RUBIDIUM AND CESIUM FREQUENCY STANDARDS
STATUS AND PERFORMANCE ON THE GPS PROGRAM
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ABSTRACT

This paper describes the on-orbit operational performance of the frequency standards on the GPS 1-10 Navstar satellites. The history of the Rb frequency standards showing the improvements incorporated at various stages of the program and the corresponding results are presented. Also presented is the operational history of the Navstar Cesium Frequency Standards. The frequency standards configuration data presented will cover the chronology of events from the concept validation satellites, Navstars 1-10, starting in 1978 to the present, including the configurations of clocks to be used on the GPS Production Program.

Data will be presented additionally showing the results of long-term laboratory testing of a production Rb frequency standard with the necessary data taken to calculate Delta F, drift, time error, and Allan variance.

INTRODUCTION

The evolution of the Rb frequency standards (RFS) on the GPS program started with the Block I concept validation program beginning with a proposal program in 1973, followed by the (GPS 1-8) prototype space vehicle contract in 1974. The full scale developmental (GPS 9-11) models, contracted in 1978, provided both navigation and nuclear detection capability. The production qual vehicle (GPS-12) was contracted in 1980, and the production vehicles (GPS 13-40) in 1982. During the proposal phase of this program, the on-board frequency standards were considered the most critical item within the GPS navigational system for achieving user position accuracy. Therefore, a considerable amount of effort was devoted to the frequency standards. To minimize the risk to the GPS program on this critical item, the initial GPS vehicles (GPS 1 through 3) incorporated three Rb frequency standards, each with a backup mode. This was achieved by operating a high performance VCXO without Rb reference. This design concept resulted in the redundancy potential of six frequency standards per vehicle. Later space vehicles, starting with GPS 4, included an additional cesium frequency standard, also with a backup VCXO mode. This extended redundancy was deemed necessary in lieu of the more conventional dual redundancy. The actual on-orbit GPS frequency standard operating history, shown in Figure 1, illustrates the results of this hardware implementation.

As of mid-1973, no space-borne suppliers of atomic frequency standards existed. Therefore, Rockwell pursued a plan to review all credible candidates for conversion from commercial to aerospace units. The plan to develop a Rb frequency standard was to select the best available voltage-controlled crystal oscillator (VCXO) and phase lock it to a small Rb standard. The design was to be such that if the Rb atomic physics package failed, the VCXO could be utilized as a backup device. This condition would still maintain frequency stability for a specific period of time to maintain navigation accuracy over the test area. The development of this Rb frequency standard started during the GPS proposal phase. Efratom commercial units were procured and underwent the following modifications and tests:

1. Commercial parts were replaced with high reliability parts.

2. One unit was repackaged to allow thermal dissipation in a vacuum.

3. Fabrication of special Rb components with multiple buffer gases were designed to reduce temperature sensitivity.

4. The unit was repackaged to accommodate the GPS boost vibration environment.

5. One unit was subjected to radiation tests to verify operation to GPS requirements.

6. The National Bureau of Standards was contracted to perform both ambient and vacuum stability tests.

This plan has resulted in the development of very stable, high-reliability Rb frequency standards, but not without the normal development problems associated with new hardware. As this program progressed, ten different models of the Rb standards have evolved. The part numbers of the different models of each frequency standard are shown in Figure 1. The first Rb standards on Navstar's 1 and 2 accumulated a total of 44 months of operation with six failures, which necessitated switching to the backup mode (1978-1980). The last 42 months of GPS Rb clock operation on Navstar's 5, 6, and 8 have been failure free. This vast improvement can be mostly attributed to the clock improvements as the program progressed.

Although Rockwell was not directly involved in the early stages of development of the cesium frequency standards, the on-orbit chronology of events were very similar to the Rb clocks. The first engineering development model failed a few hours after turn-on. The problem was corrected in the pre-production models (PPM) as verified by a total of 77 months of operation for two units with only one failure. This failure will be addressed in the subsequent paragraphs as well as a description of the corrective actions taken to eliminate the problem.

RFS ORBITAL ANOMALIES

On-orbit operation data of GPS Rb frequency standards started with Navstar 1 in March, 1978, followed by Navstar 2 in May, 1978. The original Dash 001 part number clocks were used in Positions 1, 2, and 3 on Navstar 1 and in Positions 3 on Navstar 2. Dash 002 clocks were used in Positions 1 and 2 and Navstar 2. The only difference in the Dash 002 from the Dash 001 clocks was a time constant change in the servo control loop. As shown in Figure 1, three types of problems were experienced:

1. Power supply transformer failures

2. Lamp failures

3. Low frequency oscillation of the VXCO heater control

The operating summary of GPS standards is shown in Table 1. The following paragraphs will address each type of problem, corrective actions taken, and results.

Transformer problems were experienced on both the Dash 001 and Dash 002 standards. The transformer problem was isolated to be a short circuit between the primary and secondary windings, which took time to materialize. After extensive analysis and testing, the cause of the problem was isolated to a number of factors in the transformer design and fabrication processes:

1. The potting compound, used in the transformer, softened the wire insulation.

2. The transformer core, around which the wire was would, had sharp edges and gradually wore through the insulation which has thinned when stretched over the sharp edges on the core.

3. There was an insufficient amount of detail in the transformer assembly and process instructions.

4. The transformer level screening test were inadequate to identify or screen out this type of problem.

The primary corrective actions taken to alleviate this problem are:

1. A new potting resin, compatible with the wire insulation coating, was selected.

2. A very stringent inspection criteria was initiated on all transformer cores.

3. A parylene/RTV coating was applied to the cores.

4. Very detailed fabrication and process instruction procedures were prepared.

5. Each transformer was exposed to a very detailed Acceptance Test Procedure which included post-potting test, thermal cycling, and burn-in testing.

6. Extensive quality inspection controls were instituted.

The new transformer was installed in all Dash 003 and subsequent clocks. Results of this change are very apparent from the data shown on Table 1. A total of 186 months (15.6 years) of on-orbit operation have accumulated with no transformer failures. Referring to Figure 1, note that Frequency Standard 1 on Navstar 3 has been operating continuously for 70 months (approximately six years); this provides a very high degree of confidence that the transformer problem has been corrected.

The Rb lamp failures were perhaps the most critical on-orbit problem encountered on the early space vehicles. To investigate the problem, a team was assembled that consisted of representatives from Rockwell, the National Bureau of Standards, Duke University, the USAF, Aerospace Corporation, and Efratom. Once the clock failure was established to be the lamp, a plan was initiated to duplicate the on-orbit failures in the laboratory. Lamps were prepared with an intentionally low Rb fill, installed into the physics packages, and subsequently installed into several frequency standards. Laboratory testing on these standards duplicated the on-orbit lamp failures. All units exhibited the same lamp voltage decay characteristics symbolic of the suspected lamp failures as illustrated in Figure 2.

To determine the amount of Rb in the lamps, a three-fold corrective plan of action was instituted:

1. For Rb lamps already built, the fill would be determined by neutron activation.

2. The fill of newly fabricated lamps would be determined by sampled destructive analysis.

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3. A calorimetric measurement utilizing a differential scanning calorimeter is now used.

NEUTRON ACTIVATION ANALYSIS OF Rb LAMPS

Neutron activation analysis was one of the methods used to determine the quantity of Rb-87 in the lamps. The procedure is as follows: Lamps are inserted into a nuclear reactor and irradiated with thermal neutrons for about an hour. In addition to the lamps being tested, a special lamp with no Rb, and another lamp with a precisely weighed milligram quantity of Rb metal also are irradiated. The thermal neutrons are absorbed into the Rb in the lamps, producing one or more short-lived radioactive species. The resultant radioactivity is measured by counting with a lithium-drifted germanium gamma ray spectrometer the intensity of certain gamma rays emitted by the activated Rb. The empty bulb provides the background counting rate, and the bulb with a known milligram quantity of rubidium is used to determine the number of counts per second (less background) per milligram of Rb. The amount of rubidium in each lamp then is obtained from the single ratios of counts less background to the known standard. This technique is no longer used due to cost.

DESTRUCTIVE ANALYSIS

Destructive analysis is a method by which the Rb fill of a sample of lamps was made from the same production manifold. Since all of the lamps on the manifold are filled at the same time, it was assumed that the remainder of the lamps had the same fill as the sample. Good results were achieved using this technique. However, the production yield was small. With a manifold of five lamps, three were used to determine the Rb fill and only two remained for clock usage.

The frequency standard dash numbers were changed to identify the types of lamps. Dash 4, 5, 6, and 7 clocks had the lamp fill measured by neutron activation, and the Dash 8, 11, and 12 clocks had the fill measured by destructive analysis. The usage of these dash numbers on the GPS satellites starting with Navstar 5 is shown on Figure 1. Table 1 summarizes the operating history of these frequency standards thorough November 1984. Note that 44 months of failure-free, on-orbit operation has accumulated.

CALORIMETRIC MEASUREMENT

The newest technique that is used to determine the amount of Rb fill is making use of a differential scanning calorimeter, Perkin-Elmer DSC-2C. This instrument is used to measure the heat energy required to melt the Rb in a lamp. This allows (using the known heat of fusion of Rb)(6.2 cal/gram) the amount of Rb to be determined with a resolution of a few micrograms. Life test data shows that the Rb consumption (due to Rb diffusion into the glass) closely obeys a power law model and thus allows an estimate of lamp life to be made. The key variable is the initial Rb fill and its measurements.

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VCXO ON-ORBIT PROBLEM

Rb Frequency Standard 2 on Navstar 2 was turned on May 2, 1978. At turn-on, the Kalman filter residuals indicated a cyclic error with a period of 54 seconds. The trouble shooting plan to determine which part of the frequency standard was at fault, was to switch the standard to the backup mode, record range data, and process this data to determine the delta range residuals. This data was processed by the Aerospace Corporation. The residual errors showed the same cyclic period as the primary mode except the range error magnitude had increased by a factor of the servo loop gain. This increase in short-term error clearly showed the problem to be associated with the 10.23 MHz VCXO.

Laboratory testing was initiated at both Rockwell and Frequency Electronics Inc., (FEI) the VCXO manufacturer. The initial hypothesis was that the oscillation was caused by either the inner or outer oven heaters. To verify this hypothesis, the outer heater was forced to oscillate with a 30-second period. No effect was observed on the VCXO output frequency. This test verified the problem was not caused by the outer oven.

The investigation of the probable causes of the inner oven oscillation was isolated to two areas:

1. A mechanical bond separation at the thermistor, heater winding, or heater transistor

2. A short across the inner oven feed back resistor.

FEI, after extensive testing including aging, vibration, x-ray, and neutron radiography, could not detect any thermistor bond defects. The conclusion reached was that the oscillation was not related to a bond separation.

A computer simulation of the inner heater circuitry showed that a short across R8 would cause an oscillation with a 53-second period. Laboratory test with a short across this resistor duplicated the spacecraft anomaly. Further investigation of the Autonetics test data indicated that the anomaly was not present prior to launch and therefore was caused by the launch environment. The final conclusion was that the short across R8 was caused by an isolated workmanship defect in the routing of jumper wires in the assembly. This conclusion is substantiated by that fact that the oscillation has not re-occurred on any space vehicle Rb clocks.

A very significant fact about the effectiveness of these changes and the improved reliability can be seen by noting the total operating history of the Dash 3 and subsequent standards. Clock 1 on Navstar 3, has been operating for 73 months; Clock 3 on Navstar 4 for 35 months; and the 44 months accumulated on Navstar's 5 through 8 yield a total of 152 months (approximately 13 years) of failure-free operation.

CFS ORBITAL ANOMALIES

As previously stated, the first GPS satellite to have a cesium frequency standard (CFS), in addition to three Rb standard, was Navstar 4. A government-furnished engineering development model (EDM-002), built by Frequency and Time Systems (FTS), was installed into GPS-004 on February 17, 1978; successfully completed all ground space vehicles testing; and was launched on December 11, 1978. A total of 493 space vehicle operating hours were accumulated prior to launch. On February 23, 1979, it was turned on, operated correctly for approximately 12 hours, and failed. The results of an Air Force anomaly team concluded that the spacecraft telemetry indications were not conclusive to isolate the exact cause of the problem. The frequency standard had switched to the backup mode of operation because the cesium-half of the power supply was off. There are two possible failures that would cause this condition: (1) the relay that feeds the second inverter could have failed, and (2) the high-voltage power supply could have failed. The conclusion reached was that the cesium-half of the power supply had apparently failed. The results of the team's investigation verified that, if required, the backup VCXO mode of this clock was still operational.

Numerous design changes were incorporated into the pre-production model power supplies. Table 2 is a summary of the operating history of clocks with modified power supplies. PPM-2 operated on Navstar 5 for 31 months with no problems. The unit was turned off because of a space vehicle attitude control problem. PPM-11 operated on Navstar 6 for 44 months. This unit was turned off because of a depletion of cesium. The two dash 0001 Rockwell units on Navstar's 9 and 10 have a total of 7 months operating time. A resultant total of 84 months of operating time has accumulated on all CFS's with no power supply related problems. This record clearly shows that the problem has been corrected.

As stated in the previous paragraph, PPM-11 was turned off because of the depletion of cesium. Under normal operating conditions, the one gram of cesium in these units was considered to be more than adequate to satisfy the specified 5-year operating life of the PPM units. After reviewing the on-orbit operating data, it became apparent that a cesium leak developed in the cesium oven assembly after 8 months of operation. This additional loss of cesium over a 36-month period caused the earlier than expected depletion of cesium. This same problem developed on another PPM unit (S/N 10) during space vehicle testing. The unit was returned to FTS and a failure analysis was performed. The results of this analysis showed that there was a microscopic tunnel in a braze joint in the oven assembly. Because of the suppliers proprietary nature of this information, no additional details are presented.

As a result of this analysis, the following corrective actions were instituted by FTS in both their commercial and high-reliability tube fabrications:

1. A new brazing procedure was developed.

2. Helium leak testing is performed on all brazed joints.

3. Stricter quality control and inspection points were instituted during the fabrication process.

In addition to these actions, FTS also has increased the amount of cesium fill to 1.5 grams to provide an additional safety margin for the production tubes that have 7-1/2 year specification requirement.

The only corrective measure, in effect at the time the tubes were fabricated for the standards on Navstar's 8, 9, and 10, was the stricter quality control and the institution of inspection points. Therefore, the effectiveness of all of these changes will not be fully verified by on-orbit data of the present satellite constellation. However, the Naval Research Laboratory (NRL) has life testing in progress on two tubes that were fabricated with all improvements. Twenty-four months of continuous operating time have been accumulated on each tube with no failures.

Another significant data point demonstrating the reliability of the cesium frequency standards is the testing of PPM-14 at NRL. This unit has the same tube configuration as the units operating on Navstar's 9 and 10. The test started at NRL on November 17, 1982, and is still in progress. Adding to this, the 6-month operating time of PPM-14 at Rockwell yields 30 months of operation with no problems.

RFS LONG-TERM LABORATORY TEST

An unmodeled deviation of a GPS vehicle clock from GPS time, leads to errors in navigational accuracy. These errors may be minimized by the periodic recharacterization of the clocks in terms of the time difference or phase offset, frequency offset, and the frequency drift with respect to GPS time. In the event the vehicle is not uploaded with this data, the rate at which time error is accumulated depends on the validity of the previously uploaded characterization data.

In order to predict precise user time errors for systems such as GPS, David Allan of the National Bureau of Standards (NBS) has published a model (References 1, 2) for the prediction of time error based on the previous performance of the clock in terms of the Allan variance, $\sigma_y(t)$, and the length of test data. This model has set GPS autonomous operation standards and prediction of available navigational accuracy versus time from upload.

An internal project was initiated in an effort to better characterize the Rb frequency standards developed for GPS associated with the autonomous operational goals. In order to perform this task, an 140-day stability test was completed from February to June 1983, with the necessary data taken to calculate drift, time error, and Allan variance. During this test, the phase accumulation between the test RFS and the reference cesium clock, frequency performance, and test telemetry were recorded to determine the actual time prediction error accumulated during the test (Reference 3).

This time prediction error is the difference in the actual phase accumulation and the predicted phase. The time error is sensitive to external and internal environmental influences on the clock.

The beat frequency, $\Delta f/f$, is shown in Figure 3. The frequency was calculated from 1,000-second period average data, which was then averaged over 10 data points to conform to computer storage requirements. Examination of the entire 140-day period shows an initial "warmup" period of about 50 days, during which the drift changes from about minus 6×10^{-14} $\Delta f/f/\text{day}$ to minus 2×10^{13} $\Delta f/f/\text{day}$. The frequency drift is relatively constant from Day 50 to Day 140, except for a dip from Day 70 to Day 86. This dip correlates to a drop the clock baseplate temperature of about 0.8°C. This points out the critical role that temperature stability plays with frequency and time prediction error.

The Allan variance, σ_y, can be calculated both with and without the warmup period data. It can be seen in Figure 4 that the main effect of the behavior is on the long-term values or the "random walk." The total data σ_y represents the usual RFS Allan variance signature; whereas, the day 50-150 σ_y values are better in terms of random walk. If μ is the slope of the random walk portion of the Allan variance plot where $\sigma_y \sim t^\mu$ for large t, then $\mu = 0.7$ for Day 0 to Day 140 data, and $\mu \simeq 0.1$ for Day 50 to Day 140 data.

Excluding the data which was affected by the warmup or temperature change, the time prediction error is found to be very small. This points out the importance to the time error of small temperature changes to the RFS. Since the on-orbit Rb standards now have a baseplate temperature controller that controls the clock temperature to within $+0.1^{\circ}\text{C}$, excellent time error values on orbit are expected as evidenced in Navstar 8.

This test has shown that time prediction error is very sensitive to environmental influences, both external and internal to the RFS. Specifically, the apparent aging of the Rb lamp represents an internal, systematic change and correlates with the clock frequency characteristics. This characteristic influences both the clock warmup time and the apparent random walk portion of the Allan variance. Measuring the long-term Allan variance during this warmup period gives a random walk slope in the $t = 10^5 - 10^7$ region. However, this does not represent random walk behavior of the clock that has warmed up, but a systematic change. Once the RFS has been on for 50 to 60 days, the lamp voltage curve begins to straighten out and the RFS random walk values decrease dramatically. Data beyond this 60-day warmup period best characterizes the frequency standard if the temperature is held within $\pm 0.1^{\circ}\text{C}$.

It was seen from the baseplate temperature that a 0.8°C temperature plateau resulted in a small frequency shift. For a 15-day period, this gave a 600 to 700-nanosecond offset. This period influenced longer data length prediction intervals before, during, and after the occurrence of the plateau. All subsequent RFS's now are being controlled to $\pm 0.1^{\circ}\text{C}$ by a temperature controller.

The final test period (beyond the lamp warmup and the 0.8°C temperature variation) data resulted in excellent time prediction error values with the longer period plots, satisfying the 131-meter, 14-day user range error requirement. This is significant in the view of the GPS autonomous operation requirements, which were previously thought optimized by only the cesium standard.

CONCLUSION

Considering there were no space qualified Rb or cesium frequency standards available 11 years ago at the start of the GPS program, the development and on-orbit performance of both types of standards has been outstanding. This is not to say that this program has not experienced the normal types of problems associated with new hardware. As substantiated by on-orbit performance data, the corrective actions taken to eliminate the problems have been very effective. No transformer or VCXO oven oscillation problems have occurred since the implementation of corrective actions in the Dash 0003 Rb frequency standards. No lamp problems have occurred since the corrective action implementation in the Dash 0004 standards. The same results are apparent in the cesium frequency standards. The corrective actions taken associated with the power supply problem have not re-occurred in any of the PPM or Dash 0001 units. Although there is not sufficient on-orbit data to verify the corrective measures taken to eliminate early depletion of the cesium, more than 24 months of laboratory data have accumulated at NRL that demonstrates the effectiveness of this change.

The validation of the approach taken on the GPS program to have frequency standards with both a primary and secondary mode of operation is very apparent. If this approach had not been taken, both Navstar's 1 and 2 would have been inoperative in less than 3 years. Both Navstar 1 and 2 have been operating in the backup mode for approximately 4 years. The backup mode of operation is still available on all other Navstar space vehicles, if required at some later time to illustrate the effectiveness of this approach. A total (all clocks) of 312 months (26 years) of on-orbit time have accumulated in the primary mode of operation and 428 months (35.7 years) including the backup mode of operation.

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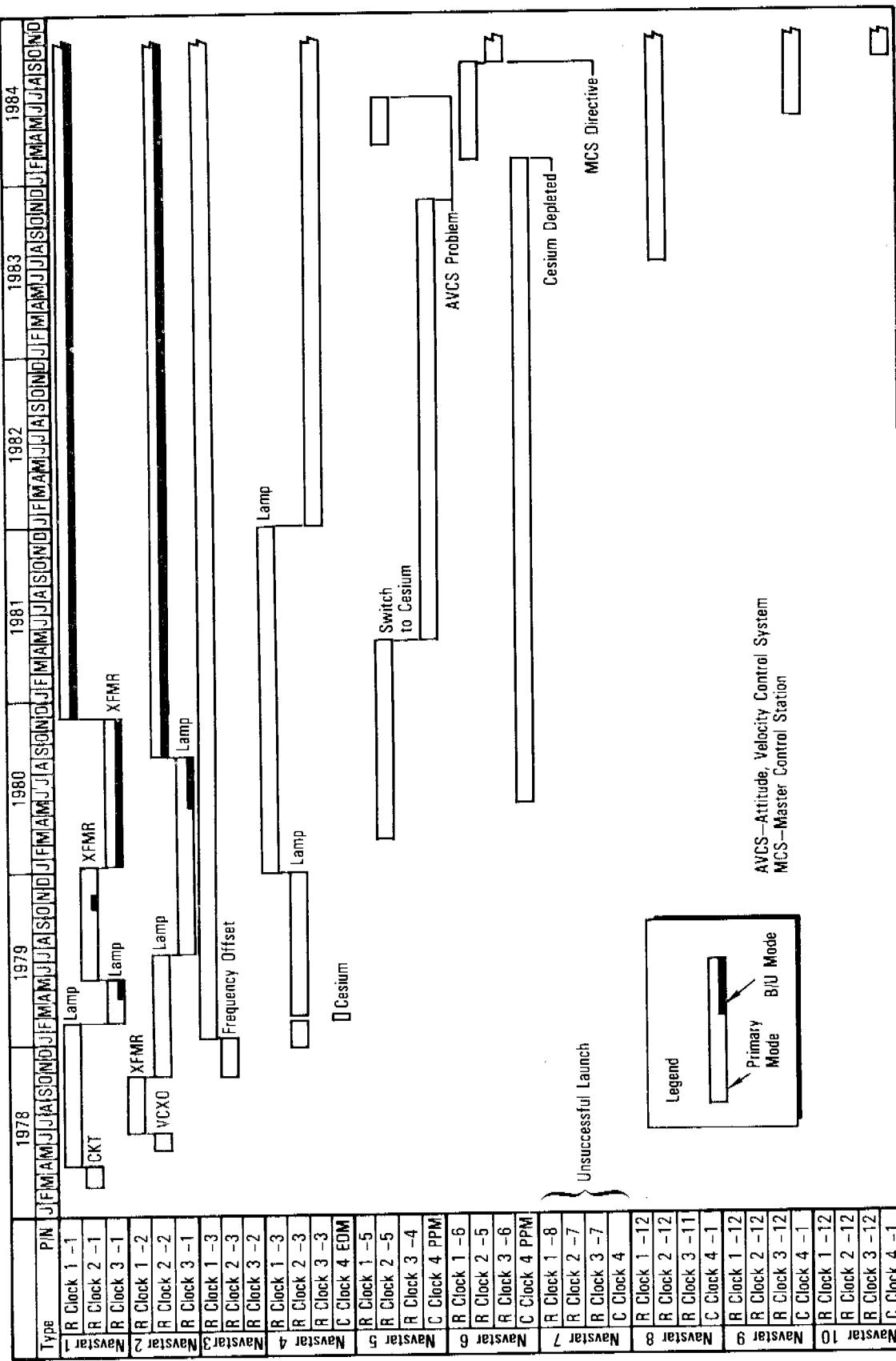
ACKNOWLEDGEMENTS

Figure 1. Navstar Clock Operating History

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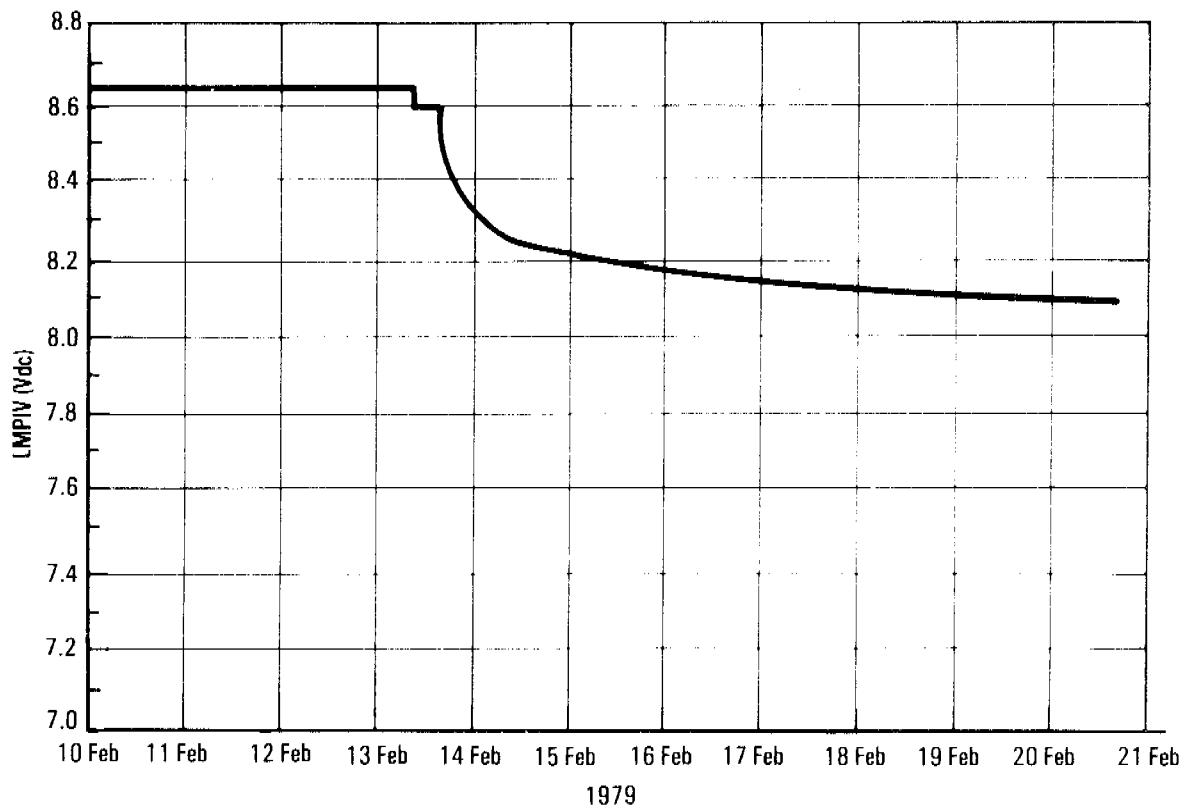
Figure 2. Navstar 1 Frequency Standard No. 1 LMPIV Anomaly
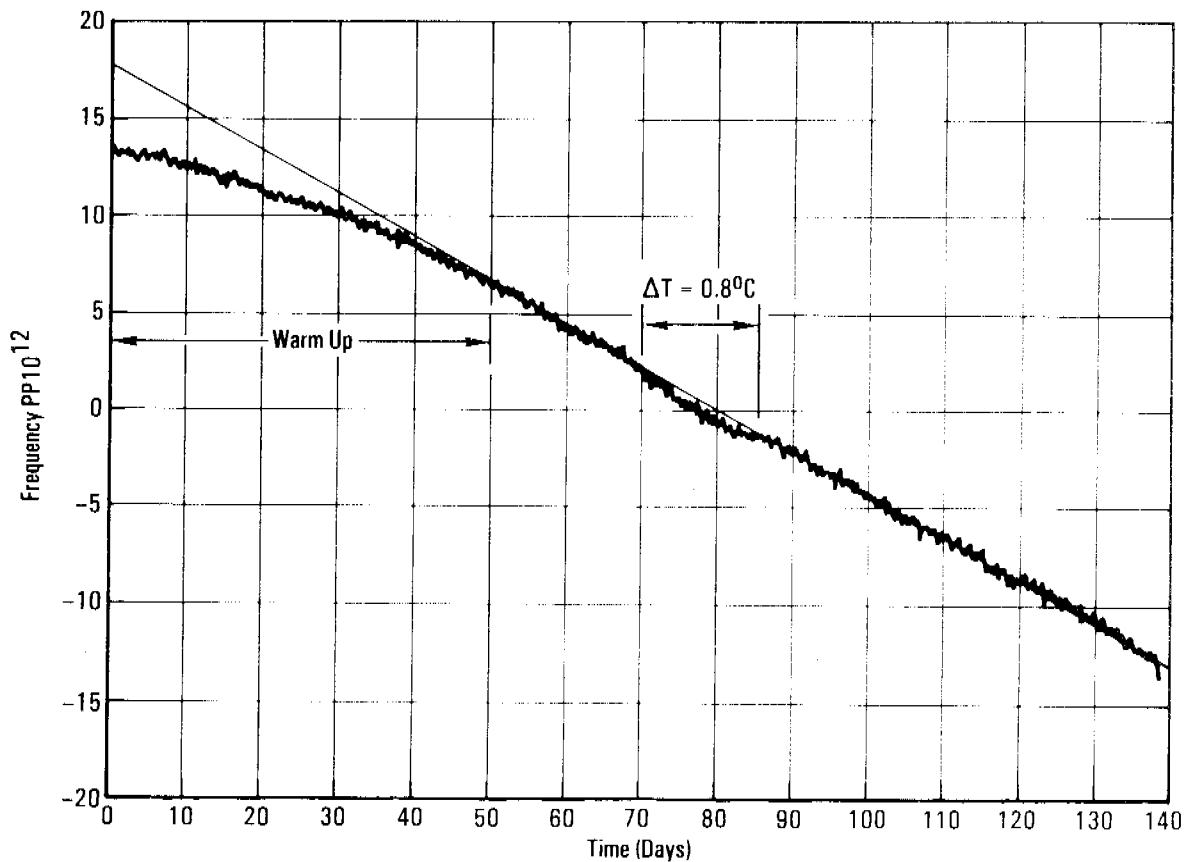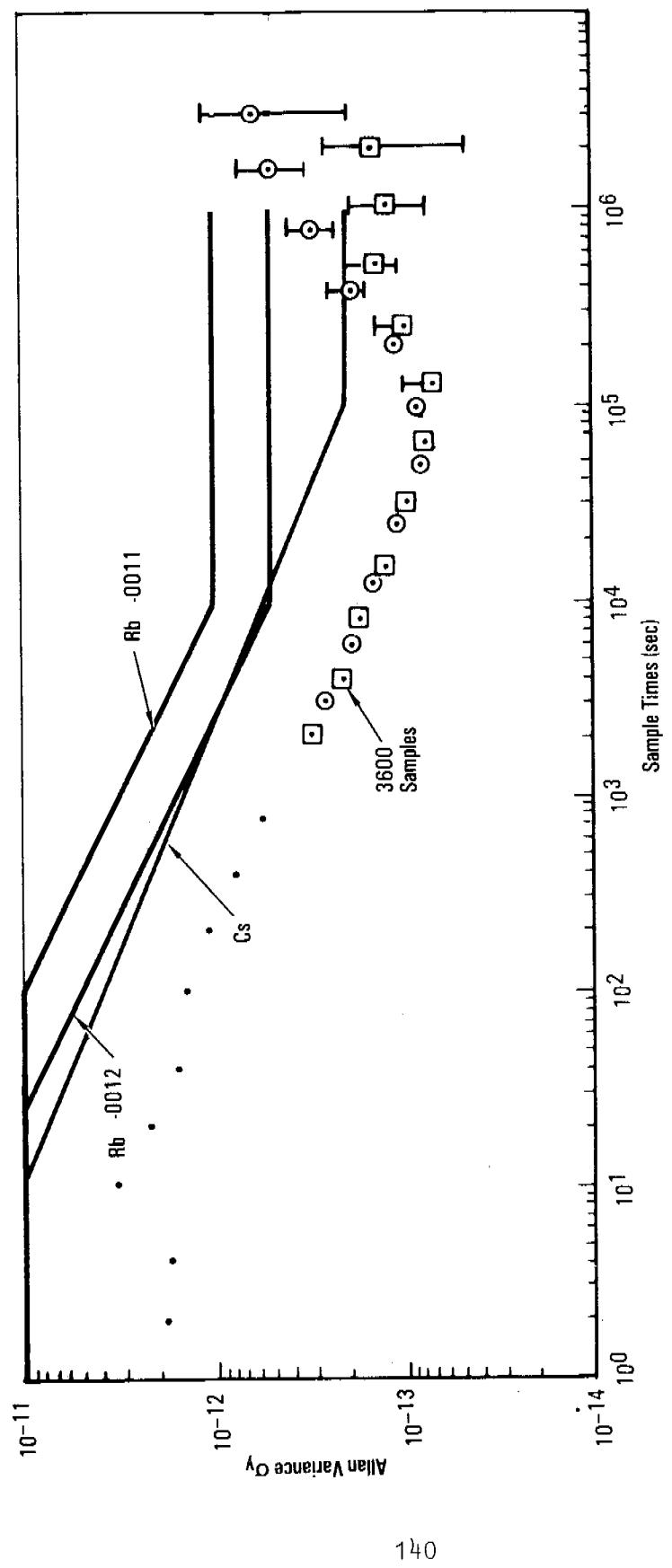
Figure 3. GPS 140-day Rb Stability Test

Figure 4. IR&D Time Error 140-day Stability Test Rb Frequency
Standard No. LQX0001

Table 1. GPS Rubidium Frequency Standard Operating Summary (Primary Mode)

Navstar	P/N	Months of Operation							Total (months)	Failures	Failure Mode	Comments
		1978	1979	1980	1981	1982	1983	1984				
1	-0001	10	12	B/U	B/U	B/U	B/U	B/U	22	3	Lamps, XFMR	B/U--backup mode Must update every orbit
2	-0001 -0002	6	12	4	B/U	B/U	B/U	B/U	22	3	Lamps, XFMR	Low frequency oscillation Nonoperational
Total		16	24	4	0	0	0	0	44	6		Months of operation/failure 44/6 = 7.3
New Power Supply XFMR Design (-0003 and subsequent)												
3	-0003	2	12	12	12	12	12	11	73	1	Frequency offset	Second Rb clock on for 70 months (5.8 years)
4	-0003	0	12	12	12	12	12	11	71	2	Lamps	
Total		2	24	24	24	24	24	22	144	3		Months of operation/144/3 = 48
Rubidium Lamp Change (-0004 and subsequent)												
5	-0004 -0005	0	0	10	4	Cs Op	Cs Op	3	17	0	None	AVCS problem Cs--Cesium clock
6	-0005 -0006	0	0	Cs Op	Cs Op	Cs Op	Cs Op	10	10	0	None	Cs--Cesium clock
8	-0011 -0012	0	0	0	0	0	4	11	15	0	None	
9	-0012	0	0	0	0	0	0	Cs Op	0	0	None	
Total		0	0	10	4	0	4	24	42	0	None	No failures--42 months of operation

Table 2. GPS Cesium Frequency Standard Operating Summary

Navstar	P/N	Months of Operation							Total (months)	Failures	Failure Mode	Comments
		1978	1979	1980	1981	1982	1983	1984				
4	EDM	0	0	0	0	0	0	0	0	1	High voltage power supply	Backup (VCXO) mode still operational
5	PPM	0	0	0	0	12	11	0	31	0	None	
6	PPM	0	0	7	12	12	12	1	44	1	Depletion of Cs	Backup (VCXO) mode still operational
9	-0001	0	0	0	0	0	0	5	5	0	None	
10	-0001	0	0	0	0	0	0	2	2	0	None	
Total		0	0	7	23	24	23	8	82	2		Months of operation/failure 82/2 = 41
	PPM 14											Additional testing: 24 months at NRL, 6 months at Rockwell