perturbations as thermal gradients and barometric sensitivity. These, and other, design considerations have also resulted in a unit that is remarkably free of the frequency jumps and wandering that usually limit the medium-term stability and modelability of Rb frequency standards. There is, therefore, good reason to believe that the performance of these two prototypes can be duplicated or exceeded as further experience is gained as more units are built.

CONCLUSIONS

This paper has presented the results of further stability tests on two prototype GPS Rb clocks. These units have consistently displayed low drift and scatter (1×10^{-14} at 10^5 to 10^6 seconds), a level of performance not normally associated with rubidium frequency standards. Such performance makes possible the wider use of Rb clocks in demanding applications where their intrinsic advantages of light weight, small size, low power, and long life can be combined with high stability.

REFERENCES

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3. S. Goldberg, T.J. Lynch and W.J. Riley, "Further Test Results for Prototype GPS Rubidium Clocks," Proceedings of the 17th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, pp. 145-155, December 1985.

4. Data Sheet, Model TVC-1A Thermovac Chamber, Kernco Inc., Danvers, MA.

5. S.R. Stein and G.A. Gifford, "Software for Two Measurement Systems," Proceedings of the 38th Annual Symposium on Frequency Control, pp. 483-486, June 1984.

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TABLE I. SUMMARY OF STABILITY TEST RESULTS

Parameter	Units	EG&G1	EG&G2
Record Length	Days	40	40
Average Frequency Offset	pp10^{12}	-1.4	-0.4
Average Frequency Drift	pp10^{14}/Day	-1.8	-0.8
Largest Drift-Corrected Phase Deviation	nsec	+23	-7
Largest Drift-Corrected Frequency Deviation	pp10^{13}	-2.7	-2.3
Drift-Corrected	1 Hour	4.4	5.0
Allan Deviation	1 Day pp10^{14}	1.4	1.3
(Sigma)	10 Days	3.4	1.0

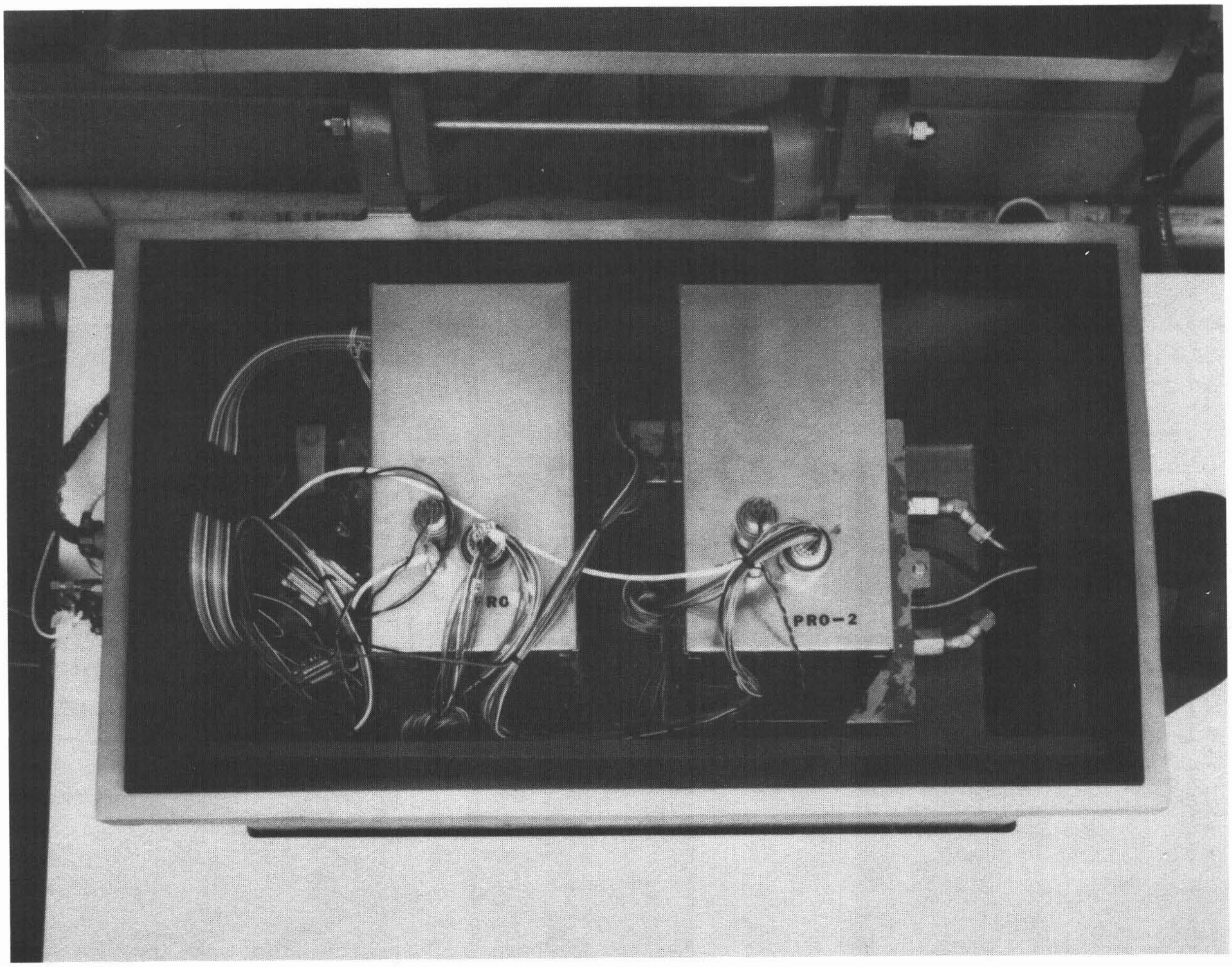

Figure 1. EG&G GPS RFS prototypes in thermovac chamber.

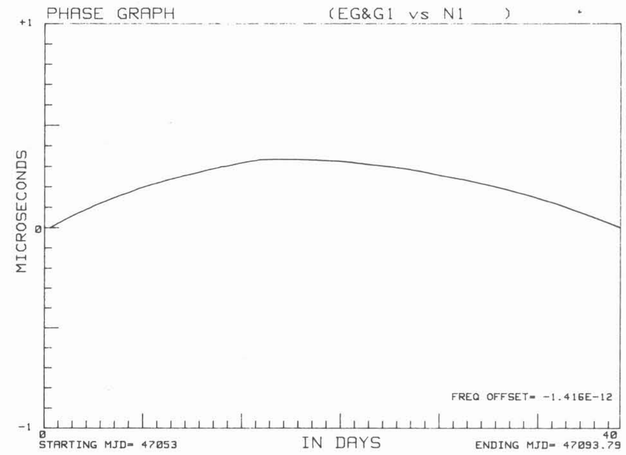

Figure 2. EG&G1 phase record.

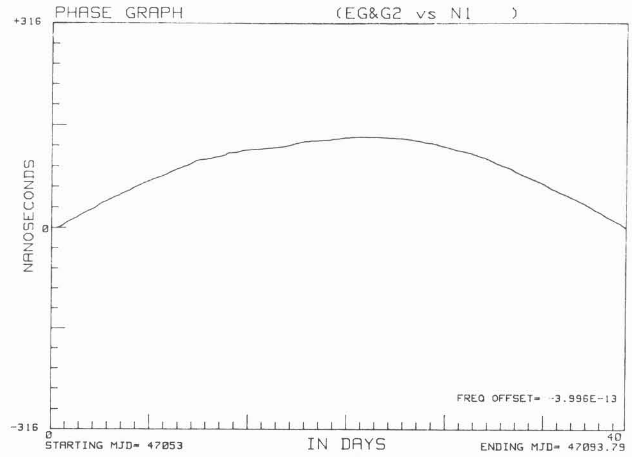

Figure 5. EG&G2 phase record.

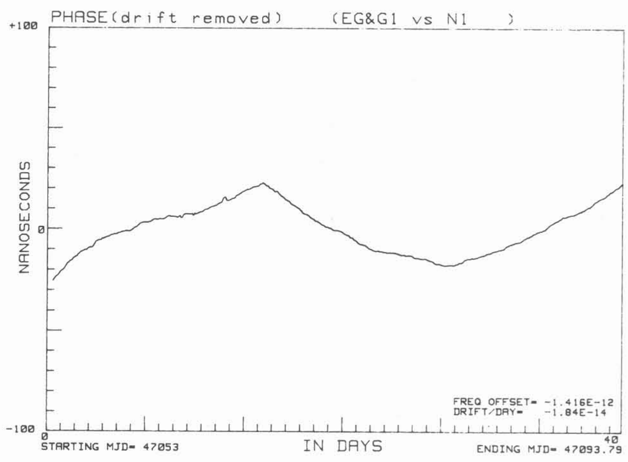

Figure 3. EG&G1 drift-corrected phase record.

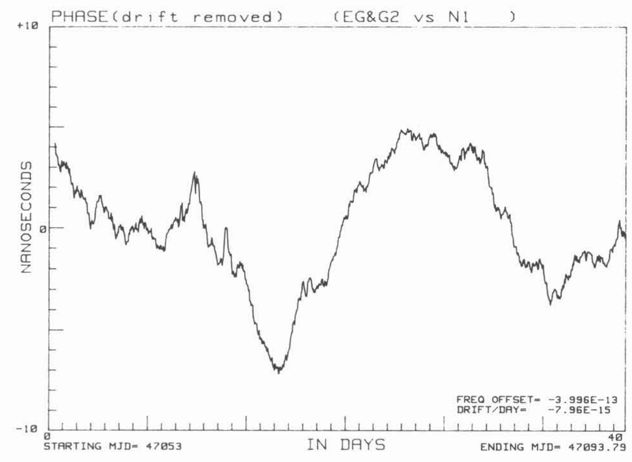

Figure 6. EG&G2 drift-corrected phase record.

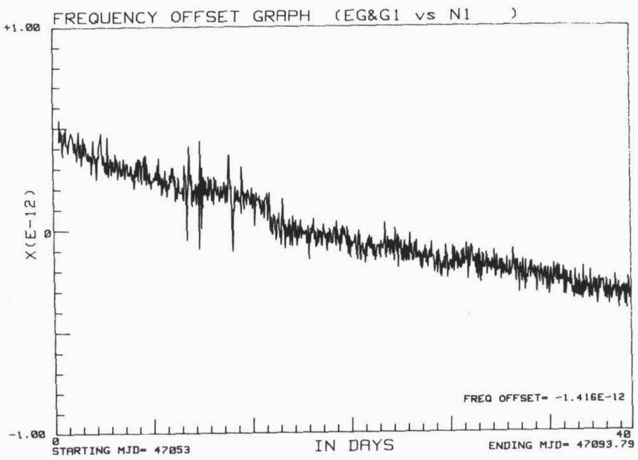

Figure 4. EG&G1 frequency record.

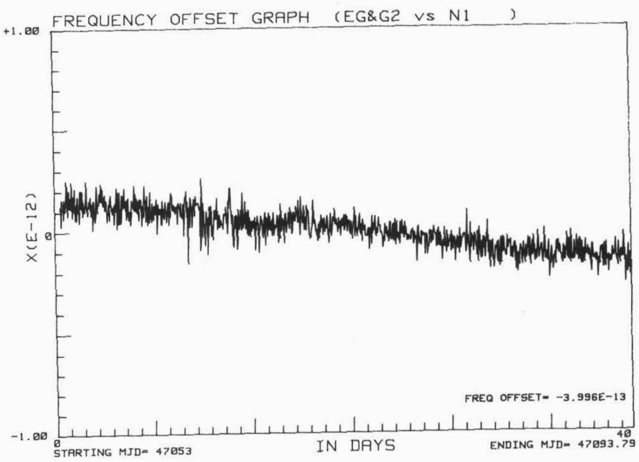

Figure 7. EG&G2 frequency record.

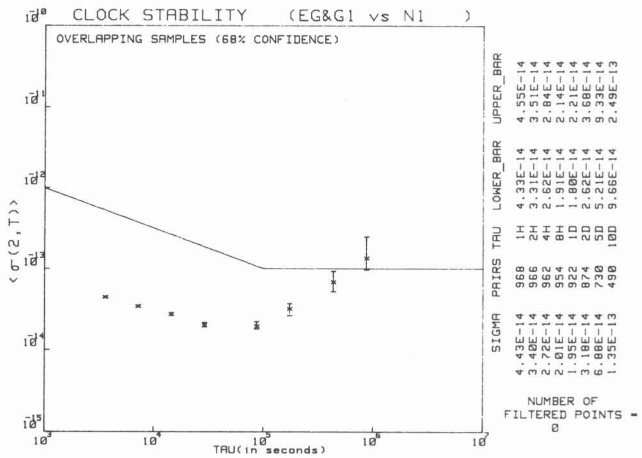

Figure 8. EG&G1 stability plot.

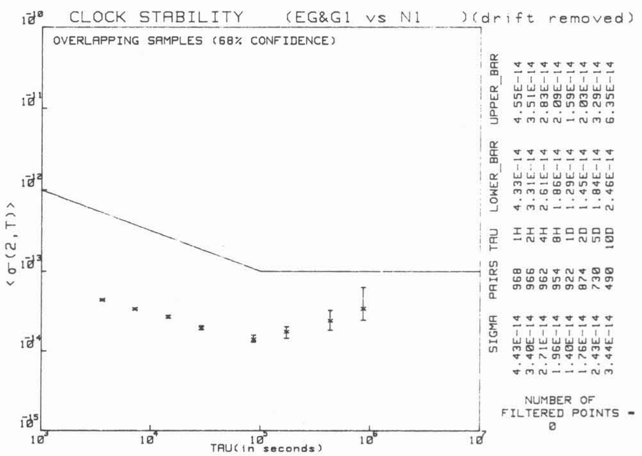

Figure 9. EG&G1 drift-corrected stability plot.

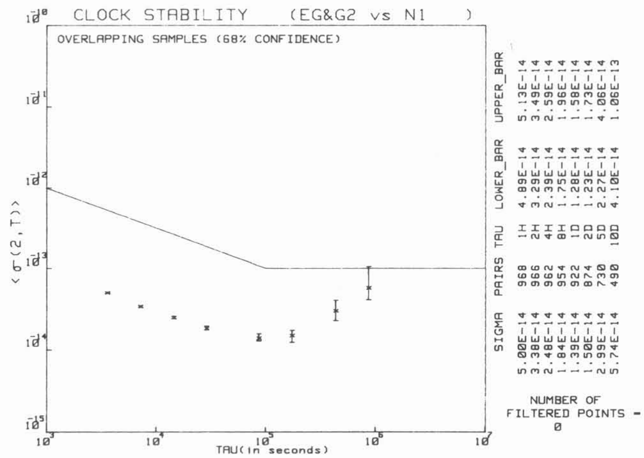

Figure 10. EG&G2 stability plot.

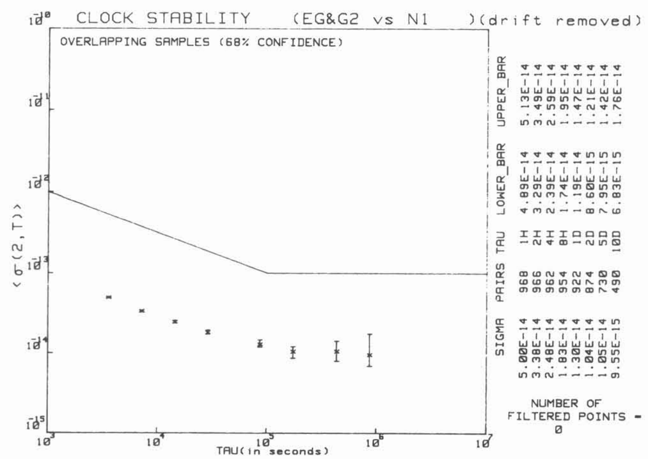

Figure 11. EG&G2 drift-corrected stability plot.

QUESTIONS AND ANSWERS

Brad Parkinson, Stanford University: Were these clocks vibrated in a launch type of environment prior to the tests?

Mr. Riley: Yes, one of them was. The history of these clocks has been published in prior PTTI Proceedings. One of these clocks was subjected to levels somewhat above qualification levels. This testing started after those tests. The other one had been subjected to prior stability testing at NBS and other places, but no mechanical abuse. The second one was the better of the two and it had had the qualification test.

Robert Frueholtz, The Aerospace Corporation: Do you have any idea what the variance on your drift coefficient is? How stable was it over the time of analysis?

Mr. Riley: It's probably a 10%, maybe a 20% change from the beginning to the end of the record. Certainly, if you take one of these units and turn it on after it has been off for a while, even if it has run for an extended period of time, you would expect a period of about two weeks for it to get back on an aging track again. From then on, you would expect no more than a 10% change in that over a period of a month.

David Allan, National Bureau of Standards: For a 40 day data length, the ten day number for σ_y will be biased due to the removal of the frequency drift, so I think that that is not a fair number. Let me just say congratulations for the best data that I have ever seen on a rubidium. It is fantastic.

Mr. Riley: Thank you, Dave. I am glad that you said that. The first point, that is. In the testing that was done at NBS, which was 140 days, the maximum likelihood analysis showed that the act of removing the drift removes some of the noise component for periods of time that are a large part of the record length. It didn't seem to make a big difference, though. A factor of maybe 1.5 or so.

Mr. Cutler: I have to congratulate you also for the best data that I have ever seen also.

Mr. Riley: Thank you, Len.

Jess Myers, Bendix Corporation: You mentioned larger cells. Were there any other things done to get these fantastic results?

Mr. Riley: I would say that the next most important thing would certainly be the operating temperature. The absorption cell here operates at 65 degrees. The typical operating temperature in the small military units is about 80 degrees because one faces upper ambient temperatures of about 68 degrees on the baseplate. Sixty–five degrees turns out to be an ideal temperature for a rubidium cell to operate at. It is also consistent with the 45 degree upper baseplate temperature for GPS. If you go up just ten degrees above the 65 degrees, you would lose signal–to–noise ratio very significantly.

Mr. Allan: How much of that noise is the flicker floor in N1?

Mr. Riley: I certainly don't want to stand up here and start talking about a contest between rubidiums and hydrogen masers. If you did look at the data on the N1 maser, it is in the references in the paper for the N1 which is a Harry Peters, Sigma Tau Corporation maser, there was some data against a Bob Vessot maser and the numbers are practically the same.