GPS BLOCK IIR RUBIDIUM FREQUENCY STANDARD LIFE TEST

RESULTS

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Abstract: The life test of two Perkin-Elmer (formerly EG&G) rubidium atomic frequency standards (RAFS) at the U.S. Naval Research Laboratory (NRL) in a simulated space environment and flight configuration began 31 March 1997. These clocks were production clocks from the Global Positioning System (GPS) Block IIR build and especially provided for this test by the GPS Joint Program Office and the Block IIR satellite contractor team led by Lockheed Martin. This continuously running test was designed to provide information on long term performance, operation, and potential unique characteristics of these clocks. This included potential failure mechanisms, and day-to-day characteristics of the clocks and their internal monitors. GPS Block IIR was the first on-orbit use of this design and there was initially significant concern over their lack of actual space experience. The test clocks operate in a vacuum chamber with a sensitive baseplate thermal controller that simulates the GPS satellite conditions. The routinely used telemetry outputs and the manufacturer’s engineering test monitors are recorded at high resolution every five minutes. The output signal phase is measured against the NRL reference hydrogen maser at 20-second intervals.

This paper summarizes the test results to date and compares those results with the observed on-orbit performance of the Perkin-Elmer rubidium clocks in the GPS constellation. Overall, the performance of the RAFS units has been exceptionally good. There are, however, a number of interesting features in the data. These include a significant number of small frequency jumps, environmental sensitivities, and trends in the telemetry monitors. The similarity of life test data and operational data collected from units in the operational Block IIR satellites will be presented and discussed. The utility of life testing in supporting operation and new space clock introduction into the system will be highlighted.

Keywords: GPS, Block IIR, RAFS, Life Test

I. INTRODUCTION

The purpose of the life test is to evaluate the reliability, characteristics, and performance of two flight-qualified units [1,2]. Their performance is measured under laboratory conditions in simulated space-like conditions and space vehicle implementation as close to the on-orbit Block IIR rubidium clocks as possible [3]. The performance of the on-orbit clocks cannot be measured directly since they are input to the on-board Time Keeping System (TKS) that actually drives the space vehicle transmitter. The signals are influenced by the ionosphere and troposphere, and when received are subject to increased measurement noise due to the receiving equipment. The life test was designed to increase the confidence in the design of the clock for flight operations in the Block IIR space vehicles [4]. The Naval Research Laboratory is conducting the jointly developed test plan in cooperation with a number of participants: (1) The GPS Joint Program Office (JPO) and Aerospace Corporation have had oversight responsibility and monitored the test. (2) The 2nd Space Operations Squadron (2SOPS) monitored the test and assisted in collection of data from the on-orbit Block IIR rubidium clocks. (3) Lockheed-Martin provided the two flight-qualified rubidium clocks for the test and provided analysis of the telemetry data collected from the Block IIR rubidium clock on Navstar 43. (4) ITT mounted the clocks to be tested in the environmental chambers at NRL and provided analysis of telemetry data collected from the Block IIR rubidium clock on Navstar 43. And (5) Perkin Elmer (formerly EG&G), who manufactured the Block IIR rubidium clocks, supported the test with flight acceptance test data and analyses of clock operation.

II. TEST CONFIGURATION

The test configuration is depicted in schematic form in Figure 1, which shows the two rubidium atomic frequency standards (RAFS), serial numbers 28 and 30, mounted in thermal vacuum chambers [1]. Analog sensors monitor 25 parameters for each clock. The output of the monitors is sampled every 5 minutes for analysis. A numerically controlled oscillator reduces the 13.4 MHz RF output of the clocks to 5 MHz. The 5 MHz signal is then sent to a phase measurement system where the phase is collected every 20 seconds and sampled for analysis every five minutes.

![Figure 1. RAFS Life Test System Configuration](image)

The reference clock for the phase measurement system is a Sigma Tau hydrogen maser (S/N 03). Continuous comparison against the DoD Master Clock shows the reference clock to have a frequency stability at a sample time

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of one day of approximately 1 pp10\(^{15}\) which, as expected, has been below the noise floor of the rubidium clocks under test. The frequency offset of the reference clock from the DoD Master Clock was 1.61 pp10\(^{13}\) on 20 July 1997. The drift had a magnitude of less than 1 pp10\(^{16}\) per day. More than 27 million measurements have been collected for analysis from S/N 28 and S/N 30 from the start of the test on April 1, 1997 until May 1, 2002.

III. PERFORMANCE ANALYSIS

A. RAFS S/N 28

The linear residuals of the frequency offset of RAFS S/N 28 during the first 265 weeks of the test is shown in Figure 2 uncorrected for a number of unexplained breaks in the frequency. A total of 78 unexplained frequency breaks have occurred since the test was begun. The two largest breaks were 1.75 and 1.11 parts in 10\(^{12}\). The average of the remaining breaks are 2.02 pp10\(^{13}\). The accumulated offset in the frequency since the test began in April 1997 is shown in Figure 3. During the first ten months a pattern can be seen consisting of a negative break followed by two positive breaks. By March 1998 there began to be from three to seven positive breaks between each negative break. Then in August 2000 the size of the breaks dramatically increased when two negative breaks occurred in succession. Since that time far fewer breaks have occurred. The total accumulated frequency offset due to the breaks was approaching 1 pp10\(^{14}\), but is now reduced to 6.2 pp10\(^{12}\).

The frequency drift history, for the period from powering up of the clock on March 31, 1997 to May 1, 2002 was estimated and plotted in Figure 4 using pairs of corrected one-day average frequencies separated by one day. A number of uncorrectable system anomalies have required data to be purged since the data was not representative of the actual clock behavior. Beginning in late 1998, a strong cyclic component was apparent in the drift, although it appears to have lessened since September 2000. At present the drift is approximately -4 pp \(10^{14}/\text{day}\).

![Figure 4. RAFS S/N 28 Drift Offset](image)

The frequency stability history based on the Hadamard deviation, which adaptively removes the drift, for a sample time of one day using data uncorrected for the frequency breaks is presented in Figure 5. In spite of the frequency breaks, the frequency stability remains within the specification of 6 pp10\(^{14}\) except in the vicinity of the three largest breaks [5].

![Figure 5. RAFS S/N 28 Frequency Stability History](image)

The frequency stability profiles shown for one-year periods and sample times of 15 minutes to 36 days, is presented in Figure 6. The profile based on the Hadamard deviation has had the drift removed. Averaging over the entire 5 years yields a value of stability at one day of 2.7 pp10\(^{14}\), which is still well within the specification of 6 pp10\(^{14}\).

B. RAFS S/N 030

RAFS S/N 030 has been a much better performing clock with only eleven small, unexplained breaks in the frequency.
The linear residuals of the frequency offset are presented in Figure 7 where the breaks, because of their small size, are barely visible.

In Figure 8 is shown the cumulative breaks in the frequency since the test began in April 1997. It can seen that the total frequency offset due to the breaks is only $-4 \times 10^{-14}$, which is two orders of magnitude less than that in S/N 28.

The one-day average drift, presented in Figure 9 shows the drift decaying asymptotically toward zero in an ideal manner. The value of drift is approximately the same as in S/N 28, a value of $-4 \times 10^{-14}$/day.

The frequency stability histories based on the Hadamard deviation for a sample time of one day using data uncorrected for the eleven small frequency breaks is presented in Figure 10. In spite of the frequency breaks, the frequency stability remains well within the specification of $6 \times 10^{-14}$ with values around $6 \times 10^{-13}$, except at the times of the breaks where the peak value is $2 \times 10^{-14}$. This estimator shows the stability for a sample time of one day to be almost an order of magnitude better than the specification.

The frequency stability profiles in one-year time periods since the beginning of the test for sample times of 15 minutes to 36 days is presented in Figure 11. The profile, based on the Hadamard deviation, has had the drift removed.

Figure 6. Frequency Stability of RAFF S/N 28 shown as one curve for each year of operation.
Averaging over the entire 5 years yields a value of stability at one day of 6.6 pp10^{-6}, which is well within the specification of 6 pp10^{-6}.

C RAFS Telemetry Analysis

For each of the clocks tested at the NRL Precision Clock Evaluation Facility, there were 25 analog parameter sensors monitored. These sensors may be grouped in four categories: (1) those corresponding to the on-orbit telemetry sensors, (2) laboratory engineering sensors, (3) instrumentation sensors, and (4) environmental sensors.

Telemetry Sensors:
1. Second Harmonic Voltage
2. Lamp Output Voltage
3. Crystal Oscillator Control Voltage
4. Lamp Oven Voltage
5. Filter Oven Voltage
6. Cavity Oven Voltage
7. Lock Status Voltage
8. Thermistor A Voltage
9. Thermistor B Voltage

Laboratory Engineering Sensors:
1. Clock Baseplate Heater Voltage
2. +15-Volt Power Supply Voltage
3. -15-Volt Power Supply Voltage
4. 28-Volt Power Supply Voltage
5. Auto Level Control Voltage
6. C-Field Voltage
7. 5-Volt Power Supply Voltage

Instrumentation Sensors:
1. Main Power Supply Voltage (Switched)
2. Main Power Supply Voltage (Unswitched)
3. Main Power Supply Current
4. 13.4 MHz RF Power

Environmental Sensors:
1. Vacuum Chamber Pressure
2. Clock Baseplate Temperature
3. Room Temperature
4. Room Humidity
5. Room Barometric Pressure

By far the most interesting parameters were the Second Harmonic and the Lamp Output. In this paper only these two will be presented. In a subsequent NRL publication a more extensive treatment of the data from the analog sensors will be presented.

In Figure 12 is presented the mean residuals of the Second Harmonic sensor data for RAFS S/N 28. Two events are labeled on the plot which influenced the sensor results. The first is a vacuum pump failure in early 1998 and the second is the installation of a new measurement system in mid-1999, which had a different calibration value. Both are manifested as discontinuous steps in the Second Harmonic value. All the other jumps are directly correlated with the numerous frequency breaks. It can be seen that the sensor settled after the frequency breaks subsided in late 2000. In Figure 13 is presented the second harmonic data for RAFS S/N 30, which had far fewer frequency breaks than RAFS S/N 28. In Figures 14 and 15 are presented the RAFS S/N 28 and 30 Lamp Output sensor results, which also show the correlation with the frequency breaks in the respective RAFS.

IV. COMPARISON WITH BLOCK IIR ON-ORBIT

To put the life test results of RAFS S/N 28 and 30 in proper perspective a comparison of the two ground RAFS stability results with the six on-orbit Block IIR RAFS currently in operation in the GPS constellation is presented in Figure 16.
Because of the influence of the system noise on the on-orbit short-term stability estimates, stability estimates will begin with an averaging time of one day. The results shown are for a two-year time frame or less, depending on the amount of on-orbit data available. It can be seen that, at a one-day sample time, the Navstar 44 is the worst of the eight RAFS timing signals and, in fact, is slightly out of spec. The ground RAFS, S/N 28, which has the many frequency breaks has the second highest stability but is within specifications at one-day. The other five on-orbit RAFS are clustered around 2 pp $10^{-15}$ with the best out to 10 days being Navstar 51. The ground RAFS S/N 30 is by far the best performer, at $6 \times 10^{-15}$ for one-day. It must be stated again that the ground RAFS are pure clock results as opposed to the additional noise source corruption included in the on-orbit RAFS timing signals.

**A NAVSTAR 43**

Like RAFS S/N 28 the timing signal generated by RAFS S/N 6 on NAVSTAR 43 has been characterized by unexplained repetitive frequency breaks. But unlike the clock being tested in the laboratory, the repetitive breaks in the timing signal of NAVSTAR 43 did not begin until nearly two years after activation in orbit. Moreover, except for three negative breaks, the positive breaks have all been of the same magnitude and cyclic in nature with an average period of 30.2 days. Figure 17 presents 30th order regression residuals to the phase uncorrected for the frequency breaks, but corrected for the change in drift commanded by the Master Control Station on October 5, 2000. The effect on the phase of the uncorrected frequency breaks can be seen as cusps, which begin in July 1999. In this representation, the positive breaks in frequency appear as negative cusps in phase.

**B NAVSTAR 51**

RAFS S/N 34 on Navstar 51 is arguably the best-behaved clock in the constellation. Except for the system measurement noise typical of timing signals received from on-orbit clocks, it is closest to the performance of RAFS S/N 30. The residuals of a 30th order regression fit to the phase, presented in Figure 18, shows little behavior of an anomalous nature as opposed to that shown previously on Navstar 43.

**C RAFS S/N 28 and 30**

The same type of analysis was performed using one year of data from the ground RAFS S/N 28 to show the effect of the frequency breaks on its performance. The results are shown in Figure 19. To complete the analysis, Figure 20 presents the residuals to a 30th order fit to the phase of RAFS S/N30 on the same ordinate. During this time span only one small frequency break occurred. Figure 21 presents the same data as Figure 20 but now is contrasted with the on-orbit Navstar 51 results shown in Figure 18. The results are comparable between the best on-orbit RAFS and the better RAFS in the ground Life Test.
V. CONCLUSIONS

This is an ongoing project but to date some general conclusions can be reached. A number of frequency discontinuities have occurred on both the RAFS under ground test as well as the Block IIR RAFS on-orbit. Many, but not all, of the frequency breaks are highly correlated with changes in both Second Harmonic and Lamp Output sensors. At the five-year mark no catastrophic failures have occurred on either RAFS for a total operating time of 10 years. This strongly suggests that these units will be able to sustain operation in the Block IIR NAVSTAR space vehicles with the three RAFS configuration. In addition, both RAFS in the ground life test are well within the one-day stability specification with indications of possible better capabilities.

VI. FUTURE WORK

The conduct of this Life Test has been a milestone in space qualified atomic standards development and their operation on GPS space vehicles to support system performance. The lessons learned during its conduct is fundamental to successful evaluation of operational units of the future. Plans are currently underway to incorporate other units for similar evaluation to attempt to identify and correct development and implementation problems before they occur in operational space vehicles.

REFERENCES

[3] ITT Instructions 1275130 for RAFS installation