SVN 9 END–OF–LIFE TESTING

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Abstract

SVN 9 was a GPS Block I research and development satellite. When it was launched in June of 1984, questions regarding the future performance of atomic frequency standards in orbit remained to be answered. In March of 1994, after performing for twice its designed life span, SVN 9 was deactivated as a member of the operational GPS satellite constellation. During the next two months, US Air Force and Rockwell personnel performed various tests to determine just how well the atomic frequency standards had withstood ten years in the space environment.

The results of these tests are encouraging. With a full constellation of Block II/IIA satellites on orbit, as well as the anticipated launch of the Block IIR satellites, results from the end of life testing will be helpful in assuring the continued success of the GPS program.

INTRODUCTION

When the opportunity to perform end of life testing on SVN 9's navigation payload arose, the limited amount of time available to perform these tests was a major constraint. Since the length of time devoted to navigation payload testing was limited by the amount of power available from the solar arrays, the onset of earth eclipse season presented an absolute boundary that could not be re–negotiated. Balancing the expected life span of the spacecraft with the amount of time required to test other, non–payload components meant that most navigation payload components would be excluded from the test.

Most of the navigation payload components aboard GPS satellites were extensively redesigned during the interim between experimental Block I production and the manufacture of the operational Block II/IIA design. The sole exception is the rubidium frequency standard manufactured by Rockwell. This made the decision to limit the testing to the rubidium frequency standards an easy one. The following tests were approved and carried out by personnel working from the GPS Master Control Station (MCS):

Test #1: Rubidium frequency standards are heavily temperature dependent. Program specifications limit their temperature dependence to frequency changes of 20 parts in 10^{13} for every degree Celsius. By comparison, the FTS cesium frequency standards currently used on most operational GPS satellites must have a temperature coefficient less than 1 part in 10^{13} per °C. By measuring the temperature coefficient of the current clock and comparing it to the coefficient obtained during the pre–launch check–out process, we can estimate the effects of prolonged exposure to the space environment on the thermal properties of the GPS rubidium frequency standard.

Test #2: The nominal configuration of a GPS frequency standard involves locking the voltage controlled, quartz crystal oscillator (VCXO) to the stabilizing effects of the atomic physics package feedback loop. In the event that the atomic physics package becomes unusable, it may be necessary to use the VCXO in an open–loop configuration. The purpose of this test was to determine the operational feasibility of this plan.

Test #3: Due to the low reliability of atomic frequency standards, each GPS satellite carries four atomic clocks into orbit. When an operational clock fails, one of the standby clocks is powered up and brought on–line. SVN 9 was launched in June of 1984. The first clock (a cesium frequency standard manufactured by FTS) lasted an impressive nine years. In October 1993, the GPS control segment turned off the cesium clock and powered up the first of the three stand–by rubidium clocks. Test #3 was designed to initialize the two spare rubidium frequency standards after ten years of on–orbit cold storage. As part of this test, the two rubidium clocks were powered up separately and initialized according to standard Master Control Station procedures.

Test #4: The MCS can alter a rubidium frequency standard's output frequency by commanding the "C–field". This alters the magnitude of a uniform magnetic field surrounding the physics package. This ability to fine tune the frequency standard allows the MCS to adjust the 10.23 MHz output frequency as the clock ages and assumes new characteristics. When operating in the "open loop" mode, the current through the voltage controlled, quartz crystal oscillator (VCXO) can be commanded from MCS. Test #4 was designed to determined the extent to which the C–field and VCXO tuning ranges degraded with age.

NAVIGATION PAYLOAD TEST #1: Temperature Coefficient

The Active Baseplate Temperature Control Unit (ABTCU) maintains a stable thermal environment for the rubidium frequency standard. The MCS has the capability of choosing from four seperate settings: "A" (26.8 C), "B" (29.9 C), "C" (33.4 C), or "D" (37.5 C). At the operational setting of "D" the ABTCU should heat up to a temperature of 37.5 ± 1.5°C. Once the ABTCU has stabilized, the temperature should not vary by more than ± 0.1 C.

For Test #1, the ABTCU was reset to setting "C" (33.4 C). Once the frequency standard had stabilized at this lower temperature, the Kalman Filter was able to estimate the new frequency. The magnitude of the resulting frequency change yielded the temperature coefficient.

After reseting the ABTCU to "C", the clock temperature changed from 37.6 to 34.6 over a course of 20 minutes. During the next 24 hours, the Kalman estimate of Δf/f changed from -20.57×10^{-12} to -5.898×10^{-12} s/s. After subtracting the change in frequency due to the aging coefficient (A_2), we could assume the temperature change was responsible for the Δf/f of 14.792×10^{-12}. This increase in frequency yields a temperature coefficient of $-4.93 \times 10^{-12}\ \Delta f/f$ per degree Celsius.

The original value of the temperature coefficient for this clock was taken from ground test data compiled in 1982. During the ground test the temperature was raised from 31 C to 35 C over a period of ten hours. After the test was complete, the accumulated phase error was used to derive the frequency offset. This 1982 data indicates that Rb #2 had a temperature coefficient of -1.54×10^{-12} $\Delta f/f$ per degree Celsius.

The results of this test indicate that the clock's temperature coefficient increased by a factor of three. There are several reasons other than prolonged exposure to the space environment that could explain the change in the coefficient. Since all ground tests on this frequency standard took place shortly after clock turn–on (a two to three week time span), the frequency standard may not have displayed normal operational behavior during this time. The clock used for this end of life test was powered up October 1, 1993. Since the clock had approximately six months to stabilize before the onset of end of life testing, the A2 term was more stable and was more accurately characterized in the Kalman Filter.

Other conditions existing during the end of life test and not present during the ground test should also be taken into account. The on–orbit satellite experiences large variations in the angle at which the sun falls on the satellite body. During the time span covered by this test, the incidence angle of the sun on the satellite body changed dramatically over the course of the day. This exposed the components aboard the vehicle to different temperatures depending on their on–board location. By comparison, during the ground test, the frequency standard was placed in a stabilized thermal vacuum chamber where these variations do not occur.

The elapsed time for the clock baseplate to stabilize at the new temperature was less than one hour. However, since there are no temperature telemetry sensors inside the clock, the actual time for the entire component to stabilize at a homogenous temperature may have been much longer. Even after available telemetry indicated that the frequency standard has stabilized, the internal temperature of the clock may still have been different from the baseplate temperature.

Conclusion: After almost ten years in space, the temperature coefficient for FS #2 changed less than one order of magnitude. This bodes well for future operations. The test indicates that ground test data for temperature related issues remains valid for several years and, if normal precautions are taken, can be trusted for operational use.

NAVIGATION PAYLOAD TEST #2: VCXO Open–Loop Run

For this test, the feedback loop that ties the rubidium physics package to the VCXO was severed. At the same time, the MCS Kalman Filter was directed (via the SVCLKSEL directive and a modified KKS file) to increase the process noise (qs) for the clock states. All q values were increased by three orders of magnitude. The qs for A_0 (clock phase) increased from 1.11×10^{-22} to $1.11 \times 10^{-19} s^2/s$; the qs for A_1 (clock frequency) increased from 3.33×10^{-32} to 3.33×10^{-29} s^2/s^3; the qs for A_2 (clock frequency drift) increased from 1.35×10^{-43} to 1.35×10^{-40} s^2/s^5. These larger values compensated for the greater variation in measurement process noise brought on by the frequency instabilities of the VCXO.

Once the VCXO was tuned to an acceptable frequency, SVN 9 was treated as a normal member of the GPS constellation. Monitor stations tracked it; the Kalman Filter modeled it; and routine navigation uploads were performed according to the daily contact schedule. Contingency uploads due to high ranging errors were not performed because of the excessive burden this would have placed on the MCS operations crew.

We performed the test twice. The first trial involved the VCXO from Frequency Standard #2; the next trial used Frequency Standard #1. The first run lasted 56 hours from 22 to 25 March. The second VCXO test lasted 73 hours from 8 to 11 April.

At the conclusion of the tests, each VCXO exhibited the following characteristics:

VCXO Clock State	VCXO Test #1	VCXO Test #2
VCXO Clock Bias (A_0)	-8.77×10^{-4} (s)	-1.32×10^{-3} (s)
VCXO Clock Drift (A_1)	-2.55×10^{-10} (s/s)	-5.79×10^{-10} (s/s)
VCXO Clock Drift Rate (A_2)	1.20×10^{-15} (s/s^2)	5.91×10^{-15} (s/s^2)
Maximum Drift Movement	1.03×10^{-10} (parts/day)	5.49×10^{-10} (parts/day)

These values are all too large in magnitude for sustained operational use. Through heavy Kalman Filter intervention and frequent adjusts of the payload timing (PRN) signal, it was possible to maintain a navigation signal for the duration of this test.

The rate at which the timing signal aboard the satellite diverged from GPS time would have required frequent PRN timing adjusts. The available space in the navigation message mandates that the SV–GPS time offset be less than 976,000 ns. If no adjustments to the timing signal had been performed, this absolute limit would have been exceed exceeded every two to three days. In the case of SVN 9, this timing adjust was performed at the beginning of the test for each frequency standard. Each iteration of the test was concluded before this clock phase limit could have been exceeded.

The instabilities associated with the VCXO output signal necessitated intense control segment maintenance. Ranging errors associated with an incorrect navigation upload accumulated at a rate of 10–20 meters per hour. New, more accurate navigation uploads would have been required every 30 to 60 minutes in order to maintain ranging errors within the allowable operational limits. This is beyond the capability of the MCS in its current configuration.

Conclusions: The results of this test are mixed. The VCXO–specific process noise values (qs) contained in the KKS file provided the Kalman Filter with the flexibility needed to model the very erratic VCXO clock states. This in turn allowed the MCS operations staff to build and transmit navigation uploads in order to monitor ERDs and other performance parameters. In this respect, Test #2 proved that the MCS is capable of handling a vehicle operating in the VCXO open–loop mode.

The discouraging result of the test was the accumulation of range error and the rapidly increasing SV–GPS timing discrepancy. Through sustained Kalman maintenance along with frequent navigation uploads and PRN timing adjusts, it is possible to maintain a healthy navigation signal. The ability to do this would impose an unacceptably large burden on the operations crew if the situation existed for an extended period of time.

NAVIGATION PAYLOAD TEST #3: New Clock Initialization

Test #3 offered a chance to witness the start–up performance of the two standby rubidium clocks. The test followed standard MCS procedures for powering up and initializing a new rubidium clock. Although some procedures were customized to accommodate the specifics of each individual frequency standard, the following steps were common to all new rubidium clocks.

The new clocks were powered up and allowed to thermally stabilize for one to three days. A C–field tune was done soon afterwards to minimize any frequency residuals. As soon as the C–field tune was complete, the satellite was provided with a routine navigation upload. This entire process was completed within four days for both new frequency standards.

At this point, the satellite had to be monitored constantly to determine the rate of error accumulation in the ranging signal. Normally a rubidium frequency standard will settle down and exhibit acceptable operational characteristics after the passage of another week. Although a rubidium clock will continue to change its performance characteristics for the next few months, this luxury of time required to observe this phenomenon was not available. Each iteration of the test was concluded after two weeks.

To minimize the burden on the operations crew, the vehicle was only uploaded once per day regardless of the size of the ranging errors. The test ran for approximately two weeks on each of the two rubidium clocks. Two weeks is the normal initialization period for a new rubidium clock. After this time, we are usually prepared to set the SV healthy.

The test of Rubidium #1 ran 14 days from 25 March to 8 April. The test of Rubidium #3 ran 11 days from 11 April to 22 April. Both tests recorded Kalman Filter data as the clocks warmed up. The Kalman estimates of the clock states by the end of the respective tests are shown below. Also shown are the NIST estimates of the clock stability based on the Allan deviation.

Clock State	FS #1	FS #3
Clock Bias (A_0)	-1.45×10^{-4} (s)	2.45×10^{-4} (s)
Clock Drift (A_1)	-6.74×10^{-11} (s/s)	3.03×10^{-11} (s/s)
Clock Drift Rate (A_2)	1.12×10^{-17} (s/s^2)	1.66×10^{-17} (s/s^2)
Stability (τ =vone day)	1.1×10^{-12}	2.5×10^{-13}
Maximum Drift Movement	1.27×10^{-12} (parts/day)	1.43×10^{-12} (parts/day)

At the end of the test, the clocks exhibited characteristics similar to all new rubidium frequency standards. The phase offsets (A_0) and frequency offsets (A_1) are both slightly high but would be acceptable for normal operations. We would definitely need to adjust these parameters later in order to keep these clocks on–line. The one day stability for FS #1 is fairly high, but would be expected to come down with time. The one–day stability for FS #3 is better and meets program specifications (5.0×10^{-13}).

When a new clock is warming up, random variations in frequency should be expected. The maximum variations in frequency each day were 12 to 15 parts in 10^{13}. Movements of this magnitude are higher than normal, but are partially attributed to the large A_2 term. This large frequency drift value will cause both the phase offset and frequency offset values to increase in magnitude over time.

The frequency drift value (A_2) is often the biggest obstacle to overcome when setting a vehicle with a new rubidium clock healthy. Both of these clocks exhibit a value of A_2 that is approximately one order of magnitude higher than normal. Experience has shown that the A_2 term on most new rubidium clocks will slowly decrease in magnitude and become negative in sign. Since this process usually takes several months, the observation of this phenomenon was beyond the scope of this test.

Ranging errors for both clocks were slightly high but acceptable. By uploading SVN 9 once per day, ERDs (Estimated Range Deviations) exceeded ten meters daily. This exceeds the operational limits imposed on the MCS and indicates that the stability of the clocks and their estimate in the Kalman Filter were not yet at the optimal level.

Conclusions: After ten years in orbit, the two stand–by rubidium clocks powered up and began the initialization process as expected. After a two week warm–up period, the time allotted for the tests had expired. By this time, most of the characteristics measured by the GPS Kalman Filter identified these clocks as normal. The one–day stability measured by NIST also showed characteristics common to other, operational GPS clocks. The A_2 term for both frequency standards was higher than those measured on any of the operational rubidium clocks, but this is not too unusual for a clock undergoing the initialization process. We would expect to see these values drop if the clocks remained on for an extended period of time.

NAVIGATION PAYLOAD TEST #4: C–Field and VCXO Tuning

Method: A rubidium frequency standard normally operates with the atomic loop closed and a C–field tune of about 50%. This mid–field tune allows the MCS the potential to either increase or decrease the output frequency by an equal amount. For test #4, the C–field was tuned to the minimum possible frequency. Once the MCS Kalman Filter settled on a solution for the frequency, the command was sent to the clock ordering the maximum C–field tuning value. This procedure was repeated for the VCXO operating in the open–loop configuration.

The following chart details the C–field tuning values and their associated frequency residuals. This actual residual should be compared to the anticipated change in frequency based on ground test data collected in February 1982.

C–field tune	actual $\Delta f/f$	anticipated $\Delta f/f$
55.655%	3.14727×10^{-11} (s/s)	$2.9185482 \times 10^{-10}$ (s/s)
0.0%	-2.650×10^{-9} (s/s)	-2.840×10^{-9} (s/s)
100.0%	2.398×10^{-9} (s/s)	2.404×10^{-9} (s/s)

The analysis of these test results indicates that the overall range of the C–field decreased with age. The initial C–field range of 5.244×10^{-9} s/s decreased by 3.73% to 5.048×10^{-9} s/s. Because the range decreased asymmetrically, the mid–field frequency value shifted 1.75% (9.2×10^{-11} s/s) towards the positive end of the scale. This is a well observed phenomenon and must be accounted for during every new clock initialization.

After the atomic loop was disconnected from the VCXO, we tested the tuning characteristics of the VCXO. The following chart details the VCXO tuning values and their associated frequency residuals. This actual residual should be compared to the anticipated change in frequency based on ground test data from 1982.

VCXO tune	actual Δf/f	anticipated Δf/f
0.0%	-2.51283×10^{-7} (s/s)	-2.52333×10^{-7} (s/s)
100.0%	1.91467×10^{-7} (s/s)	$+2.20254 \times 10^{-7}$ (s/s)

The analysis of these test results indicates that the overall tuning range of the VCXO decreased with age. The initial VCXO tuning range of 4.726×10^{-7} s/s decreased by 6.32% to $4.4275 \times 10^{-7} Z$ s/s. Based on the asymmetry in the decrease of the total range, it appears that the entire frequency range shifted 3.16% (1.4×10^{-8} s/s) towards the negative end of the scale.

Conclusion: The C–field and VCXO tuning capabilities diminish during the accumulated time the satellite spends on–orbit. This loss of capability does not pose a problem to the normal operation of the frequency standard, because most C–field tunes differ from the mid–field tune by less than 10lost capacity observed in this test lies outside of the nominal tuning range.

This lost capacity, along with the shift in frequency of the center point (or "mid–field tune") requires the addition of a calibration factor to ensure accurate tuning performance. In practice, this may require transmitting more than a single tune command word to ensure the proper tune. Current operational practice allows for several (two or three) tunes to correct the satellite's frequency offset. This shift of the mid–field tune and change in tuning capacity does not hamper operational capabilities.

CONCLUSION

The end of life testing conducted on SVN 9 provided valuable insight into the aging characteristics of rubidium frequency standards. Although none of the test results yielded dramatic, unexpected results; they served to strengthen the operational practices and conventional wisdom that rule the procedures found in the MCS.

We confirmed the reliability of the published thermal coefficients as well as the VCXO and C–field tuning values (Tests #1 and #4). Slight changes in the magnitude of these values did nothing to lessen the confidence we now maintain in the ground test results.

The abilities of the MCS to initialize new clocks and maintain an SV in the VCXO open loop mode (Tests #2 and #3) were observed with some relief. These seemingly routine sets of circumstances do not appear so routine in light of SVN 9's prolonged exposure to the space environment. The challenge to the operational crew to support the intense maintenance, while quite formidable, is something that could be overcome with increased manpower and ground segment support. Similarly, the somewhat poor performance of the two new initialized clocks should not be judged solely on 10 or 14 days worth of data. The fact that these clocks powered up and could be characterized in a normal manner, after twice the expected lifetime of the satellite had passed, is a success.

Tests such as these enhance the ability of the MCS to perform GPS operations. With the expected demise of SVN 10 in spring of 1995, the last of the Block I vehicles will have expired. Their passing should not be seen as the disposal of a valuable resource; instead it is an opportunity to validate and improve the operational performance of the GPS Master Control Station.

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QUESTIONS AND ANSWERS

THOMAS CELANO (TASC): I was wondering if you have any plans for the end–of–life testing for the last Block I.

GREGORY HATTEN (USAF): We should. PRN 9 is taking its slot in the A.1 position. So we have dual coverage with that satellite. So they will probably will give us a few months to do some tasks. I would anticipate that starting probably no earlier than March. So it's not expected to live past May or June, I don't think.

SIGFRIDO M. LESCHIUTTA: Two comments and one question. The first comment, I was really delighted to see the history of equipment working for 12 years.

The second comment, I think the figures shown is a tribute to the ingenuity of the designers of those clocks.

And third, the probability of a thing concerning the temperature coefficient. Do you have an idea of what could be the reason that there's more degradation in regard to efficient temperature? The physics of the cell?

GREGORY HATTEN (USAF): I really don't know. That would probably be more a question for the manufacturer. With my limited experience on that, I really couldn't answer that. Sorry.

JAMES COMPARO (AEROSPACE CORP.): I was going to ask you about Frequency Standard Number 3. You said the stability at one day was about a factor 10 worse than nominal for that rubidium clock. Was that clock on for nine days, and you took stability measurements everyday?

GREGORY HATTEN (USAF): No, it was on for -- we requested NIST to go ahead and give us some stability data after we thought it had settled out and we performed our last C–field tune. I believe it had been on -- pardon me, that was 11 days. And I believe it had been on eight days when we started taking tests. They took four, so the error bars at one day would be fairly large after a four– or five–day sample.

JAMES COMPARO (AEROSPACE CORP.): And were there any Allan Variance measurements taken at time scales shorter than one day?

GREGORY HATTEN (USAF): Yes, there were. And I don't think I have that data with me. But I do have it. NIST did provide it for us.

PARTICIPANT: What are the units of time on your frequency drift? Is that per second?

GREGORY HATTEN (USAF): Second per second squared.