

FURTHER TEST RESULTS FOR PROTOTYPE GPS RUBIDIUM CLOCKS

S. Goldberg, T.J. Lynch and W.J. Riley
EG&G, Inc.
Salem, Massachusetts

ABSTRACT

This paper presents the results of further stability and qualification-level environmental tests on two prototype rubidium frequency standards for the GPS navigation satellite program.

One unit was subjected to a 140-day thermovac stability retest that confirmed the efficacy of two improvements that reduce frequency drift and frequency and light intensity fluctuations. The observed drift was -1.4×10^{-14} /day and the stability was 6×10^{-14} at 10^5 seconds. This was accomplished by using an absorption cell made from glass having low helium permeability and a lamp having a lower (normal) rubidium fill.

The other unit was successfully subjected to qualification levels of thermal, mechanical and EMI retesting. Several electrical, high temperature, and mechanical problems associated with the ovenized crystal oscillator were corrected. Improved design and filtering of the control/monitor cable and power supply satisfactorily resolved several EMI problems.

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) This paper describes the results of further tests on these units. During this latest effort, several design changes were made to correct previous deficiencies and to improve performance. This has resulted in a fully compliant device with exceptional stability(3).

CONTINUATION PROGRAM OBJECTIVES

The results of the previous stability, performance and environmental tests were excellent, but did leave several questions and problems unresolved.

The purpose of the latest continuation effort was to resolve these matters. The specific objectives were as follows:

1. Investigate and improve the frequency drift and frequency and light intensity jumps observed during stability testing at NBS.
2. Confirm the corrective actions taken to fix several deficiencies in the secondary loop crystal oscillator.
3. Investigate and correct the deficiencies found in the EMI characteristics of the unit.
4. Perform qualification-level retesting to verify the adequacy of the overall RFS package with improvements to meet the specified environmental conditions.

All these objectives were met as described in the following paragraphs.

STABILITY IMPROVEMENTS

During the previous long-term thermovac stability testing, both prototype units had a drift of about -2×10^{-13} /day, twice the specification of $\pm 1 \times 10^{-13}$ /day. An extensive analysis effort ruled out many possible causes of this drift.⁽⁴⁾ Then helium permeation through the absorption cell envelope was identified as a possible cause of the observed drift. EG&G conducted experiments that verified helium permeation as a significant drift factor (see Appendix). The Continuation Program therefore included the substitution of absorption cells with less permeable glass and a 140-day stability retest to confirm the expected improvement in drift.

The original Prototype No. 1 absorption cell, S/N 663, had an envelope made from Corning No. 7070 borosilicate glass, chosen primarily for its low dielectric constant (4.1) and low electrical loss factor (0.06% at 1 MHz and +20°C). This glass, however, has a relatively high helium permeability (2×10^{-10} cc (STP)/sec/cm²/mm/cm Hg at +70°C). A similar borosilicate glass, Corning No. 7056, has a helium permeation rate about 50 times lower. Thus the effect on frequency drift of helium diffusing at first into the cell during storage and test in air, and then out of the cell during operation in vacuum, which is significant for a No. 7070 cell, can be reduced to a negligible factor by using No. 7056 glass. The higher loss (0.15%) of this material is not a problem. Its higher dielectric constant (5.7) can be compensated for by using thinner glass. The only disadvantage of the thinner glass is a somewhat higher (10 vs 7×10^{-11} /atm) barometric coefficient, which is not important during constant vacuum operation.

A new absorption cell, S/N 1216 having an envelope made from No. 7056 glass with thinner walls (0.045 in. vs 0.060 in.) and windows (0.045 in. vs 0.075 in.) was therefore substituted into Prototype No. 1. A similar cell also replaced the original one in Prototype No. 2.

This change was highly successful. The drift observed during the last month of the stability retest was -2×10^{-14} /day, as shown in Fig. 1. This is one-fifth the specified value, and an improvement of ten-to-one.

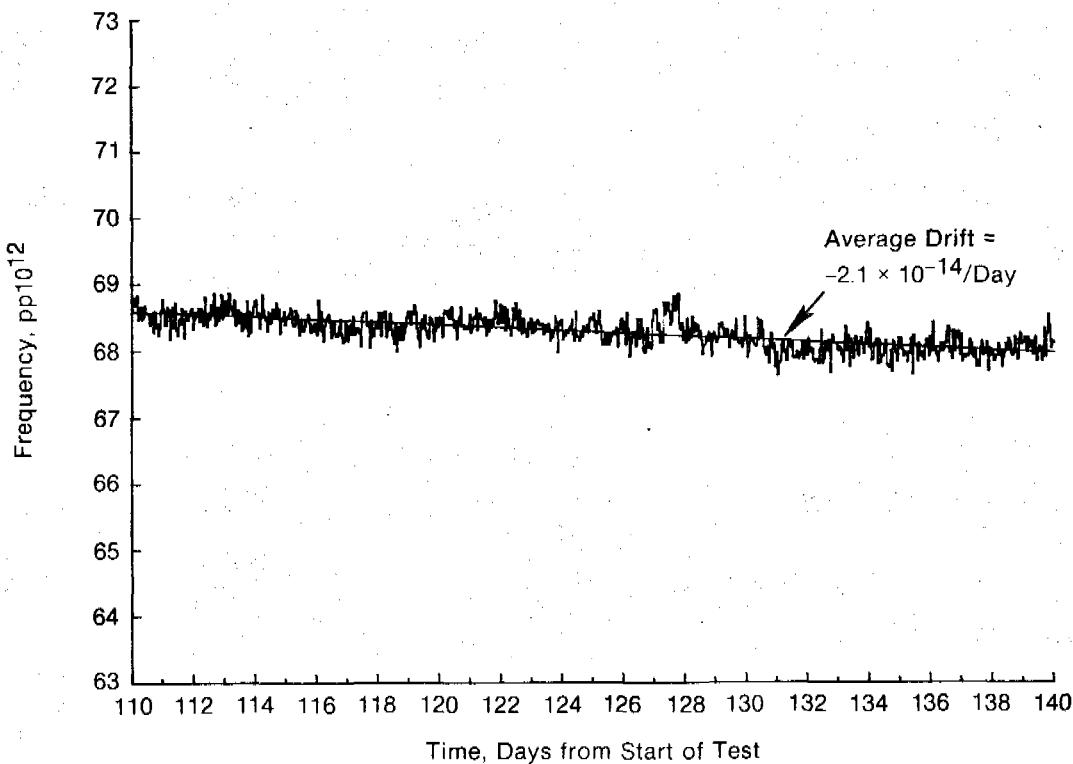


Fig. 1 - EG&G GPS RFS P-1 stability test in thermovac 2/12/85 to 3/12/85 (last month).

During the previous long-term stability testing at NBS,⁽⁴⁾ Prototype No. 1 showed frequency jumps of about 5×10^{-13} which were associated with jumps in light intensity having a period of about 3 weeks. These jumps were the major limitation to the modelled stability. All evidence indicated that the excessive Rb fill in the lamp was the reason for the instability. There were no such frequency jumps or light fluctuations in Prototype No. 2, which had a normal lamp Rb fill.

The original Prototype No. 1 lamp, S/N 719, which had a high (474 μ gram) Rb fill, was removed on October 11, 1984. Visual inspection indicated that most of the rubidium was located in the relatively cool upper tip of the lamp in a "pool." Just below the edge of the pool, were dots of rubidium. In the area where the rubidium extended farthest down the side (even beyond the dots), the front of the rubidium deposit was shaped like a drip. This appearance supported the explanation that the frequency jumps observed at NBS were due to light increases caused by the sudden flow of rubidium, under the action of gravity, onto hotter surfaces of the lamp and then the gradual return to the cooler tip of the lamp through vaporization and condensation.

The Continuation Program therefore included the substitution of a lamp having normal Rb fill into Prototype No. 1 before performing its stability retest. The new lamp (S/N 990) had a normal Rb fill (103 μ g). It was burned in for about 11,000 hours (\approx 15 months) in a test fixture and its Rb consumption was measured

using calorimetry.(5) A 22-year life is predicted for this lamp (using the most pessimistic \sqrt{t} model), so this Rb fill is definitely adequate to ensure lamp life for the 7.5-year GPS mission.

This change was also highly successful. No light intensity jumps were observed at any time during the 140-day stability retest. The unit displayed a stability of 6×10^{-14} at 10^5 seconds, well below the 2×10^{-13} requirement.

STABILITY RETEST

The purpose of the stability retest on Prototype No. 1 was to confirm the improvements made as a result of the frequency drift and jump investigations. This 140-day stability retest was conducted under thermovac conditions at EG&G between October 10, 1984 and March 12, 1985. The test set-up is shown in Fig. 2. The major elements of the RFS test set-up are as follows:

1. thermovac chamber with baseplate temperature controller,
2. dc power supply and battery for RFS,
3. ground tuning simulator,
4. frequency measuring system,
5. monitor data logger, and
6. uninterruptible power system for computer.

The test set-up is similar to the one used for the original stability test at NBS.(4) The main difference is that the reference for the frequency measurements is a single cesium beam standard. This is adequate to determine the frequency drift and jump characteristics of the RFS under test, but the single cesium reference has insufficient stability to define the short- and medium-term performance of the RFS.

The complete frequency record for the 140-day stability retest of Prototype No. 1 is shown in Fig. 3. This record shows the $\tau = 1$ hour frequency data versus a HP 5061A option 004 cesium standard. The gaps in the record are due to failures of the thermovac chamber, the frequency measuring system, or unlock of the cesium standard. The longest gaps in the record are during periods of partial loss of vacuum. The excursions at days 70-71 are due to the RFS itself. The short-term scatter is determined primarily by the cesium reference.

The record begins on October 22, 1984 shortly after turn-on and pump-down, following installation of a new lamp and absorption cell. The new lamp replaced one having excessive rubidium fill that caused occasional jumps in light output and frequency. The new absorption cell replaced one made from a type of glass more permeable to helium, which was the dominant drift factor.

The unit required about 1 week to settle in frequency and about 3 weeks to reach a steady drift below the $1 \times 10^{-13}/\text{day}$ specification limit. Operation was uneventful for the first 48 days of the test.

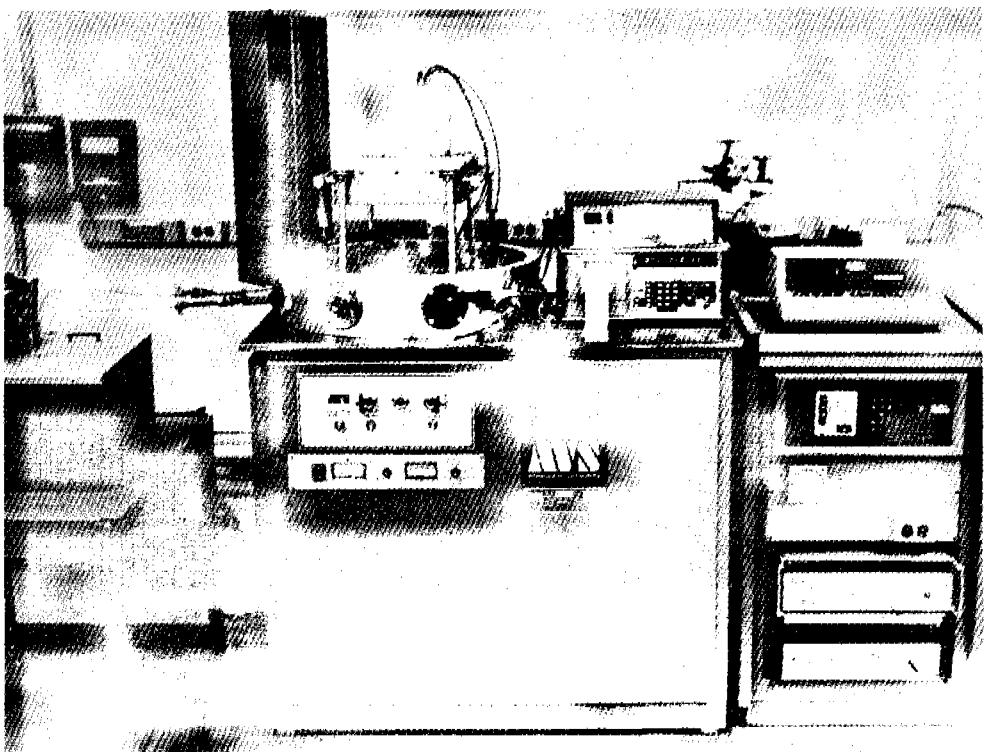


Fig. 2 - 140-day thermovac stability test set-up at EG&G.

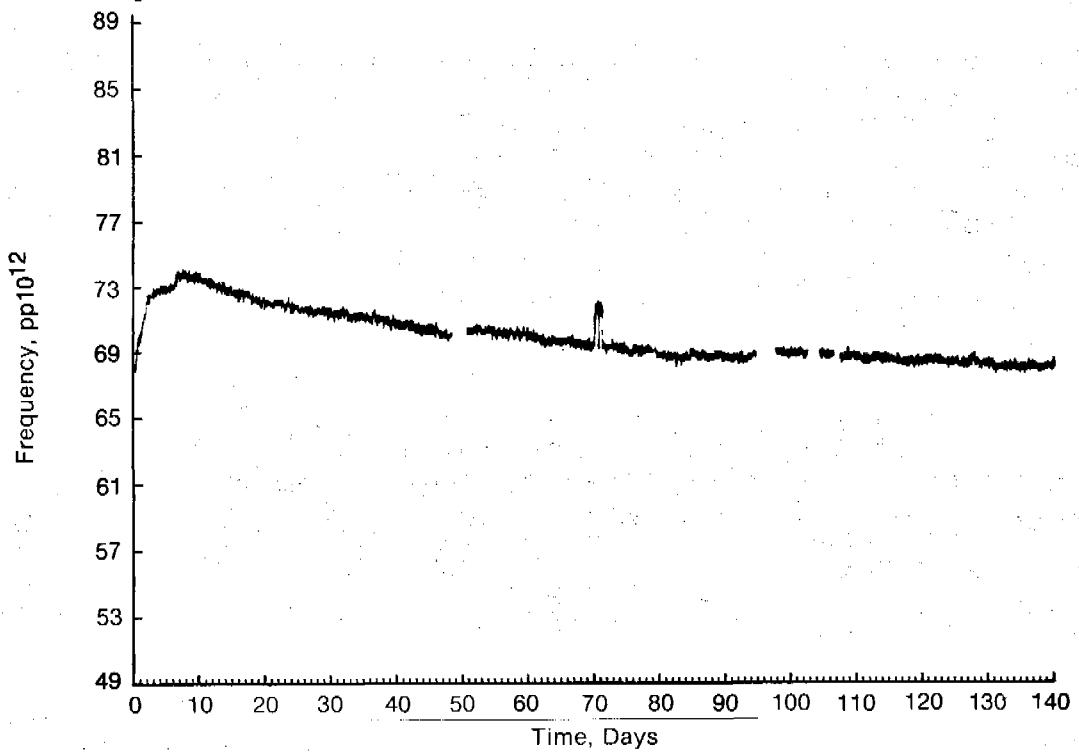


Fig. 3 - EG&G GPS RFS P-1 stability test in thermovac 10/22/84 to 3/12/85.

During days 49-50, the unit experienced a partial loss of vacuum. The pressure inside the bell jar increased to about 50 Torr, which caused thermal and barometric changes inside the RFS. After repair of the thermovac system, the RFS frequency and all monitor readings returned to normal. There was no permanent frequency offset or change in drift or scatter. The continuity of the test was therefore not affected.

During days 70-71, the unit showed two separate frequency excursions of about $+2 \times 10^{-12}$ and back that lasted for several hours. Each transition was abrupt and involved only the RFS signal and frequency. There was no change in the light or any other monitor indication. There was no permanent frequency offset or change in drift or scatter. During the excursions, the signal change was about -8%. Such a signal change (without a light or temperature change) is almost certainly due to a change in cavity microwave power.

These excursions were definitely not the same as the jumps that were observed during the NBS test with the heavy fill lamp. Those jumps involved the light level, and they did not recover abruptly.

These excursions seem characteristic of a discrete effect, such as the making and breaking of an electrical contact, probably causing a change in the microwave power. The exact cause was, however, never determined.

On days 94-97 there was another episode of poor vacuum. The RFS monitors and frequency recovered normally after good vacuum was restored.

Thereafter, except for two computer outages between days 103-105 and 107-108, the stability test continued without interruption.

The unit accumulated the required 140 days of uninterrupted operation and showed excellent stability. A plot of the last month's stability record was shown in Fig. 1. The average drift during the last 30 days was $-2.1 \times 10^{-14}/\text{day}$, well below the $\pm 1 \times 10^{-13}/\text{day}$ specification and x10 lower than observed during the original stability test at NBS. This improvement is due to the lower helium permeation absorption cell envelope. The unit showed no jumps in light intensity as it did before substitution of a lamp with normal rubidium fill.

A detailed teardown and inspection after the 140-day stability test revealed no internal problems or failures.

A plot of the time-domain stability is shown in Fig. 4. The stability is considerably better than the previous run for long averaging times, due primarily to the absence of the lamp-induced frequency jumps. The medium-term stability is limited by the single cesium reference.

Overall, the results of the 140-day stability test were excellent and all objectives were met.

DESIGN CHANGES

Several changes were made to the RFS design during the Continuation Program. Electronic design changes were made to improve the EMI characteristics.

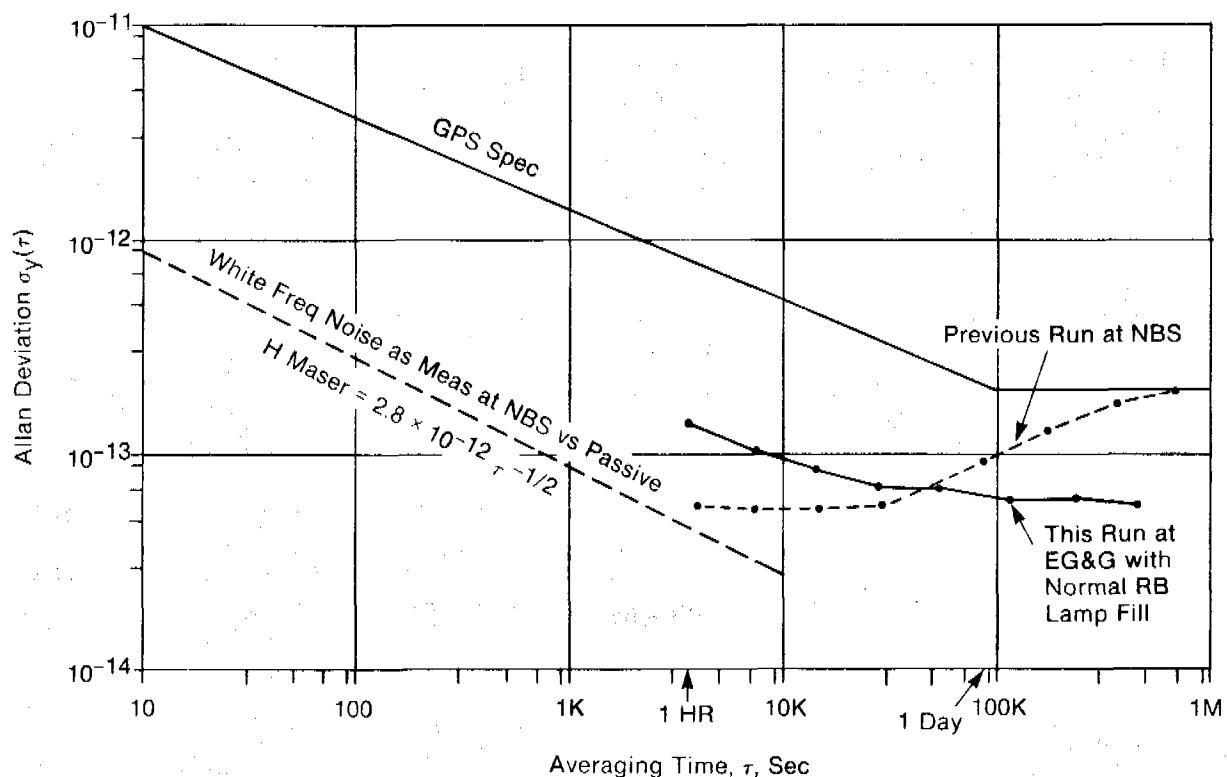


Fig. 4 - Drift-corrected time domain frequency stability of EG&G GPS RFS P-1.

Mechanical design changes were made to stiffen the VCXO mounting. These design changes raised the total RFS failure rate slightly from 5.61 to 5.68 per 10^6 hours. The predicted reliability of this clock for the 7.5-year space mission is now 0.688, still believed to be the highest reliability of any of the Rockwell-sponsored GPS clocks.

OCVCXO IMPROVEMENTS

During the previous qualification-level testing there were several deficiencies associated with the secondary loop OCVCXO of the RFS. It had insufficient varactor tuning range, insufficient upper temperature range, lacked dc isolation to its case and had inadequate ruggedness. The OCVCXO failed twice during vibration testing and was never exposed to shock testing. Also, the OCVCXO was not able to maintain lock at high temperatures during the thermal vacuum and thermal cycling tests. A new OCVCXO was purchased to be fully compliant with its specifications in order to correct these deficiencies. The Continuation Program therefore included qualification-level retesting to confirm that the new OCVCXO was satisfactory. These test results were also successful.

EMI IMPROVEMENTS

During the previous test, there were several deficiencies in the EMI characteristics of the unit.

Significant improvements were made in the radiated and conducted emission characteristics of the unit by changes in the construction of the external control/monitor cable and by adding internal filters for all control/monitor leads. Deficiencies associated with the conducted susceptibility of the unit were corrected by the addition of an internal 5V dissipative regulator and other minor power supply changes. These changes resulted in satisfactory EMI compliance as confirmed by retesting of all previous EMI deficiencies.

ENVIRONMENTAL RETESTS

Environmental retests were performed on Prototype No. 2 because of the OCVCXO problems during the initial test program. The environmental retesting also verified the thermal and structural adequacy of the improvements for drift and EMI. The tests performed were thermal-vacuum, temperature cycling, vibration, and shock.

The original test procedures were repeated except that in the thermal vacuum test, the margin between the specified maximum operating temperature and the maximum achievable operating temperature was determined.

The qual-level retesting verified the adequacy of the newly acquired OCVCXO and the improvements made to the RFS. There was a margin of 10°C in vacuum above the high temperature specification of 50°C. The RFS remained in lock during vibration.

ADDITIONAL TESTING AT NRL

The two EG&G GPS RFS prototype units have now been transferred to the Naval Research Laboratory where they are undergoing additional testing. Preliminary results have confirmed their excellent stability, including a scatter below 10^{-13} at 10^5 seconds.

CONCLUSIONS

All objectives of the EG&G GPS RFS Continuation Program were met as scheduled. Significant improvements were made in the two most important RFS performance factors, drift and long-term stability. All previous qualification-level test deficiencies were corrected.

The development of a second-source rubidium clock for the GPS navigation satellites is therefore complete. This program has resulted in the highest performance and most reliable such devices yet reported.

ACKNOWLEDGMENTS

This work was supported by Rockwell International Satellite Systems Division and the U.S. Air Force Space Division.

Many persons contributed to the success of this effort at EG&G. In particular, J. McDonald supervised the processing of the improved absorption cells and P. Labrecque and K. Lyon were deeply involved with the RFS testing activities.

REFERENCES

1. W.J. Riley, "A Rubidium Clock for GPS," Proceedings of the 13th Precise Time and Time Interval (PTTI) Applications and Planning Meeting, pp. 609-630, December 1981.
2. T.J. Lynch and W.J. Riley, "Test Results for Prototype GPS Rubidium Clocks," Proceedings of the 15th Precise Time and Time Interval (PTTI) Applications and Planning Meeting, pp. 269-280, December 1983.
3. "Final Technical Report for EG&G GPS RFS Continuation Program," EG&G, Inc., Salem, MA, June 7, 1985.
4. "Final Report, 140-day Stability Test, EG&G GPS RFS Prototype No. 1," EG&G, Inc., Salem, MA, February 1983.
5. C. Volk et al, "Lifetime and Reliability of Rubidium Discharge Lamps For Use In Atomic Frequency Standards," Proc. 38th Annual Frequency Control Symposium (1984), pp. 387-400.
6. P.L. Bender, E.C. Beaty, and A.R. Chi, "Optical Detection of Narrow RB⁸⁷ Hyperfine Absorption Lines," Phy. Rev. Letters, Vol. 1, No. 9, Nov. 1958, pp. 311-313.

APPENDIX
HELIUM TESTING OF RFS

Testing was performed on EG&G GPS RFS Prototype No. 2 to determine if helium permeation of the absorption cell could be a cause of frequency drift. A helium bottle with a pressure regulator and flow meter was connected to a vacuum regulator and a micrometer leak valve to the vacuum system to allow flow of helium into the thermovac chamber surrounding the RFS. The chamber was evacuated and helium was allowed to flow into the chamber with the valve to the diffusion pump partially closed. The settings of the various regulators and valves were adjusted until a steady pressure of about 12 microns of helium was achieved. (This is about 3X the concentration of helium in air.) Pressure was set initially using a Granville-Phillips Series 275 Vacuum Gauge and monitored using the vacuum system thermocouple gauge; pressure values should be considered nominal only. As shown by the first eleven days of Fig. A1, the RFS frequency exhibited a drift of $+8.5 \times 10^{-13}/\text{Day}$ while exposed to 12 microns of helium.

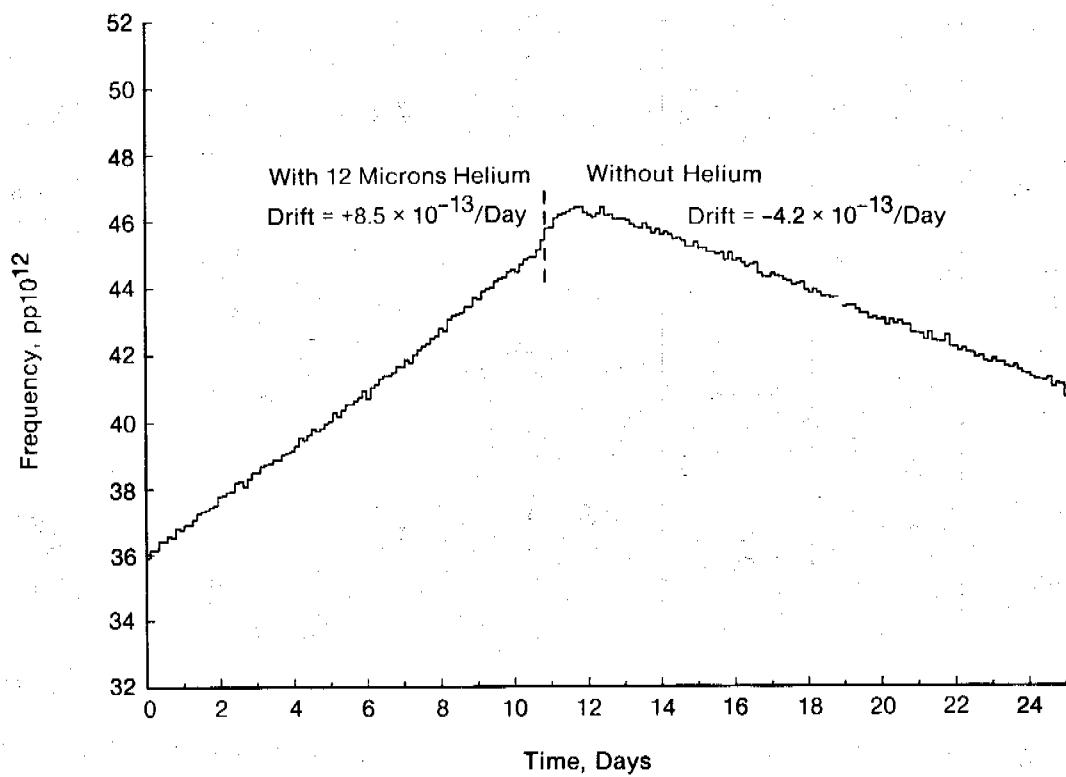


Fig. A1 - EG&G GPS RFS P-2 stability with and without helium 5/12/83 - 6/6/83.

The helium flow was then shut off, and the chamber pumped down to hard vacuum for the remainder of the 24-day test period. Upon exposure to hard vacuum, the RFS frequency drift changed in magnitude and direction to $-4.2 \times 10^{-13}/\text{Day}$.

Helium was again introduced into the chamber in an attempt to eliminate the drift. Using the two drift values corresponding to helium pressures of 12 microns and 0 (hard vacuum), the required pressure was calculated to be about 4 microns, which would presumably be the partial pressure of helium inside the absorption cell. The results of the first month of test are shown in Fig. A2, which shows $\tau = 10^4$ seconds frequency data versus a laboratory cesium standard. The RFS frequency exhibited a very low and stable drift.

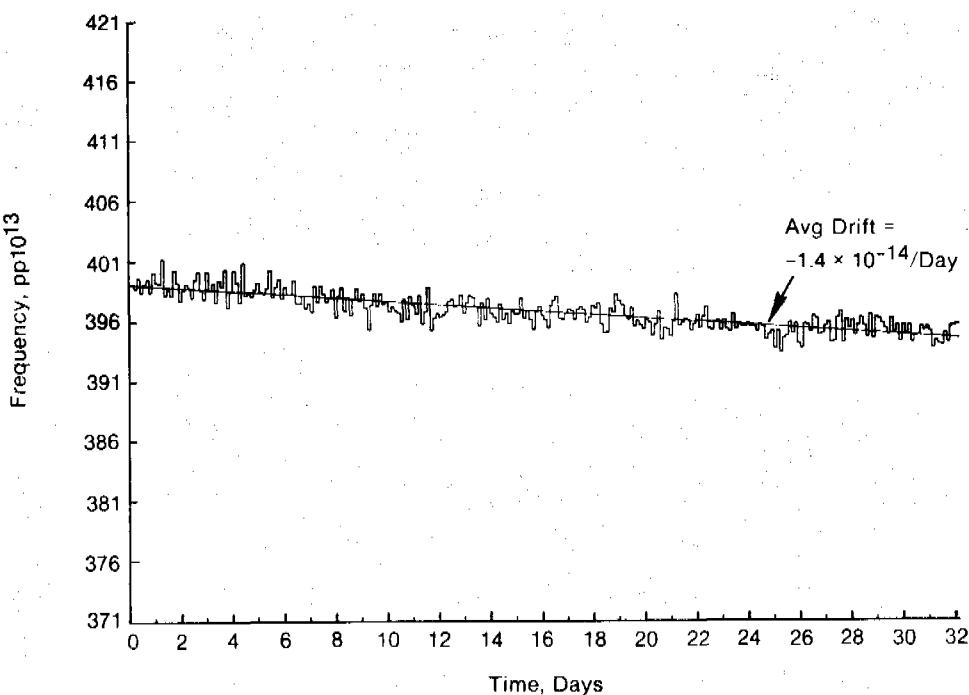


Fig. A2 - EG&G GPS RFS P-2 stability in 4.5 microns He 6/16/83 to 7/18/83.

These results show that helium permeation can be a significant contributor to the drift of a rubidium frequency standard. The observed drift with and without helium is in good agreement with that predicted by considering the pressure shift coefficient of helium (+720 Hz/Torr)(6) and the helium permeability of the absorption cell envelope at its operating temperature.

