# GPS BLOCK IIF RUBIDIUM FREQUENCY STANDARD LIFE TEST

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**Abstract**

***Since August 2008, two production PerkinElmer Rubidium Frequency Standards (RFS) built for the GPS Block IIF satellites have been under test at the Naval Research Laboratory (NRL) Precision Clock Evaluation Facility (PCEF). NRL, in conjunction with the GPS Wing, GPS Block IIF prime contractor Boeing, and the RFS manufacturer PerkinElmer, is conducting a minimum 3-year life test on the GPS IIF RFS units, serial numbers 5 and 25. The primary objectives of the program will be the verification of the design's life and reliability. A secondary objective will be the long-term characterization and evaluation of the GPS IIF RFS performance parameters. The two units are being operated in independent thermal vacuum chambers with high-resolution monitoring of the clock's frequency compared to the NRL hydrogen maser references. The units' internal monitors that would normally be sent as telemetry and environmental test conditions are monitored and recorded with high resolution. A status will be presented of the GPS IIF RFS units under test.***

## INTRODUCTION

The U.S. Naval Research Laboratory (NRL) is conducting the third in a series of GPS atomic frequency standard life tests. The current life test involves two production Perkin-Elmer GPS Block IIF Rubidium Frequency Standards (RFS) located at the NRL Precision Clock Evaluation Facility (PCEF), in conjunction with the GPS Wing, GPS Block IIF Prime Contractor, Boeing, and the rubidium frequency standard manufacturer, Perkin Elmer. The current IIF RFS test began on 22 August 2008 and is scheduled to run for a minimum of three years **[1]**.

The first life test conducted was on the GPS IIR Rubidium Atomic Frequency Standard (RAFS), which began in 1997 and lasted more than 7 years **[2,3]**. Each Block IIR satellite contains three RAFS units. Launching of the Block IIR satellites began in 1997 and the last launch occurred in August 2009. Each Block IIF satellite will contain two RFS units and one Cesium Atomic Frequency Standard (CAFS) unit. Life testing of the GPS IIF CAFS began in August 2004 and has been on hold since October 2006.

## TEST OBJECTIVES

The primary objectives of the life test program will be the verification of the design's life and reliability, and the identification of any potential risks which might be associated with the updated rubidium frequency standards for satellite applications. A secondary objective will be to perform long-term characterization and evaluation of the IIF RFS performance parameters, providing the ability to enhance the confidence in the IIF RFS design for future GPS development. Plans to combine IIF RFS on-orbit life data with the ground test data in support of reliability and life analysis will occur once the Block IIF satellites begin to launch.

## TEST CONFIGURATION

The two RFS units chosen for the life test, serial numbers 5 and 25, were provided by the prime contractor, Boeing, and are flight candidate production units. The units were not modified for the test and evaluation program. The life test's principal objective is that the test RFS units be evaluated under continuous operation in a simulated space-like environment replicating their operation in the GPS spacecraft as closely as possible. Two thermal vacuum chambers with independent baseplate temperature controllers are being used to house each of the units. Boeing personnel installed each RFS test unit into its thermal chamber at NRL using the same procedures and materials used for satellite installation. Installation of the units occurred on 17 July 2008.

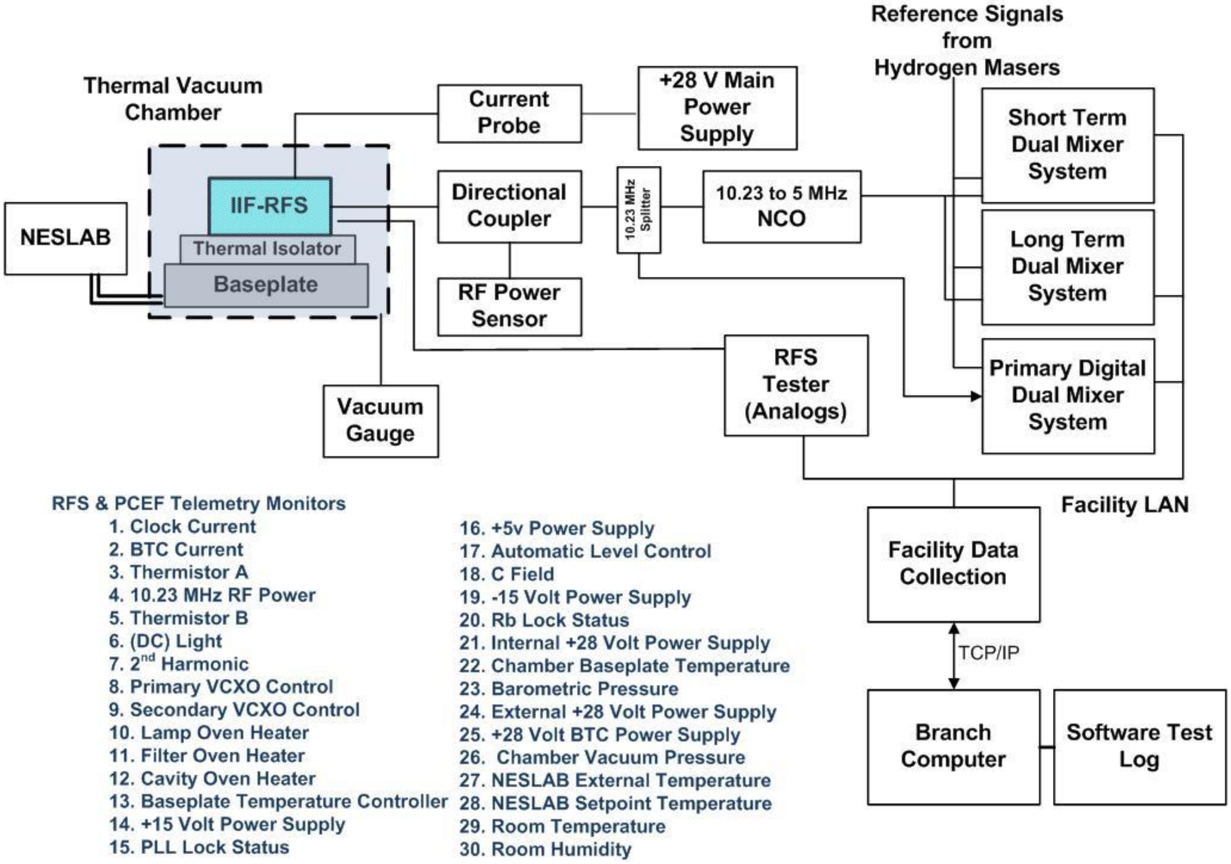
Prior to the start of the life test, a series of pre-tests and analyses were performed at the NRL PCEF. Before the delivery of the RFS units, NRL performed equipment checkout and data collection testing to validate the calibration and operation of the test equipment. Each vacuum chamber's baseplate that is the test unit's thermal interface was evaluated at a nominal 23 degrees Celsius ($^{o}$C). For the actual life test, the baseplate for each unit has been set to the maximum and minimum temperature that the clock panel mounting panel is expected to see in orbit. RFS SN05 is set to 17$^{o}$C, the minimum expected in-orbit clock panel temperature and RFS SN25 is set to 29$^{o}$C, the maximum temperature. Additional tests included RFS warm-up characteristics, initial stabilities for in-air and in-vacuum. Various telemetry parameters were also evaluated.

The test configuration setup shown in Figure 1 is identical for each RFS. There are three phase measurement systems in use to perform high-precision phase comparisons between the RFS test units and the NRL reference hydrogen masers. The Primary Digital dual-mixer system phase measurements are collected at 1-second intervals and sampled at 20 seconds for analysis. The backup measurement systems require the 10.23 MHz signals from each unit to be converted to 5 MHz by a Numerically Controlled Oscillator (NCO) so that they can be input into the Long Term and Short Term dual-mixer phase measurement systems. These data are collected at 20-second intervals and serve as backups should the primary system experience a temporary outage.

Any of the NRL reference masers, shown in Figure 2, can be employed as the reference for the phase measurement data. The reference clock used for the data to be shown in this paper is the Symmetricom hydrogen maser designated N3. It has a frequency stability at a sample time of 1 day of approximately $1 \times 10^{-15}$.

The high-precision 1-second and 20-second phase measurements from the NRL hydrogen masers and RFS units are collected using dedicated collection systems. High-resolution analog sensors monitor 21 clock parameters and nine PCEF environmental parameters, which are collected every 20 seconds. Every 15 minutes, the phase measurements and telemetry data are transferred to a LINUX database server, where the data are made available for analysis using in-house and commercial software packages.

Software test logs are also maintained to record information regarding the state of the test, normal, and anomalous events as necessary. On a monthly basis, performance reports are generated for each RFS reviewing the current month and the overall test period. The reports are made available on a secure Web site for test participants to review.



RFS & PCEF Telemetry Monitors

1. Clock Current
2. BTC Current
3. Thermistor A
4. 10.23 MHz RF Power
5. Thermistor B
6. (DC) Light
7. 2nd Harmonic
8. Primary VCXO Control
9. Secondary VCXO Control
10. Lamp Oven Heater
11. Filter Oven Heater
12. Cavity Oven Heater
13. Baseplate Temperature Controller
14. +15 Volt Power Supply
15. PLL Lock Status
16. +5v Power Supply
17. Automatic Level Control
18. C Field
19. -15 Volt Power Supply
20. Rb Lock Status
21. Internal +28 Volt Power Supply
22. Chamber Baseplate Temperature
23. Barometric Pressure
24. External +28 Volt Power Supply
25. +28 Volt BTC Power Supply
26. Chamber Vacuum Pressure
27. NESLAB External Temperature
28. NESLAB Setpoint Temperature
29. Room Temperature
30. Room Humidity

Figure 1. IIF RFS life test configuration and list of telemetry monitors.

The NRL Precise Clock Evaluation Facility (PCEF) shown in Figure 2 includes the IIF RFS thermal vacuum chambers and associated monitor and data collection systems. Additional thermal vacuum chambers and data collection systems are used for other tests with some additional capability available. The environmental chamber, containing the NRL reference hydrogen masers, the primary digital dual mixer system, and an International GNSS Service (IGS) GPS receiver, is used to maintain this equipment in a controlled environment to minimize possible effects being reflected in their operation and, correspondingly, in test data. Other components of the PCEF include the Long Term and Short Term dual mixer systems, test GPS receivers, the Channel 5 TV carrier-phase system, data collection computers, and database servers **[4]**.

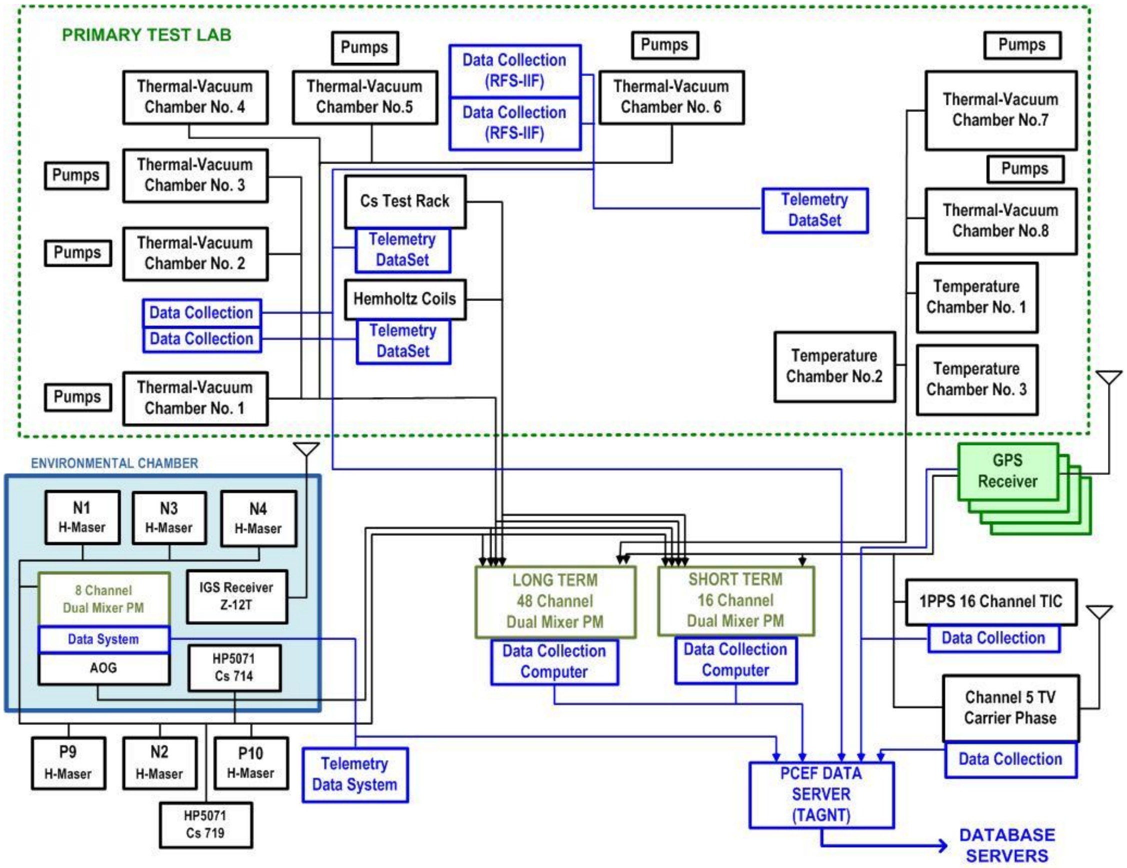


Figure 2. NRL Precise Clock Evaluation Facility (PCEF).

# PERFORMANCE ANALYSIS

The data presented in this paper covers just over 1 year of data collected from 22 August 2008 (MJD 54700) to 30 September 2009 (MJD 55104). The phase data consist of continuous 20-second measurements against the reference. The performance of the frequency offset, drift offset, and frequency stability will be presented for each RFS unit.

During this period, there have been no failures associated with either unit. However, RFS SN05 was shut down by the NRL protection circuit on 20 October 2008 (MJD 54759). The protection circuit is designed to shut off the clock in the event that the chamber baseplate, or clock's internal temperature monitor (Thermistor B), exceeds preset limits. After investigation, it was determined that neither limit was exceeded and the clock was running at its nominal temperature. This behavior had also been seen once in the pre-test setup period. At that time, no underlying cause was found, although the Omega sensor module that measures Thermistor B was suspected. A new module was installed and further investigation revealed that the sensor module was not at fault in this instance. Because the shutdown circuit operated very close to the logic threshold, occasional noise bursts were sometimes sufficient to trigger the logic. To prevent similar problems in the future, modifications were made to the logic input to provide additional threshold margin and to better filter the incoming signal lines. In this case, the clock was turned off to prevent possible damage to the unit. All other test components continued to operate without interruption, and the integrity of the test was not compromised. RFS SN05 was restarted on 23 October 2008 (MJD 54762).

No such problem has been seen on RFS SN25, even though the protection circuit is of the same design. Since the unit would need to be shutdown in order to change the circuitry, it was decided not to change the circuit for RFS SN25.

Since the RFS SN05 restart, the unit experienced two small frequency jumps. The first, of $2.0 \times 10^{-14}$, occurred on 13 December 2008 (MJD 54813) and the second frequency jump, of $4.4 \times 10^{-14}$, occurred on 8 August 2009 (MJD 55051). The jumps could not be correlated with any of the RFS telemetry monitors or external factors such as temperature. RFS SN25 did not experience any frequency jumps or resets during the test period. Clocks of this type have a tendency to experience frequency jumps, and specific causes have yet to be determined.

These units, just as others of this type have done, exhibit an initial phase change characteristic that has been known as a start-up transient. In order to mitigate the effects of this start-up transient, which appears like a changing drift coefficient, a logarithmic fit to the data was done. The data shown below are residuals to this fit. To perform the log fit, the 20-second phase data was converted to frequency and a logarithmic fit to frequency of the form, $y(t) = a \ln(b t + 1) + c$, was applied. The integral of this fitted model was removed from the phase data to provide the fit residuals. The Overlapped Hadamard deviation was calculated from these residual to determine the frequency stability.

Figure 3 shows the frequency offset residuals for RFS SN05. The frequency changes were not removed from this plot and can be clearly seen. Examination of the telemetry and PCEF environment monitors at these times show no correlation. Consequently, the cause of these abrupt changes is unknown. The frequency offset residuals for RFS SN25 are shown in Figure 4. As can be seen, there are no abrupt frequency changes in these data.

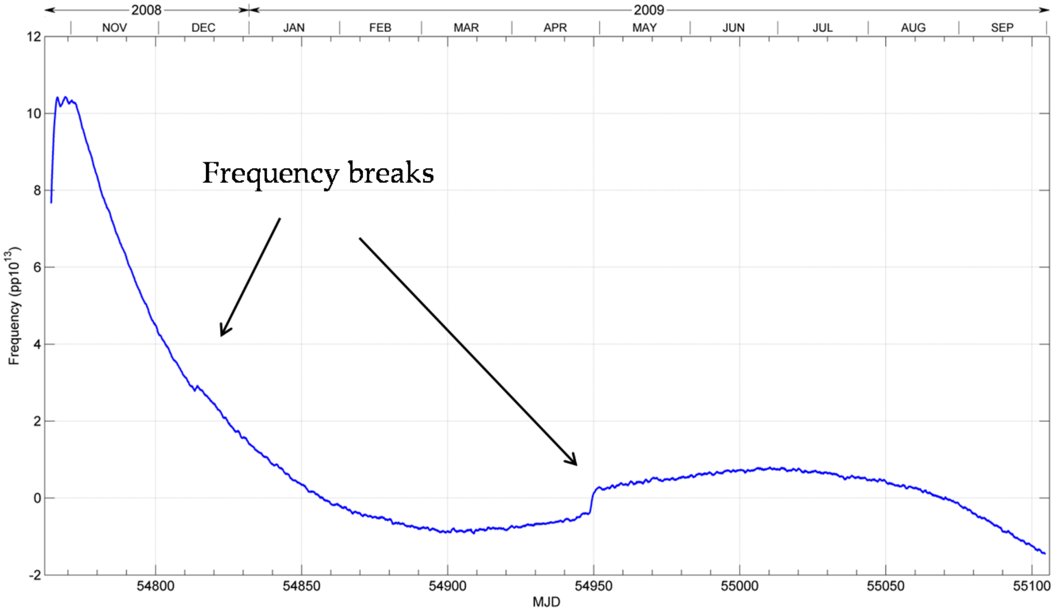


Figure 3. RFS SN05 average daily frequency offset residuals.

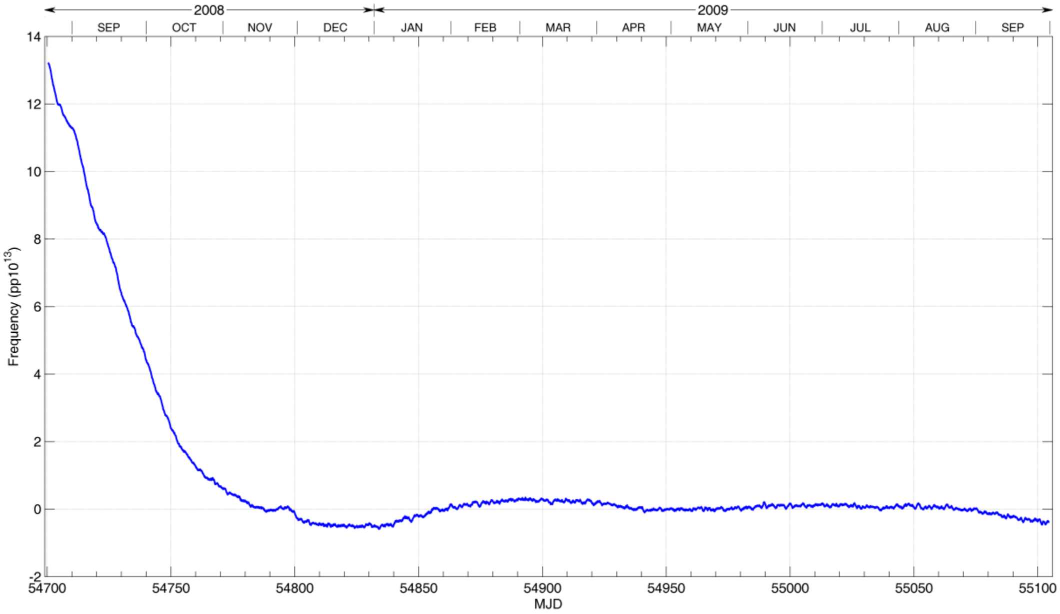


Figure 4. RFS SN25 average daily frequency offset residuals.

The 1-day drift is calculated for each unit from the phase data prior to forming residuals with the log fit. Figure 5 shows that, after the RFS SN05 restart, the 1-day drift offset leveled off to -7 × $10^{-14}$ per day. The RFS SN05 restart and unknown frequency changes can again be seen. After 404 days of continuous operation, Figure 6 shows the 1-day drift offset for RFS SN25 is approaching -4 × $10^{-14}$ per day.

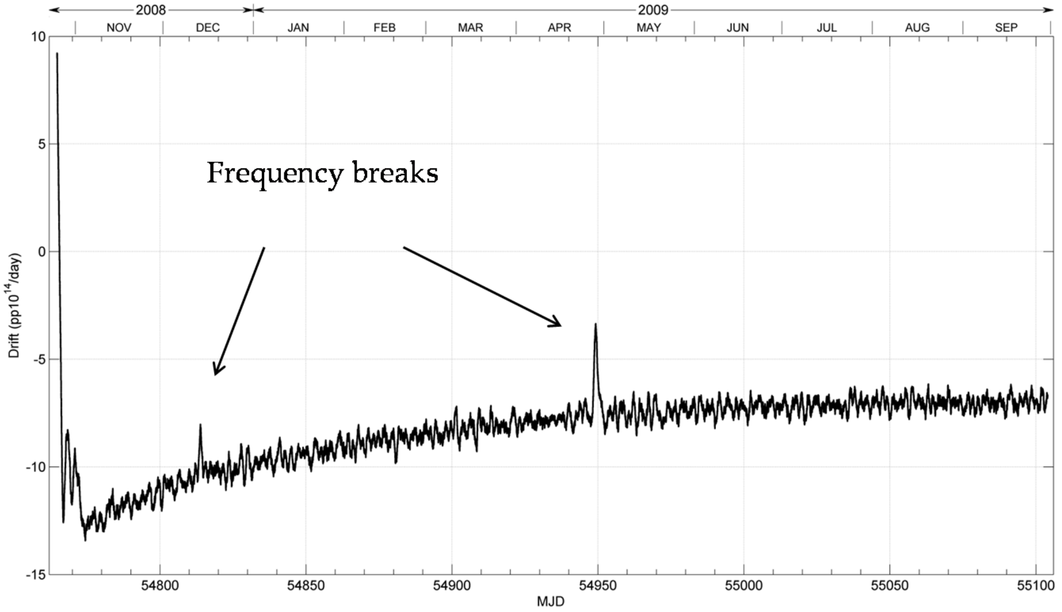


Figure 5. RFS SN05 daily drift offset.

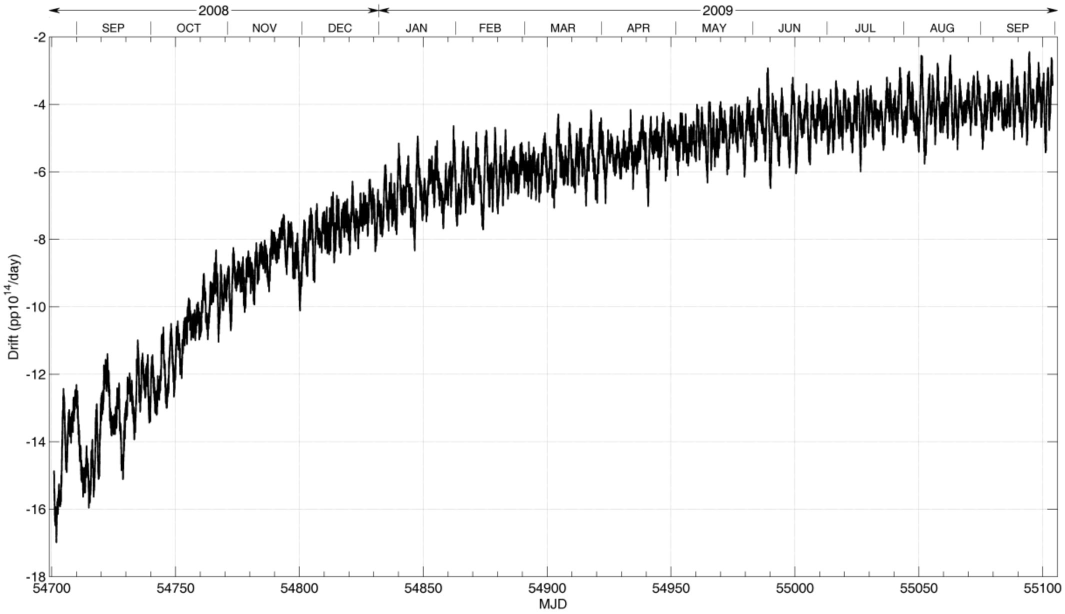


Figure 6. RFS SN25 daily drift offset.

The 1-day frequency stabilities shown below have been calculated over a data interval of 140 days, with a sample period of 20 seconds. Figure 7 shows the stability of RFS SN05 to be just above $2 \times 10^{-15}$ at 1 day. Figure 8 shows the stability of RFS SN25 is just below $4 \times 10^{-15}$ at 1 day.

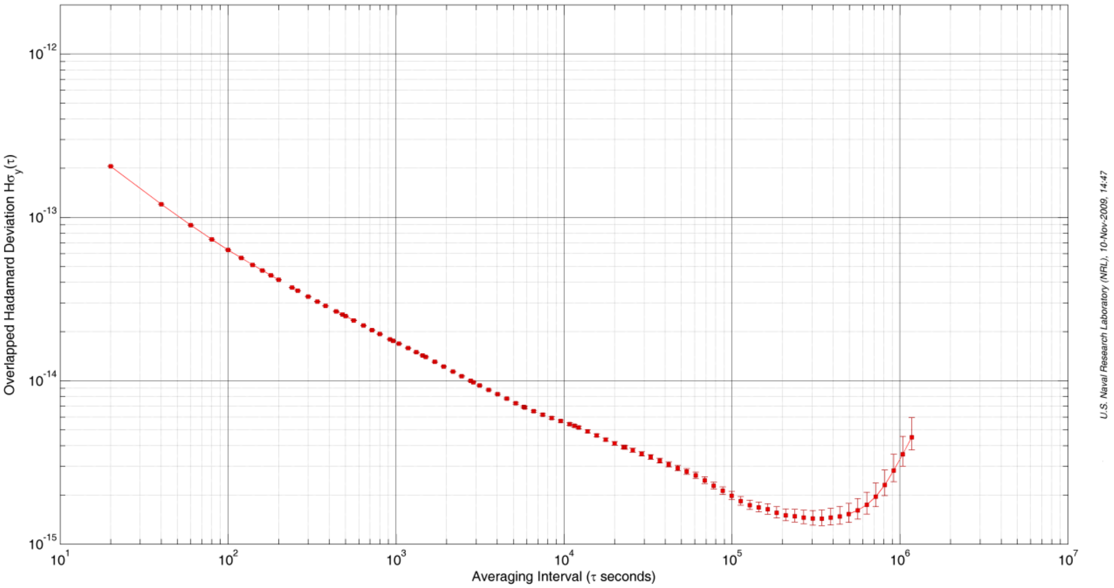


Figure 7. Frequency stability of RFS SN05.

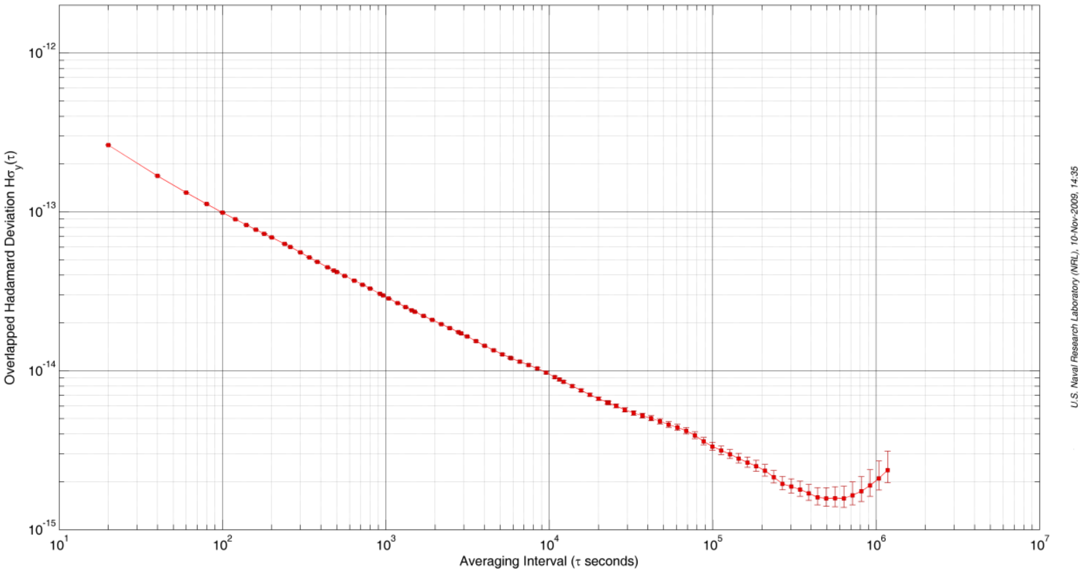


Figure 8. Frequency stability of RFS SN25.

## SUMMARY

After just over 1 year of operation, the two RFS units are performing well and display excellent stability and drift stabilization. Neither unit has experienced any failures. All telemetry parameters are performing within specification. Once the IIF satellites begin to launch, comparisons between the life test units and on-orbit RFS units will be conducted.

## REFERENCES

**[1]** GPS Block IIF Rubidium Frequency Standard (RFS-IIF) Life Test Plan, dated 10 July 2007, U.S. Naval Research Laboratory.

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