THE END OF AN ERA: SVN 10 END-OF-LIFE FREQUENCY STANDARD TESTING

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Abstract

When SVN 10 was boosted into its disposal orbit on June 20, 1996, it marked the end of the first phase of the Global Positioning System (GPS) program. SVN 10 was the last of the operational Block I GPS satellites. On 18 November 1995, it was set unhealthy to users for the final time after being operational for over 11 years. Due to its solar array capacity degradation, SVN 10's electrical power subsystem was no longer able to support its navigation payload after more than double its design life of 5 years. Personnel at the Master Control Station (MCS) were able, however, to maintain a navigation signal long enough to perform several end-of-life tests on the four onboard frequency standards. These tests on the one cesium and three rubidium standards varied in length and complexity. Several of the tests continued research begun during SVN 9's end-of-life testing. Areas of interest included temperature coefficient determination, voltage-controlled crystal oscillator (VCXO) open-loop operations, new clock initialization, C-field and VCXO tune range determination, Ramsey pattern generation, frequency standard failure analysis, and clock reinitialization performance characteristics analysis.

The results of these tests proved to be encouraging. After over 11 years in the space environment, there appeared to be no significant degradation to the navigation payload. Many of the test results supported conclusions made during SVN 9's end-of-life testing. It is hoped that these test results will prove to be useful to the GPS community by shedding more light on the performance characteristics of space-based frequency standards.

1 INTRODUCTION

On 20 June 1996, GPS SVN 10 (PRN 12) was boosted into its disposal orbit (the orbit perigee was increased by 178 nautical miles). This occasion marked the end of an era, as SVN 10 was the last of the operating GPS Block I satellites. Because of SVN 10's solar array capacity degradation and electrical power subsystem limitations, its navigation payload was set unhealthy to users on 18 November 1995 with a disposal in June 1996. The 2d Space Operations Squadron, responsible for operating and maintaining the GPS constellation through the GPS Master Control Station (MCS), performed end-of-life testing on several subsystems, including the navigation payload. SVN 10's frequency standard end-of-life testing was accomplished from 25 January 1996 to 20 March 1996.

SVN 10 was launched on 8 September 1984 and its navigation payload was set healthy to users on 3 October 1984. It provided over 11 years of timing and navigation service to the GPS community, well beyond its intended design life of 5 years. SVN 10 was equipped with four frequency standards: three rubidium and one cesium. Three of its clocks were turned on for operational use. Cesium Frequency Standard (CFS) #4 was in operation from 23 September 1984 to 6 February 1992. Activation of Rubidium Frequency Standard (RFS) #2 was attempted on 6 February 1992. Due to problems discussed later in this paper, RFS #2 was never successfully activated. RFS #1 was used in operation from 6 February 1992 until SVN 10's last healthy day, 18 November 1995.

Seven tests were performed to evaluate how 11 years in the space environment affected SVN 10's navigation payload, specifically, its onboard frequency standards. Areas of interest included temperature coefficient change determination, voltage-controlled crystal oscillator (VCXO) open-loop operations, RFS #3 (unused during operational lifetime) initialization, C-field and VCXO tune range determination, Ramsey pattern generation, RFS #2 failure analysis, and RFS #1 reinitialization performance characteristics analysis. Many of these tests were also accomplished on SVN 9 during its end-of-life test period.[1] This report will analyze any trends or changes with respect to those data. To maintain consistency, many of the procedures used for testing SVN 9 were repeated on SVN 10.[1] SVN 10's frequency standard end-of-life testing was accomplished from 25 January 1996 to 20 March 1996.

2 TEMPERATURE COEFFICIENT DETERMINATION

The effects of temperature changes play a large role in determining the final frequency stability of GPS clocks. Rubidium frequency standards are more temperature-dependent than cesiums, and this is reflected in the GPS Block I program specifications for temperature coefficient. According to these specifications, Block I cesium standards must have a temperature coefficient of less than ± 2 parts in 10^{-13} per degree Celsius averaged over any 20 degrees in the 20–45 °C range.[2] Rubidium standard specifications require a coefficient of less than ± 20 parts in 10^{-13} per degree Celsius averaged over the 25 - 37°C range.[3] Because of this difference in the temperature coefficient, SVN 10's rubidium standards were equipped with Active Baseplate Temperature Control Units (ABTCUs).[4] These heaters were designed to maintain clock temperature within ± 0.1°C of one of four commandable settings.[4] These settings are (±1.5°C): "A" = 26.5°C, "B" = 29.7°C, "C" = 33.5°C, "D" = 36.5°C.[4]

The temperature coefficient of RFS #1 was measured by recording the MCS Kalman filter's estimate of A_1 ($\Delta f/f$), in the units of s/s, at ABTCU setting "D," along with the clock's exact temperature at that point. The ABTCU was then commanded to "C." Once the clock's temperature stabilized at the lower value, the Kalman filter's estimate of A_1 was again recorded (approximately 24 hours later), along with clock temperature. This process would be repeated for every lower ABTCU setting that could provide a stable temperature above the cyclic operating temperature of the rest of the payload. The standard's temperature coefficient was obtained by calculating the ratio of frequency change to temperature change. This coefficient was then compared to that obtained from ground testing in December 1981. This method of testing was also accomplished on SVN 9, with SVN 10's results serving as a good follow-up to those data.[1] Tables 1 and 2 detail these observations when testing RFS #1.

Figure 1 shows how the Kalman's estimate of A_1 changed with each new ABTCU setting.

One can see a third change in A_1, which is an attempt to set the ABTCU to setting "B." However, the payload operating temperature was above 29.7°C, and the ABTCU was unable to properly regulate the clock temperature at this lower setting. The results of testing settings "D" and "C" indicate that the temperature coefficient of RFS #1 degraded by a factor of 3.95 from December 1981 to January 1996. Therefore, it appears that 11 years of exposure to the space environment and a period of over 3 years spent on the ground has had an effect on the temperature coefficient of RFS #1. SVN 9's end-of-life testing produced similar results, showing that RFS #2's temperature coefficient degraded by a factor of three over a period of 10 years in space.[1] The extent of this effect on the navigation mission is directly related to the ability of the ABTCU to regulate temperature to within its designed range of ±0.1°C. Obviously, any degradation of the ability of the ABTCU to regulate temperature is more severe with a larger temperature coefficient.

3 VCXO OPEN-LOOP OPERATION

Nominally, GPS onboard frequency standards are operated in the VCXO closed-loop configuration. This configuration essentially combines the short-term stability benefits of a crystal oscillator with the long-term stability benefits of a physics package (rubidium or cesium). It is feasible that an operational scenario would occur in which all four physics packages aboard a satellite would prove to be unreliable, thereby necessitating the operation of one of the frequency standards in the VCXO open-loop configuration. This open-loop configuration allows the satellite time to be generated strictly off of the VCXO, without connection to the physics package. The purpose of this test is to observe standards in the open-loop configuration in order to give operators insight into how such a scenario might affect GPS operations.

The effects of operating in the open-loop configuration were tested by commanding the atomic loop open and tuning the VCXO. Also, the Kalman filter process noise values for the clock states were increased to better model the VCXO instabilities. The process noise value for A_0 (phase) was increased from $1.11 \cdot 10^{-22}$ to $2.22 \cdot 10^{-21} s^2/s$. The process noise value for A_1 (frequency) increased from $44.4 \cdot 10^{-33}$ to $8.88 \cdot 10^{-28}$ s^2/s^3, and A_2's (frequency drift) noise value increased from $9.00 \cdot 10^{-42}$ to $9.00 \cdot 10^{-41}$ s^2/s^5. At this point, the satellite's ranging signal was observed and analyzed. Navigation uploads were transmitted to the satellite when possible. This test was performed on two of SVN 10's clocks, RFS #1 and RFS #3. RFS #1 was operated in the open-loop configuration for approximately 27 hours, starting on 30 January 1996. RFS #3 was operated in the open-loop configuration for approximately 24 hours, starting on 5 March 1996. Based on SVN 9 end-of-life test results, it was expected that the open-loop configuration would not prove to be acceptable for operations.[1] It was expected to see very large clock state terms and fairly frequent and large ranging errors.[1] Table 3 details RFS #1 and RFS #3 open-loop characteristics.

All results were consistent with those obtained during SVN 9 testing.[1] Although the process noise values allowed the MCS, through the Kalman filter process, to properly model the VCXOs, the characteristics of the VCXOs did not make maintaining the payload operationally realistic. This is due to the increased number of satellite contacts needed to keep ranging errors within operational specifications. As was the case with SVN 9, the clock states obtained for SVN 10's VCXOs were several orders of magnitude away from what we would expect of a normal RFS.[1] Were SVN 10 set "healthy" during its open-loop tests, MCS operations crews would be performing navigation uploads at least once an hour to maintain its signal within specifications. Although operating a satellite in open-loop mode is feasible, it is most impractical considering MCS limitations.

4 RFS #3 INITIALIZATION

RFS #3 was a frequency standard which had eluded turn-on during the operational lifetime of SVN 10. CFS #4 and RFS #1 combined to last more than twice the design life of the vehicle, until the electrical power subsystem failed to meet demands. It was deemed useful to activate this clock during end-of-life testing to determine the effects, if any, of over 11 years of cold storage (8°C) *in orbit*. This was accomplished by activating the standard on 2 February 1996, initializing the payload, and allowing the MCS Kalman filter to model its clock states. Naval Research Laboratory (NRL) observed the clock's stability. This performance characteristic test of RFS #3 began on 8 February 1996 and lasted for approximately 4 weeks. The clock characteristics recorded by the MCS and NRL are described in Table 4.

FS #3 behaved nominally for a newly initialized Block I Rubidium standard. In the realm of stability, FS #3 met the 1-day stability program specification of $1.0 \cdot 10^{-12}$ and was easily acceptable for operational use.[5] Estimated Range Deviations (ERDs) were also acceptable, even though SVN 10 was only uploaded with a fresh navigation message on a daily basis. Contingency uploads would be necessary as long as the clock maintained a changing drift rate. It is typical for rubidium frequency standards to eventually assume a negative, more predictable drift rate. Because it usually takes about 3 months to get to this point, we were unable to see FS #3 assume a negative, more consistent, drift rate (due to the time constraints of the testing). As one can see from the maximum drift movement, the clock was beginning to settle down with expectations that it would eventually assume a constant, negative drift rate. These test results are consistent with those of SVN 9 and support all SVN 9 new clock initialization conclusions.[1]

5 C-FIELD AND VCXO TUNE RANGE DETERMINATION

All Block I frequency standards are equipped with the capability to retune the output frequency of the VCXO and the resonant frequency of the physics package via commands from the ground.[6] As was the case with SVN 9, it was deemed beneficial to test how prolonged exposure to the space environment affected the tune ranges of the C-field and VCXO.[1] This testing was accomplished by commanding the atomic loop open and tuning the VCXO to a maximum value. Once the Kalman filter had an estimate of A_1, the command was sent to tune the VCXO to a minimum value, and A_1 was re-estimated. This process was repeated with the atomic loop closed to test the C-field. Once tune ranges were established, they were compared to tune ranges measured during ground testing in August 1981 and December 1981. Tables 5 through 7 show the C-field and VCXO tuning values along with the Kalman filter's estimates of A_1. Tune ranges are listed, as well as comparisons with ground test data.

In five of the six test scenarios, the VCXO and C-Field tuning ranges of the frequency standards measured decreased during the 11-year on-orbit time of SVN 10. The only exception to this was the VCXO tuning range of RFS #3, which increased. The ranges of the C-fields shifted in the positive direction, while the ranges of the VCXOs shifted in the negative direction. Exposure to the space environment could have created these changes. The exact causes of these increases and decreases, however, are largely unknown. It is important to note that the changes and shifts in the tuning ranges are not significant (all less than 7% changes) when considering their operational applications. All test results supported the conclusions of SVN 9's end-of-life testing, with the exception of RFS #3's VCXO range data.[1] SVN 9's VCXO ranges decreased over time, while SVN 10's RFS #3 VCXO range increased.[1]

6 RAMSEY PATTERN DETERMINATION

The Ramsey pattern of a GPS cesium frequency standard can show certain conditions of the beam tube, such as where the center and side-lobe frequencies of that standard are located with respect to the clock' VCXO tuning range. It can also provide insight into the gain of the tube and the symmetry of the RF inserted into the tube. This test was devised to determine the characteristics of CFS #4's Ramsey pattern.

An operational frequency standard normally operates with the atomic loop closed and the center frequency located somewhere near the VCXO's 50% tune value. It is possible to plot the Ramsey pattern of a GPS cesium frequency standard by opening the atomic loop and commanding the VCXO to incremental tune values. In this case, increments of 10% were used. At each tuning value the beam current, indicative of the gain of the system, was recorded and plotted verses the tune percentage. The resulting plot of a Ramsey pattern shows peaks and valleys, with the peaks being either the center or side-lobe frequencies. Once the beam current is plotted verses the VCXO tune percentage, one can see where the center frequency may lie, depending on how much the VCXO has aged.

The measured Ramsey pattern for SVN 10's CFS #4 can be seen in Figure 2. According to our data, it seems as if the center frequency is located somewhere around the 70% VCXO tune. This would agree with the CFS #4 VCXO tune range test, which showed us that the VCXO tuning range shifted in the negative direction. The Ramsey pattern, however, does not clearly define the side lobes. This may be due to the fact that the gain of this standard has degraded so much that the side frequencies occur in the noise level. Also, it is possible that we needed a more granular (less than 10% tune intervals) search for those frequencies. Because there are no pre-launch Ramsey patterns to compare our results with, it is unclear exactly how much CFS #4's Ramsey pattern has changed over time.

7 RFS #2 FAILURE ANALYSIS

On 6 February 1992, SVN 10's RFS #2 was turned on due to performance degradation of the 7.5-year-old CFS #4. According to the Block I Orbital Operations Handbook (OOH), the nominal warm-up time for a Block I RFS is one hour.[6] Two hours after the clock had been turned on, the atomic loop was commanded closed. The 10.23 MHz control voltage to the VCXO read 0.45 volts. The nominal reading for this clock would have been approximately 5.4 volts. The other two clock parameters were slightly low, but were close to their nominal readings. Personnel at the MCS tried to test the clock by opening the atomic loop and exercising the VCXO's tuning capability. When the loop was open, the VCXO loop control voltage responded as commanded. However, when the loop was closed, the loop control voltage returned to 0.45 volts. After the clock was on for a total of 2 hours 31 minutes, it was deemed unusable and was turned off. At the time, because of the necessity to set SVN 10 healthy, it was impossible for MCS personnel to thoroughly test RFS #2 in order to determine the cause of its failure. Therefore, RFS #1 was turned on and eventually set operational.

This end-of-life test was devised to attempt to bring RFS #2 on line, 4 years after its initial failure and perform a re-test. If this attempt was not successful, it was hoped the cause of RFS #2's failure mode could be narrowed down, if not identified. Since RFS #2 was originally given only 2 hours and 31 minutes to warm up due to operational considerations in 1992, the clock this time was given approximately 24 hours to warm up during this testing. The VCXO's tuning capability was again exercised, and power to the frequency standard itself was cycled. The commands which open and close the atomic loop were also sent to SVN 10, which cycled the loop's closure mechanism.

As in 1992, MCS personnel were unsuccessful in getting the atomic loop of RFS #2 to close properly. The warm-up period of 24 hours did not allow the clock to operate properly. When the command was sent to open the loop, and VCXO tune words were sent to the clock, the loop control voltage again acted normally. However, there was no change when we attempted to close the loop. Cycling clock power as well as cycling the mechanism which is supposed to close the atomic loop proved to be unsuccessful. Once it was obvious the loop was not working properly, it was attempted to initialize the navigation payload and turn on L-band with RFS #2 in the open-loop configuration. After several attempts, it was impossible for MCS monitor stations to lock up on the L-band carrier.

After testing RFS #2, it is obvious there is a problem which prevents the atomic loop from being closed, similar to that encountered in 1992. However, from this testing, we learned it was not a matter of giving the clock enough warm-up time. Also, because we were unable to lock up on the L-band signal of SVN 10 when operating in the open-loop configuration at any VCXO tune value, it is assumed the problem with the standard lies with the VCXO and not necessarily with any other part of the clock (the physics package, in particular). This may indicate the VCXO had changed frequency so much that the loop could not capture the VCXO frequency.

8 RFS #1 REINITIALIZATION

RFS #1 had been operating for almost 4 years (6 February 1992–1 February 1996) when it was disabled to begin end-of-life testing on other onboard clocks. Upon deactivation on 1 February 1996, the operational characteristics of this clock were well within program specifications. Tables 8 and 9 detail values of 1-day stability and clock drift rate for RFS #1 before it was deactivated for end-of-life testing.[7,8] The 1-day stability data were obtained from NRL's Navstar Analysis Update No. 10-6 and Quarterly Report No. 96-1.[7,8] The clock drift rate data were obtained from the MCS Kalman filter's estimates of clock states.

RFS #1 was reactivated on 11 March 1996 and test data were received for 11 days, the final day being 27 March 1996. This test was designed to compare the performance characteristics of RFS #1 after being on for 4 years to the performance characteristics of RFS #1 after being off for 41 days and then powered on for 2 weeks. Also, it is was intended to determine how quickly RFS #1 would achieve its previous characteristics (especially its stability and drift rate). Our expectation was RFS #1 would eventually assume the same performance characteristics it had when we turned it off in early February 1996. Certain questions remained. Exactly how long would it take to assume those characteristics, and would the clock reach those values within the short length of our testing?

RFS #1 was powered back up on 11 March 1996. Operators at the MCS were unable to get L-band data for SVN 10 until 15 March 1996. Data were received from 15 March 1996–27 March 1996. Table 10 describes RFS #1's performance characteristics during that time.[9] The 1-day stability data were obtained from NRL's Navstar Analysis Update No. 10-7.[9] The clock drift rate data were obtained from the MCS Kalman filter's estimates of clock states.

Before any of these data are analyzed, it is important to point out that MCS operators did not get a very long period of time to examine RFS #1's characteristics in March 1996. Because the clock was only on for approximately 2 weeks, and L-band data were only collected for approximately 11 days, it is hard to derive definite conclusions from this test. Both aspects which were analyzed (clock 1-day stability and drift rate) require a much longer period of time than was operationally possible to obtain numbers that can be considered with high confidence levels. (During acceptance tests at the factory, however, clocks are normally given a 14-day warm-up period followed by a 10-day stability test period. A drift rate value is calculated from the last 5 days.) At only 11 days, the error bars for both 1-day stability and drift rate are rather large in magnitude.

We can, however, say some trends were definitely noticed. It certainly appears the March 1996 1-day stability figure obtained from NRL is consistent with 1-day stability figures obtained when RFS #1 was operational.[7,8,9] It is assumed if we had more time to look at RFS #1 in March 1996, we would have seen its stability value of $0.77 \cdot 10^{-13}$ (recorded over an 11-day period) approach $0.36 \cdot 10^{-13}$, which was recorded over a 4-month period in 1995.[7,8,9] Even after only 2 weeks of activation time, RFS #1 was well within the Block I 1-day stability specification of $1 \cdot 10^{-12}$.[5,9]

Drift rate figures obtained in March 1996 indicated RFS #1 initially assumed a positive drift rate. After approximately 9 days of activation, the drift rate started to turn in the negative direction. Normally, rubidium standards require 2 to 3 months of warm-up time to assume a negative drift rate. Table 9 gives examples of RFS #1's drift rate in 1995, and Table 11 shows its drift rate during end-of-life testing. The negative drift rate it assumed after 11 days ($-8.04 \cdot 10^{-19}$ s/s^2) was very comparable to that recorded in 1995 ($-8.97 \cdot 10^{-19}$ s/s^2). It is possible that because this clock had been previously in operation for approximately 4 years, it required a much shorter warm-up period to assume a negative, more predictable drift rate. As previously mentioned, the drift rate comparisons are hard to accurately determine due to the amount of uncertainty in the measurements. It is fair to say, however, that a trend is noticeable. This trend indicates the frequency standard, in terms of drift rate, does not start from ground zero, but retains much of its "memory" from when it was turned off.

9 CONCLUSION

Based on the results of SVN 10 end-of-life frequency standard testing, one can state that over 11 years, the harsh space environment did not significantly impact the operational capability of the onboard clocks. All characteristics testing of temperature coefficient, new clock initialization, C-field and VCXO tuning, and clock reinitialization showed RFS #1 and RFS #3 were still capable of meeting operational specifications. Data have been obtained which indicate that although operating a satellite in VCXO open-loop mode is feasible, it is not operationally practical. Additional insight has been gained as to why RFS #2 failed to initialize in February 1992; a problem with the VCXO may very well have been the cause. It has been observed that the time it takes an RFS to assume a predictable, negative aging rate after turn-on is dependent on the amount of time it has been "burned in" (in our case, this "burn-in" time was 4 years). All conclusions from this set of clock testing seem to reinforce many conclusions ascertained from SVN 9's end-of-life testing.[1] It is hoped the results of SVN 10's end-of-life navigation payload testing can serve as an additional data point in what will someday be a much larger pool of space-based frequency standard knowledge.

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ABTCU Setting	Clock Temperature (°C)	A1 Kalman Estimate (s/s)
"D"	37.0	-5.76 e-11
"C"	34.0	-6.30 e-11

Table 2. Ground Test Data vs. End-Of-Life Data

Date of Testing	Temperature Coefficient (Δf/f per °C)
December 1981 (Lab Testing)	4.5 10e-13
January 1996 (On-Orbit Testing)	17.6 10e-13

VCXO Clock State	VCXO RFS#1	VCXO RFS#3
VCXO Clock Bias (A_0)	-4.03 e-4 (s)	+1.93 e-4 (s)
VCXO Clock Drift Rate (A_2)	-1.40 e-15 (s/s^2)	+1.31 e-15 (s/s^2)
Maximum Drift Movement	1.22 e-10 (parts/day)	6.9 e-11 (parts/day)

Clock State	RFS #3
Clock Bias (A_0)	1.44 e^{-4} (s)
Clock Drift (A_1)	6.60 e^{-12} (s/s)
Clock Drift Rate (A_2)	3.10 e^{-18}(s/s^2)
Stability (τ = one day) (Allan deviation data from NRL)	2.5 e-13 (aging correction = +4.79E-13 per day)
Avg. Max. Drift Movement (days 1-14)	7.44 e^{-13} (parts/day)
Avg. Max. Drift Movement (days 15-25)	1.57 e^{-13} (parts/day)

C-field tune	On-orbit Δf/f	Lab Test Δf/f (12/81)
0.0 %	-2.376 e-9 (s/s)	-2.770 e-9 (s/s)
100.0 %	+2.451 e-9 (s/s)	+2.141 e-9 (s/s)

VCXO tune	On-orbit Δf/f	Lab Test Δf/f (12/81)
0.0 %	-2.549 e-7 (s/s)	-2.411 e-7 (s/s)
100.0 %	+2.311 e-7 (s/s)	+2.524 e-7 (s/s)

	On-orbit range Δf/f	Lab Test range Δf/f (12/81)	change (%)
C-field	4.827 e-9 (s/s)	4.911 e-9 (s/s)	-1.7
VCXO	4.860 e-7 (s/s)	4.935 e-7 (s/s)	-1.5

Table 6. RFS #3 VCXO & C-field Tune Range Data

C-field tune	On-orbit $\Delta f/f$	Lab Test $\Delta f/f$ (8/81)
0.0 %	-2.280 e-9 (s/s)	-2.913 e-9 (s/s)
50.0 %	+2.30 e-10 (s/s)	-4.008 e-10 (s/s)
100.0 %	+3.163 e-9 (s/s)	+2.551 e-9 (s/s)

VCXO tune	On-orbit $\Delta f/f$	Lab Test $\Delta f/f$ (8/81)
0.0 %	-2.571 e-7 (s/s)	-2.185 e-7 (s/s)
100.0 %	+2.402 e-7 (s/s)	+2.470 e-7 (s/s)

	On-orbit range $\Delta f/f$	Lab Test range $\Delta f/f$	change (%)
C-field	5.443 e-9 (s/s)	5.464 e-9 (s/s)	-0.4
VCXO	4.973 e-7 (s/s)	4.655 e-7 (s/s)	+6.8

Table 7. CFS #4 VCXO & C-field Tune Range Data

VCXO tune	On-orbit $\Delta f/f$	Lab Test $\Delta f/f$ (7/82)
30.0 %	-2.046 e-7 (s/s)	-1.25 e-7 (s/s)
100.0 %	+1.435 e-7 (s/s)	+2.35 e-7 (s/s)

	On-orbit range $\Delta f/f$	Lab Test range $\Delta f/f$	change (%)
VCXO	3.481 e-7 (s/s)	3.60 e-7 (s/s)	-3.3

Table 8. RFS#1 One-Day Stability as Recorded By NRL[7,8]

Time Period	One-Day Stability
2/13/92 - 11/19/95	1.34 e-13 (aging correction = -1.12 e-13 pp/day or 1/2 A_2 = -1.30 e-18 s/s^2)
9/1/95 - 1/1/96	0.36 e-13 (aging correction = -0.8 e-13 pp/day or 1/2 A_2 = -0.93 e-18 s/s^2)

Table 9. RFS#1 MCS Kalman Filter Clock Drift Rate Estimates

Time Period	Clock Drift Rate (A_2)
9/11/95 - 9/28/95	-9.15 e-19 (s/s^2)
9/29/95 - 10/13/95	-9.27 e-19 (s/s^2)
10/25/95 - 11/13/95	-8.48 e-19 (s/s^2)
Average of 3 time periods	-8.97 e-19 (s/s^2)

Table 10. RFS#1 One-Day Stability as Recorded By NRL[9]

Time Period	One-Day Stability
3/15/96 - 3/27/96	0.77 e-13 (aging correction = +0.267 e-13 pp/day or 1/2 A_2 = +3.09 e-19 s/s^2)

Table 11. RFS#1 MCS Kalman Filter Clock Drift Rate Estimates

Time Period	Clock Drift Rate (A_2)
3/15/96 - 3/27/96	+1.46 e-19 (s/s^2)
3/15/96 - 3/20/96	+1.81 e-18 (s/s^2)
3/20/96 - 3/27/96	-8.04 e-19 (s/s^2)

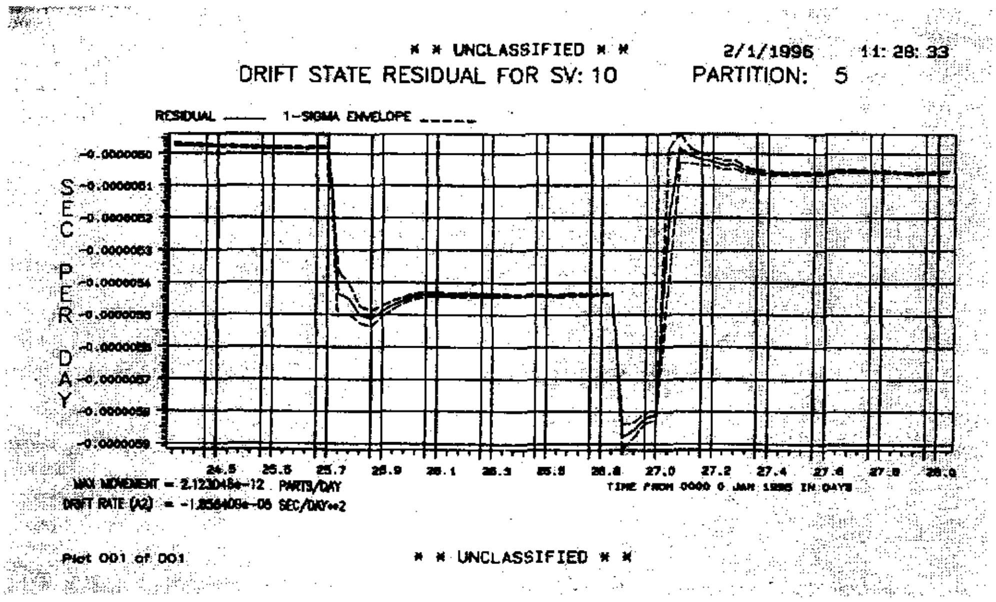

Figure 1. RFS #1 Drift Residuals During Temperature Variations

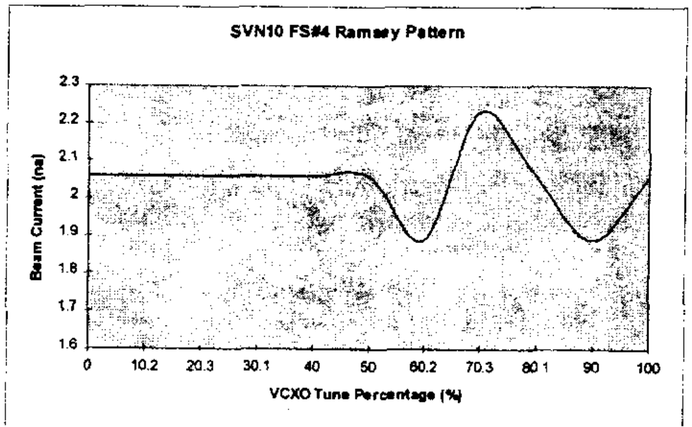

Figure 2. CFS#4 Ramsey Pattern

Questions and Answers

JAMES CAMPARO (AEROSPACE CORP.): The fact that you saw a faster return to the long-term drift rate could very well be as you're saying; it's known that it may take 30 to 60 days for the lamp's light shift to settle down and not be seen in the long-term stability. So if the liquid pool of rubidium in the lamp hadn't been moved, that could explain why it reached that normal drift coefficient so quickly.

GARY DIETER: Makes sense.

DAVID ALLAN (ALLAN'S TIME): The dynamic and steady state temperature coefficients are often quite different. Did you try to differentiate between these two at all?

GARY DIETER: No, we kind of understood that a temperature coefficient taken on the ground may be different because of natural orbital temperature variations in space. But all that we did was what we said, we just simply left it and took the measurements.

RICHARD KEATING (USNO): From time to time, there's been discussion of what sort of oscillator or clock to put on a satellite. From your presentation, it appears that you basically have ruled out crystal oscillators. Is that really true? Could it just be the type of oscillator you had?

GARY DIETER: I think what we ruled out is operating our current clocks that we have in space on their VCXs only. And when I say "ruled out," I'll say that it's, like we said before, operationally impractical.