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

M. J. VAN MELLE
GPS NAVSTAR OPERATIONS
Rockwell Space and Operation Center
Falcon Air Force Base, Colorado Springs, CO

Abstract

This paper is an update of the on-orbit operational performance of the frequency standards on the Block I GPS 8 to 11 Navstar satellites, the Block II GPS 13 to 21 Navstar satellites and the Block IIA GPS 22 to 40 Navstar satellites. A brief history of the frequency standards depicting improvements incorporated in the GPS Program with corresponding results will be presented.

The frequency standards configurations from the start to the present, including the various Block IIA clock configurations will be discussed. Topics such as clock observations and long term trending analysis which could enhance on-orbit performance analysis will be covered. endabstract

INTRODUCTION

The evolution of the frequency standards on the GPS Program started with the Block I concept validation program which included the prototype (GPS 1 through 8) space vehicle contract in 1974. The full–scale development vehicles (GPS 9 through 11) contracted in 1978 provided both navigational and nuclear detection capability. The production qualification vehicle (GPS–12) was contracted in 1980 and the production vehicles (GPS–13 through 40) were contracted in 1983. These production vehicles were divided into two groups, Block II (GPS 13 through 21) and Block IIA (GPS 22 through 40).

A considerable amount of effort was devoted to the frequency standards since there were no space–qualified Rubidium or Cesium frequency standards available at the start of this GPS Program. The initial GPS vehicles (1 through 3) utilized three Rubidium Frequency Standards (RFS), each with a back-up mode, to minimize the risk to the GPS Program on this critical item for achieving high user position accuracy. Later space vehicles, starting with GPS-4 and ending with GPS–11 included one Cesium Frequency Standard (CFS), also with a back–up high performance voltage–controlled crystal oscillator (VCXO).

All GPS production vehicles, starting with GPS–13 and ending with GPS–40, include two Rubidium Frequency Standards and two Cesium Frequency Standards, each still with a back–up VCXO mode. The CFS are considered primary because of their degree of radiation hardness and their extremely low frequency drift rate or aging.

The actual on–orbit GPS Frequency Standard operating history (shown in Figure 1 for still operating Block I satellites, Figure 2 for Block II satellites and in Figure 3 for Block IIA satellites) illustrates the results of these hardware implementations.

ON–ORBIT PERFORMANCE

The operating summary and life history of the two production models of Cesium Frequency Standards from Frequency Time System (FTS) are shown in Tables 1 and 2. All three of the first production models, P/N1, had successful operations on GPS–8, 9 and 10 as depicted in Table 1 for a total of 270 months or 7.5 years of operations per clock. The operating life history of the production model, S/N 4, P/N 1, Cesium Frequency Standard, on GPS–9 was very impressive. This particular clock was turned on 06/28/84 with no C–field tune necessary for its entire life of 9.3 years. There are several reasons why this particular clock was turned off on 10/01/93 before it had a catastrophic failure. These included poor stability, large frequency offsets, low cesium beam current, end–of–life testing on such an old clock, untried RFS's and limited projected vehicle life–time all of which will be discussed in more detail in the cesium trending section.

The differences between P/N 1 and P/N 2 CFS are the amount of cesium fill (1.0 grams to 1.5 grams) and a stricter quality control and inspection point program. All of the Block II vehicles currently have P/N 2 cesium clocks from FTS. As can be seen from Table 2, the two clocks that have failed without hope of continued operation are, GPS–14 and 15, and the one cesium clock on GPS–19 has questionable operation which may be given a second chance for use in the future. The two failures had an average lifetime of 2.75 years with the suspect clock having a life of 2.7 years. This is a far cry from the P/N 1 lifetimes. So much for stricter quality control on Cesium Frequency Standards. Of course the sample size is very small for any real conclusions.

There are several ways to acquire the exact performance characteristics of on–orbit frequency standards. The best way is to have a direct monitor point on the 10.23 MHz clock output. Since this is not available, the next performance evaluation is through the L–band signal which is affected by the FSDU and NDU trickery, atmospheric effects, ephemeris unknowns, monitor station variations and other factors. All of these factors are fed into the Kalman filter, a computer algorithm for processing discrete measurement data in an optimal fashion.

Two parameters that are helpful in evaluating the operating performance of the frequency standards are read off of the daily and/or weekly Kalman filter drift state residual plots. The first is frequency offset in sec/day, a_1 term. This is the filter's estimate of the frequency difference or offset between each satellite frequency standard and the GPS composite clock (a nominal frequency). This is a continuous absolute value. Typical values of a_1 are 1 X 10^{-8} to 1 X 10^{-6} sec/day (1 X 10^{-13} to 1 X 10^{-11} sec/sec) depending on cesium or rubidium data, respectively. Another parameter, $A1$, that has more movement and possibly more trending signature, is calculated by taking the daily average of the difference between the minimum and maximum values of a1. These values vary from 1 X 10^{-13} to 4 X 10^{-13} sec/day.

Another parameter is the motion or frequency drift in sec/day^2, (a_2 term). This is the difference between the maximum and minimum value of Kalman data averaged over a one week period. (a relative value). These values vary from 0.8 X 10^{-9} to 20 X 10^{-9} sec/day^2 (1 X 10^{-17} to 3 X 10^{-16} sec/sec^2) depending on whether a cesium or rubidium, respectively is operating.

Plots of these filter estimates provides us with a means of evaluating the performance or stability of each spacecraft's clock (Figures 4 through 6). Figures 4 and 5 depict typical a1 terms (the x–axis) for cesium clocks and very good drift rate term, a_2. Figure 6 shows the only RFS on orbit with its a_1 term and a very large drift rate term a_2 ($\approx$ 50 times greater than a typical cesium). Figure 7 through 9 shows the estimated range deviation (ERD) of three different performing satellite clocks for a particular week with excellent, good and fair performances, respectively. These performance ratings are very subjective and correspond to the following definitions: excellent performance = ERD are less than 4 meters per day, good performance = ERD are less than 8 meters per day and fair performance is when the cumulatively ERD are greater than 10 meters and require additional work by the MCS crew in the form of extra navigational uploads. One important criterion for the Kalman filter is to provide accurate continual measurement updates. Unfortunately there are periods when the spacecraft is not in view of a monitor station, and the filter must propagate aging, through the a_2 term, with no real measurement verification. In other words, some fraction of the total possible data is lost. Another factor in evaluating the filter results is that the data periods are retrieved by different monitor stations (MSs) with different clocks contributing errors into the filter estimation and subsequently the prediction process. Therefore, each MS's operational clock must have a drift plot generated daily for analysis to evaluate filter results. This becomes important for constellation analysis, i.e. when all SV clocks supposedly change when in view of the same monitor station. This would mean that the MS clock is actually drifting or that a switch from MS clock #1 to clock #2 had occurred.

The Second Space Operations Squadron (2SOPS) at Falcon Air Force Base at Colorado Springs, monitors the performance of the clocks via the daily and weekly Kalman filter estimate. From the Kalman drift state residuals plots, the continuous frequency offset from the GPS master clock is shown. Along with the clock movement in parts/day, the drift rate term (a_2) in sec/day^2 is also shown as a weekly value. Because this term is so small for the CFS, the a_2 term in the navigation message is set to zero.

Table 3 depicts the life history of the rubidium clocks on operational vehicles in 1993. (See Reference 2 for earlier history.) On the remaining operating Block I (experimental) satellites (GPS 9, 10 and 11), there are three RFS's operating in the primary mode. As can be seen, the final production model #12 RFS's have not acquired much on–orbit operating time lately since the cesiums clocks have been preferred over the rubidiums. This is because of the advantage of cesium over rubidium in terms of radiation hardness and autonomous operations (low, predictable drift rate) and no C–field tunes. Other reasons why cesiums are turned on first include the fact that there were no cesiums on the first four Block I's, only one cesium on the last six Block I's, and an equal number (2 of each) on Block II and IIA's. And now a reversal has taken place in that only one cesium is planned on Block IIR. There is one positive note on leaving the RFS's until last and that is to prove that rubidium clocks will not have any trouble turning on and operating successfully after six to nine years of radiation in space. There have been six turn–ons so far (five successes and one failure), with five more samples to test (Table 3). This is important because on the Block II and IIA's, the rubidiums will be turned on last with turn–on's expected from 1996 through 2000. There are already two vehicles on their last cesium (GPS 14 and 15) and three more vehicles with suspect cesiums (GPS 19, 22 and 23). This information is included in Table 4 "Navstar Mission Operations Status" along with a variety of performance parameters, such as a_1 and a_2 terms (discussed earlier), that help in determining the weekly operational status of each vehicle's clock.

FREQUENCY STANDARD ON–ORBIT TRENDING

One of the main objectives of performing trend analysis on a frequency standard is to prevent a long downtime of the satellite (unhealthy status). It is extremely hard to predict when a particular on–orbit cesium or rubidium clock will expire. Particularly elusive is the time frame–whether it be in days or weeks or months or the tolerance of the crews toward a clock that does not meet specification. It is the Air Force who will ultimately determine how burdensome to the MCS crew a particular clock, is based upon how many uploads must be performed to keep the estimated range deviation (ERD) under 10 meters. Multiply these extra daily uploads by two or three suspect vehicles plus the normal daily uploads to the other 22 or 23 healthy vehicles and the crew size will have to grow in number.

In order to predict the useful operating lifetime of either a cesium or rubidium, there are several parameters that must be examined. The most important performance parameter is the stability of the clock. This is what most affects the user. As seen in Figure 10, (Reference 1) the stability of GPS-9 slowly degrades with time, to the point where the user error becomes to large to comfortably handle. Frequency offset is another parameter that could affect the user to the extent that additional uploads are needed to correct the a_0 and a_1 terms (usually scheduled uploads suffice as the Kalman updates these terms continuously).

Of all the telemetry monitors on the clocks, there is only one on the cesium clock that has character or an individuality. This trending parameter is the cesium beam current telemetry monitor. It is also a fore-teller of failure. What makes this monitor hard to interpret, is that each clock starts off at a different absolute value, each has a different rate of decline and each has a different final plateau. This can be seen in Figures 11 through 14. Examining Figure 15 which depicts GPS-9 beam current over the last three years, a definite slope change can be seen in the last two months, along with poor stability and extra uploads each day. These last two correlations are important. Because if day 400 (mid-February of 1992) is taken as an example, there is also a large slope change in current but there was no correlation with poor stability or large frequency offsets or large ERD's (Figure 10). These declines were similar to the signatures of the cesiums on GPS-8 and GPS-10 just before catastrophic failure occurred (cesium depletion). Another example is GPS-15, turned off because of very unstable frequency, which had an initial beam current of 20 nano-amps and a value of two nano-amps at the end. This ratio of 20/2 or 10 to 1 relates to a reduction in loop gain, which can also be inversely correlated to another trending parameter, the loop time constant. Unfortunately, in order to measure the loop time constant of a clock, the vehicle must be set unhealthy, which the Air Force will only do under dire circumstances. If the telemetry interpretation is correct, that the beam current is really dropping, then the ratio of the original time constant ($\approx$ 12 seconds) to the final or measurement time constant (GPS-10 was equal to 120 seconds) will also be 10 to 1 (same as the ratio of original beam current to final beam current). This does not necessarily mean that a cesium depletion problem is imminent but that changes in other cesium tube parameters such as electron multiplier gain, pre-amp gain or about 10 other tube parameters may have effected the telemetry monitor value. And while the satellite is unhealthy, other tests such as Ramsey pattern retrace (should not be a flat line) and modulation tests (should be greater than 30%) should be performed, in order to determine a good or bad tube .

The rubidium clocks have only three telemetry monitor points. If the two control voltages start to change abruptly, it will be a direct and obvious verification of clock movement. Very small and gradual voltage changes are expected because of crystal aging. For example, the rubidium control voltages, 10 MHz and 10.23 MHz, on GPS-3 after 12 years of operation rose from 5 V to 13 V and 7 volts to 9 volts, respectively. In other words when the circuitry of the clock would degrade or the crystal would age, the control voltages would change in order to output the same frequencies, 10 MHz or 10.23 MHz. These voltage movements were still within the control region of both oscillators. The lamp voltage dropped from 7.6 V to 7.3 V over the 12 years with the final days of operation from 7.3 to 7.0 V (typical signature of rubidium depletion).

Another trending parameter that effects the performance of both clocks, in particular the RFS, is on-orbit temperature of the spacecraft. Studying Figure 16, prediction of temperature changes (and power constraints on aging Block I vehicles) can be made and incorporated into the trend analysis. [This eclipse data can also be used to calculate when the spacecraft's first eclipse season occurs so as to beware of the infamous bump-in-the-night phenomena. This is a known (but not completely understood) ephemeris issue and not a clock jump].

SCHEDULES

The last of the Block I satellites, Navstar 11, was launched on October 8, 1985. Of these 10 spacecraft, three satellites are currently providing good to excellent data to ground users and are situated in two orbital planes; one, GPS–10, in the 120 degree plane A/, and two, GPS–9 and GPS–11 in the 240 degree plane C/.

The last of the larger Block II satellites Navstar 15, was launched on October 1, 1990. Of these nine satellites, all nine are providing continuous service to all ground users.

These satellites have the same clock configuration of two CFS's and two RFS's. The most recent Block IIA satellite, Navstar 34, was launched on October 26, 1993, with the next scheduled for launch in March, 1994. This will complete the Block II and IIA constellation for fully operational capability (FOC) requirements. Besides the more sophisticated payloads on GPS–22 et al, GPS–29 through 34 each have a different manufacturer of cesium clocks. GPS 29, 30 and 34 have a second source cesium clock developed by Kernco which is similar to the future Block IIR clock. The performance of GPS–29, is excellent at one day, $< 1 \text{ X } 10^{-13}$ $\Delta f/f$, and is only suppassed by the only operating Block II/IIA rubidium on orbit, GPS–25. For 10–day stability and longer, this cesium is far superior, $< 3 \text{ X } 10^{-14}$. This data and more are included in the GPS Block I/II/IIA clock status charts (Table 4).

The total on–orbit times for both rubidium and cesiums are staggering for the first operational satellite system ever to utilize both types of production frequency standards. The on–orbit times for all rubidiums exceeds 600 months or 50 years of operation. The longest operating time on a RFS was 12 years and 5 months on GPS–3. The oldest operating RFS is on GPS–11, 4 years and 11 months, and still glowing.

The cesium on–orbit times are more impressive with figures of 1040 months or 86.6 years. The longest operating CFS was on GPS–9 for a total of 9 years and 3 months. The oldest operating Block II/IIA CFS, on GPS–13, was turned on June 17, 1989 and is still ticking.

Tabulation of all the individual operational hours on–orbit for frequency standards on Block II and IIA vehicles are included in Table 5.

CONCLUSION

As verified by on–orbit performance data, most of the corrective actions taken to eliminate problems in the clock, especially the rubidiums (lamps), have been very effective. Not only have these frequency standards demonstrated their combined five–year specified operating life but they have extended the operating time past the 7.5 years time frame. The usefulness of the back–up mode concept in each clock is greatly diminished because of the total success so far of the GPS constellation both in terms of numbers and performance.

The more data that are collected each day and the more clocks that are turned on, the easier it will be to predict and trend the performance and lifetime of the clocks through analysis. A total (all clocks) of 1640 months (136 years) of on–orbit time has accumulated in the primary mode.

For the more managerially inclined, instead of sifting through all the Kalman drift rate residuals, Allan variances, temperature coefficients, the ERD's, PRR's and SPR's, then Table 6 is for your review. These little quirks and idiosyncrasies of each vehicle combined with clock performance (in more detail in Table 4) are for management eyes only.

REFERENCES

1. Buisson, J. and Reid, W., *Navstar Analysis update No. 9–2*, Naval Research Laboratory Space Application Branch, 9 Sept. 1993.

2. Van Melle. M. J., *Cesium & Rubidium Freq. Standards Status,* ION, August, 1990

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- Aerospace
- Rockwell International (RFS Manufacturer)
- Frequency and Time System (CFS Manufacturer)
- Frequency Electronics Inc., and Kernco (CFS2 Manufacturers)

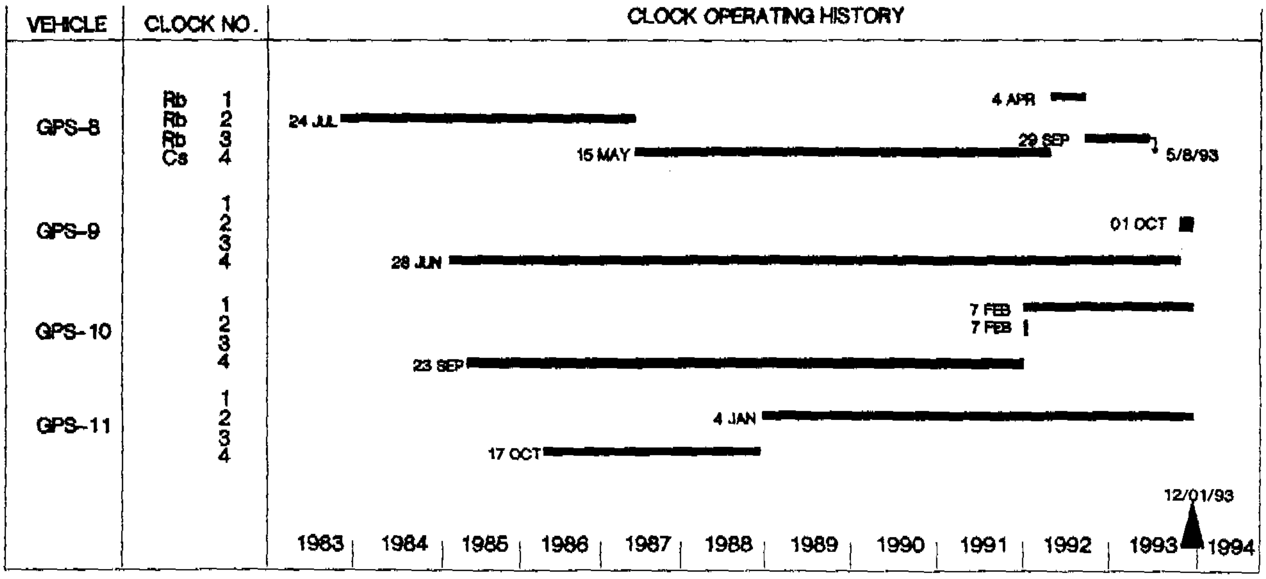

FIGURE 1: BLOCK I FREQUENCY STANDARD CONFIGURATION

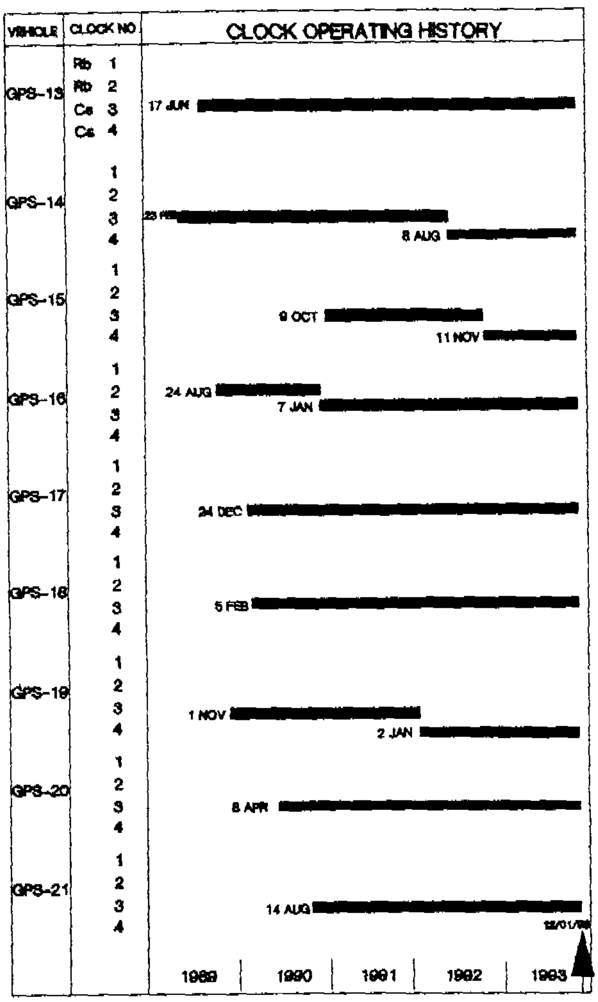

FIGURE 2: BLOCK II FREQUENCY STANDARD CONFIGURATION

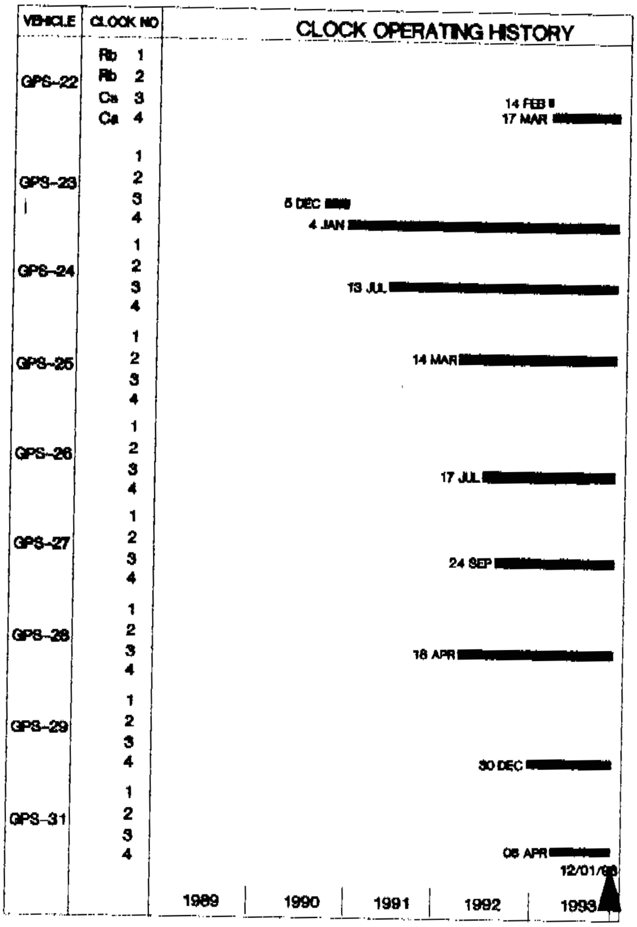

FIGURE 3: BLOCK IIA FREQUENCY STANDARD CONFIGURATION

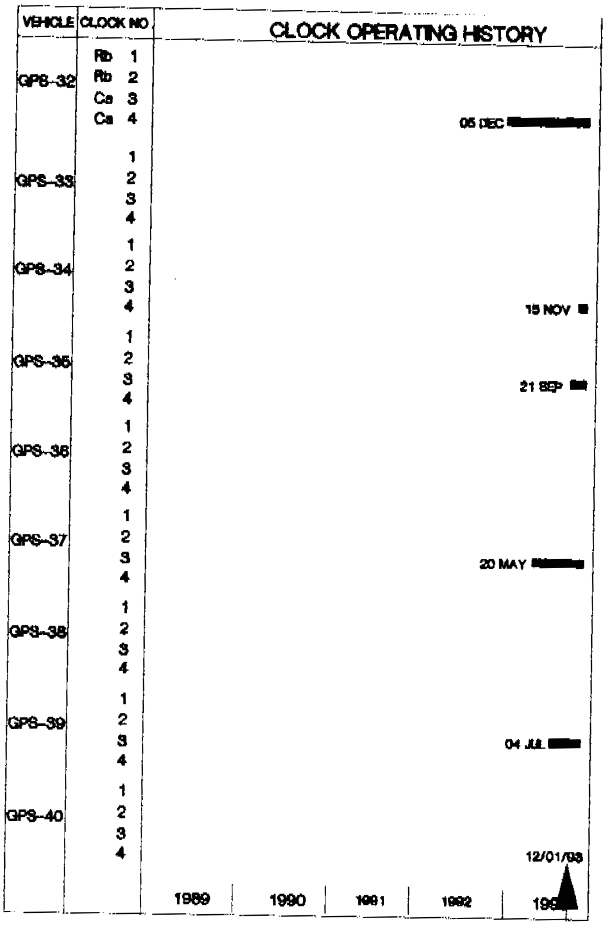

FIGURE 3 (CONT) BLOCK IIA FREQUENCY STANDARD CONFIGURATION

TABLE 1: ON-ORBIT LIFE TIME OF BLOCK I CESIUM FREQ. STD. Dec. 1993

BLK I	GPS	TIME		PROBLEM	MODEL
		YEARS	MONTHS		
	4	0 YEARS	12 HOURS	H. V. POWER SUPPLY	EDM
	11	3 YEARS	3 MONTHS	STABILITY AND DROP IN FREQUENCY	PPM
	6	3 YEARS	9 MONTHS	Cs DEPLETION	PPM
	8	5 YEARS	11 MONTHS	Cs DEPLETION - LOW CBI & Lg FREQ. VARIATIONS	1
	10	7 YEARS	4 MONTHS	Cs DEPLETION	1
	9	9 YEARS	3 MONTHS	STABILITY > 3×10^{-13}; EXTRA DAILY UPLOADS LOW CBI	1

TABLE 2: ON-ORBIT LIFE TIME OF BLOCK II CESIUM FREQ. STD. Dec. 1993

BLK II & BLK IIA	GPS	TIME		PROBLEM	MODEL
		YEARS	MONTHS		
	23	0 YEARS	1 MONTH	FREQUENCY JUMPS	2 *
	22	0 YEARS	1 MONTH	SOLAR COEFFICIENT PROBLEM WITH THE KALMAN FILTER, CBI DROP FROM 15 - 10 ns	2 *
	15	2 YEARS	1 MONTH	NOISY, LARGE LOOP TIME CONSTANT	2
	19	2 YEARS	2 MONTHS	SAWTOOTH FREQUENCY OFFSET	2 *
	14	3 YEARS	6 MONTHS	FREQUENCY FLUCTUATION & LOOP CONTROL FLUCTUATION	2

* CANDIDATE FOR REUSAGE

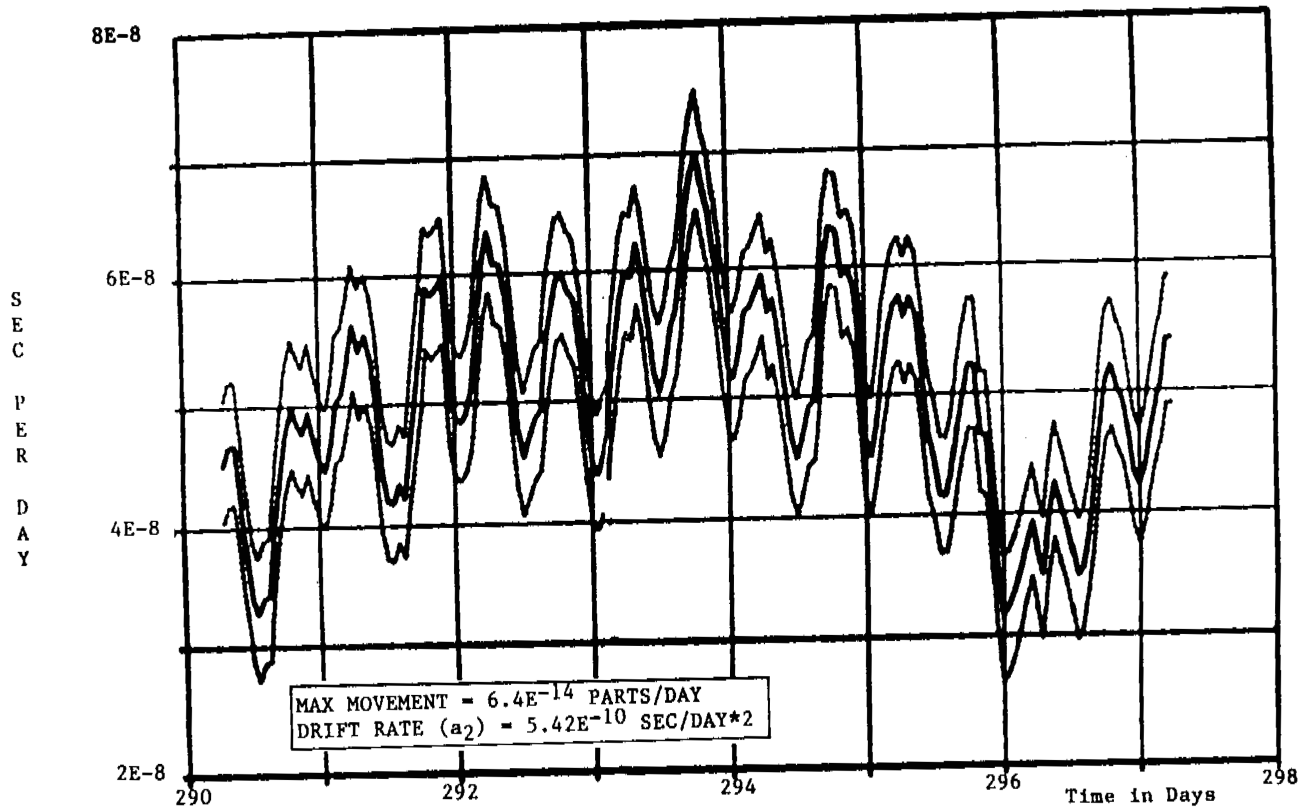

FIGURE 4: DRIFT STATE RESIDUAL FOR NAV 29

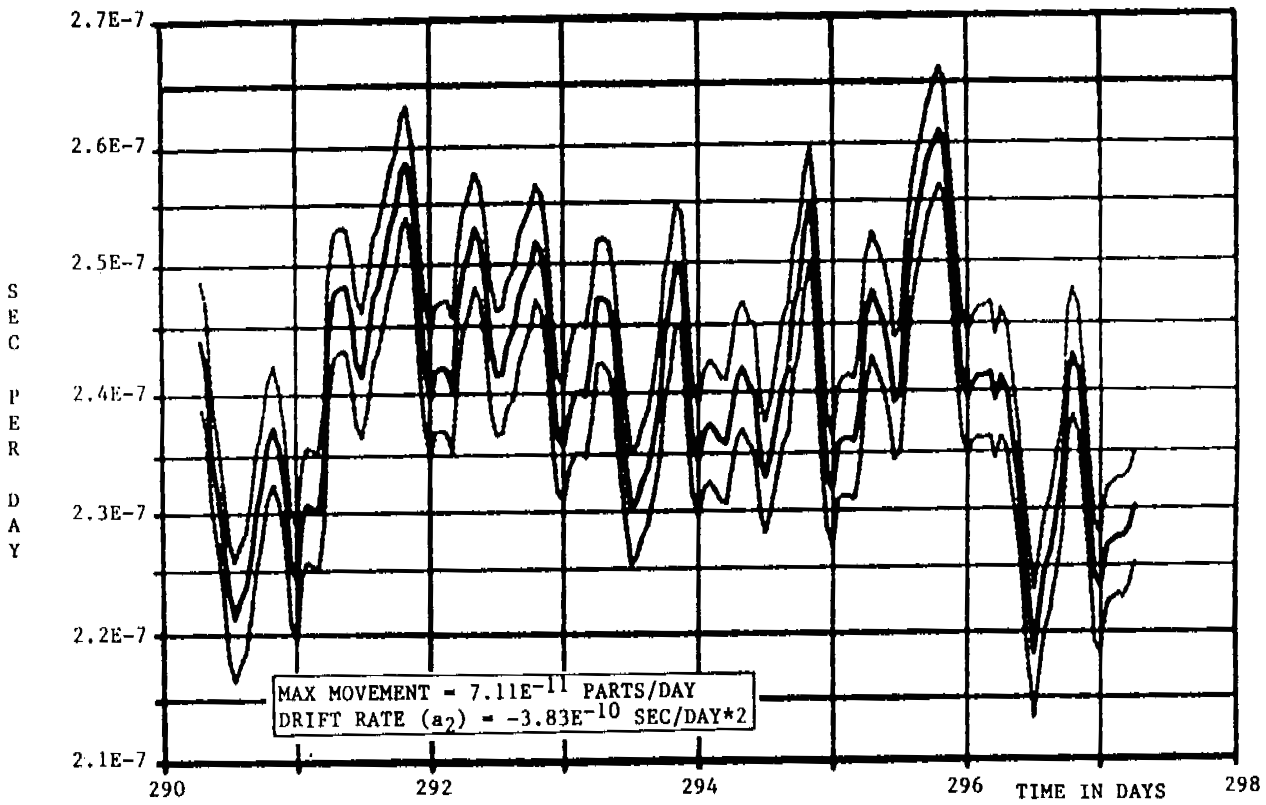

FIGURE 5: DRIFT STATE RESIDUAL FOR NAV 31

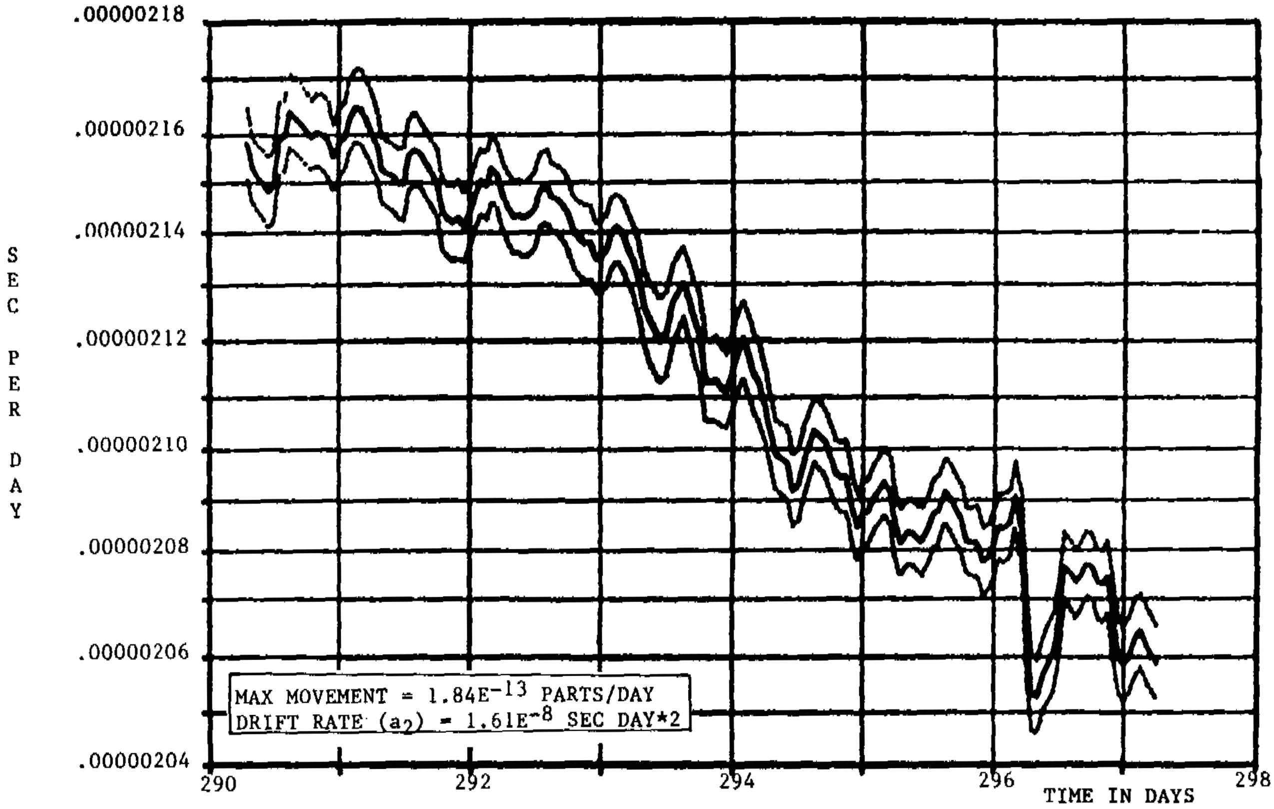

FIGURE 6: DRIFT STATE RESIDUAL FOR NAV 25

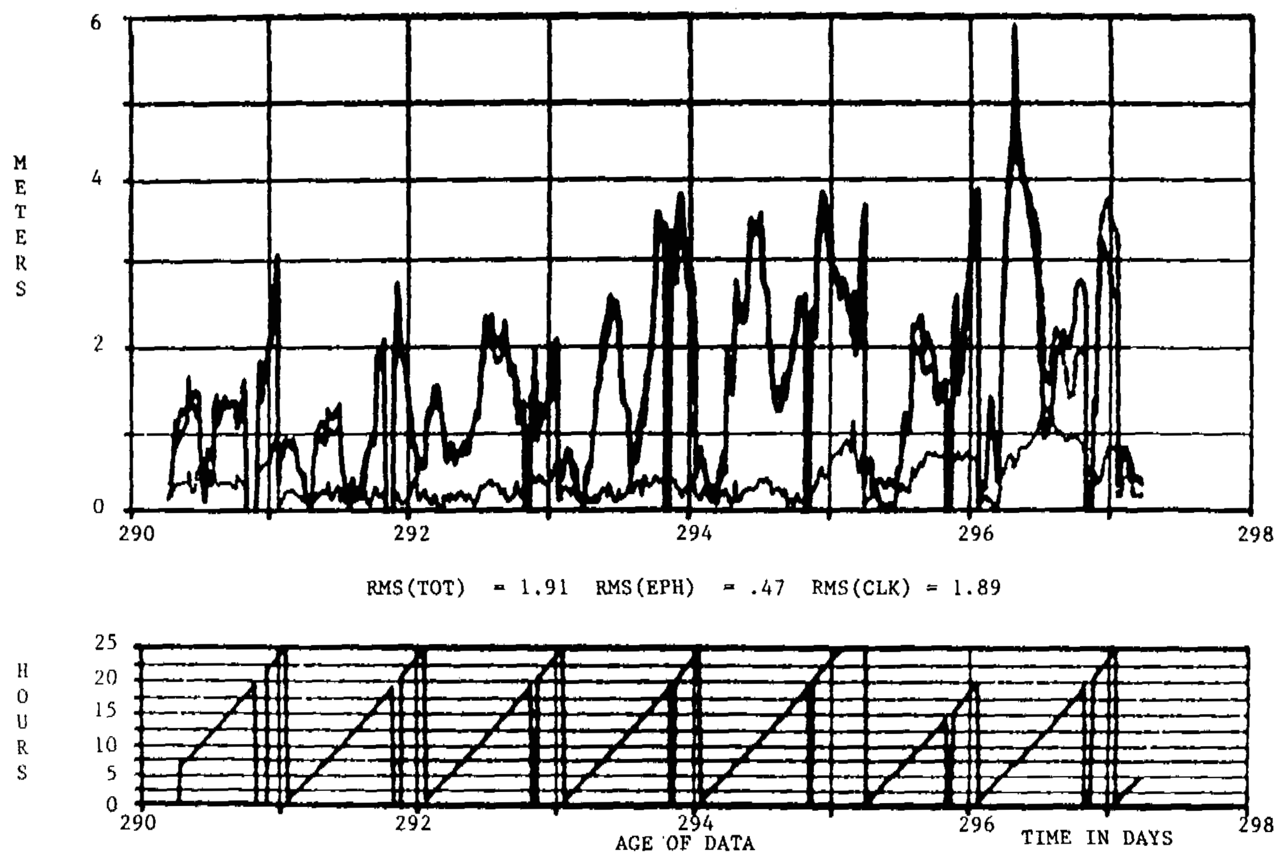

FIGURE 7: RMS-ERD FOR NAVSTAR 25

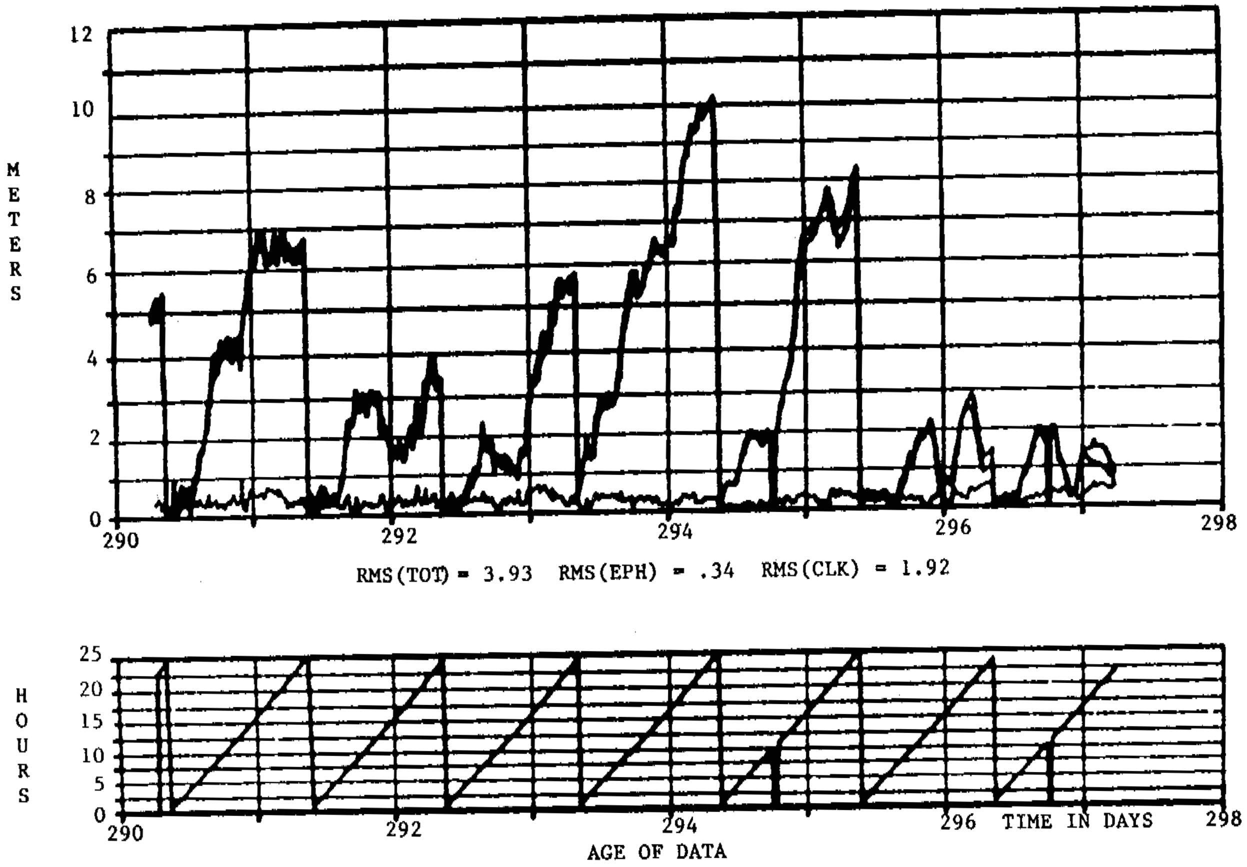

FIGURE 8: RMS-ERD FOR NAVSTAR 27

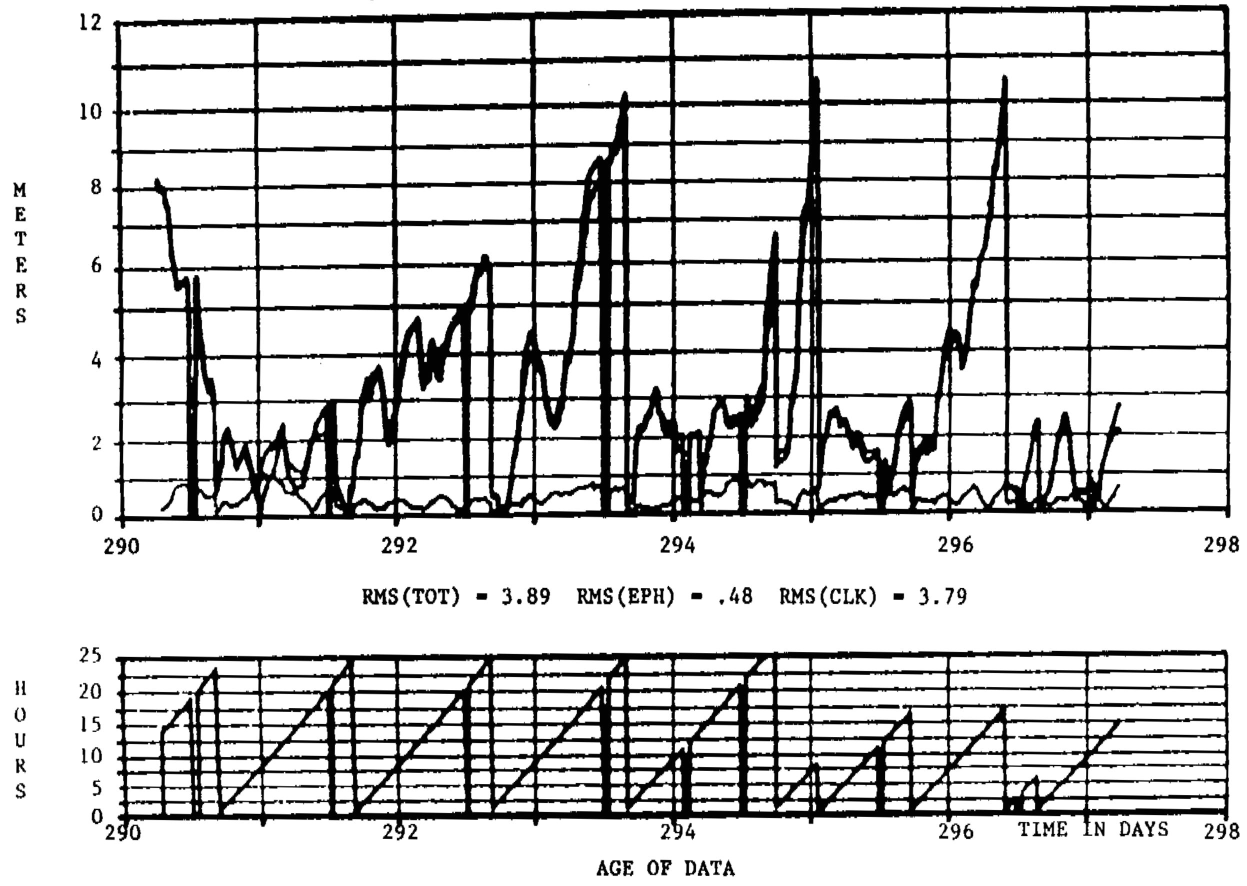

FIGURE 9: RMS-ERD FOR NAVSTAR 16

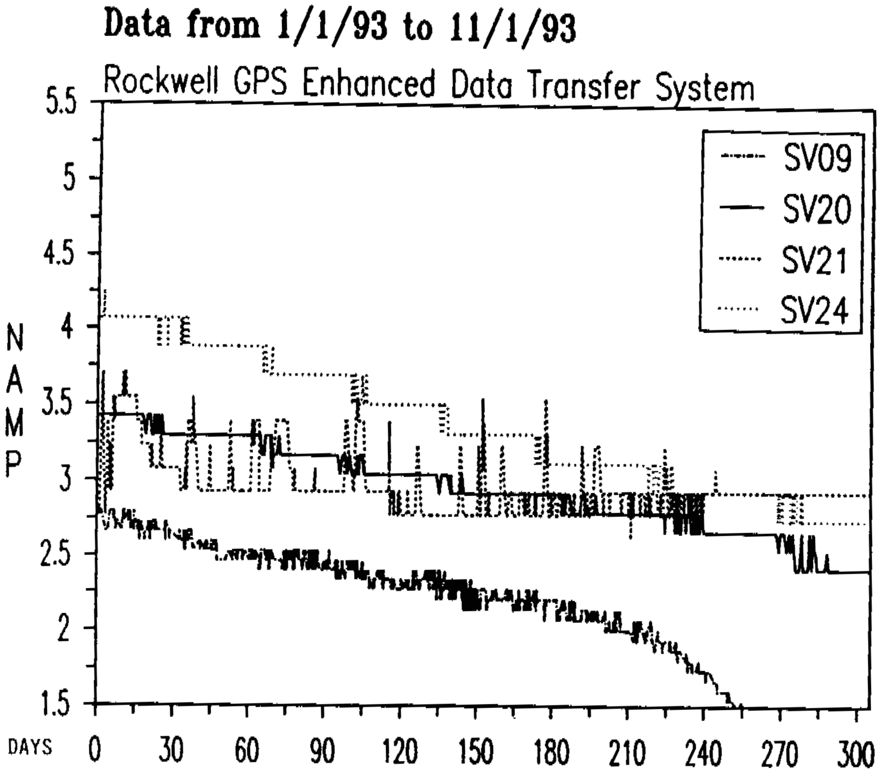

FIGURE 11: LOW CESIUM BEAM CURRENT VALUES

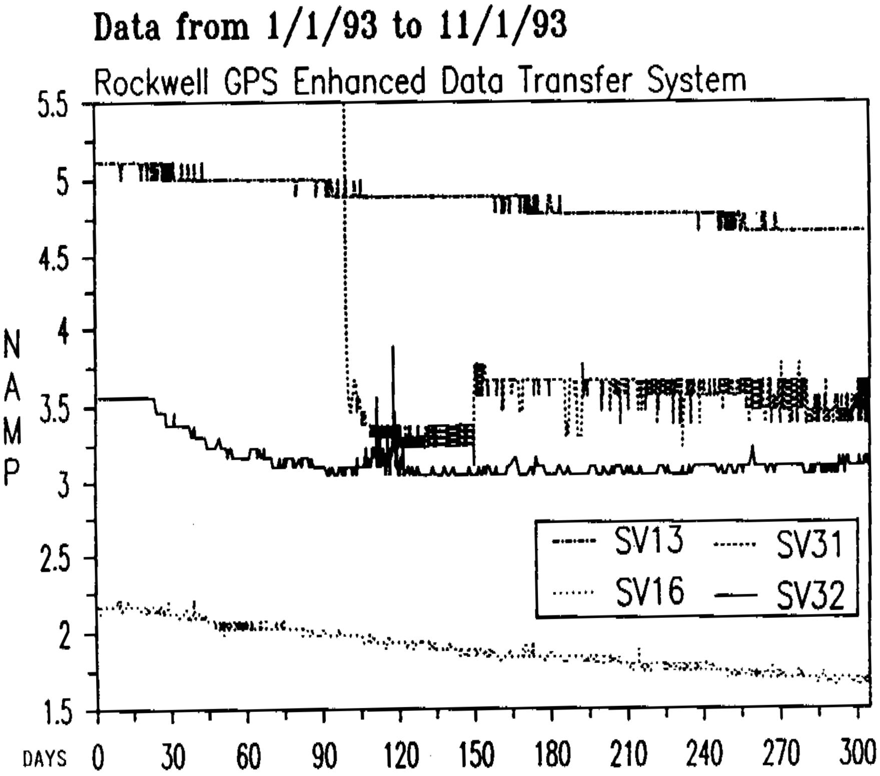

FIGURE 12: LOW CESIUM BEAM CURRENT VALUES

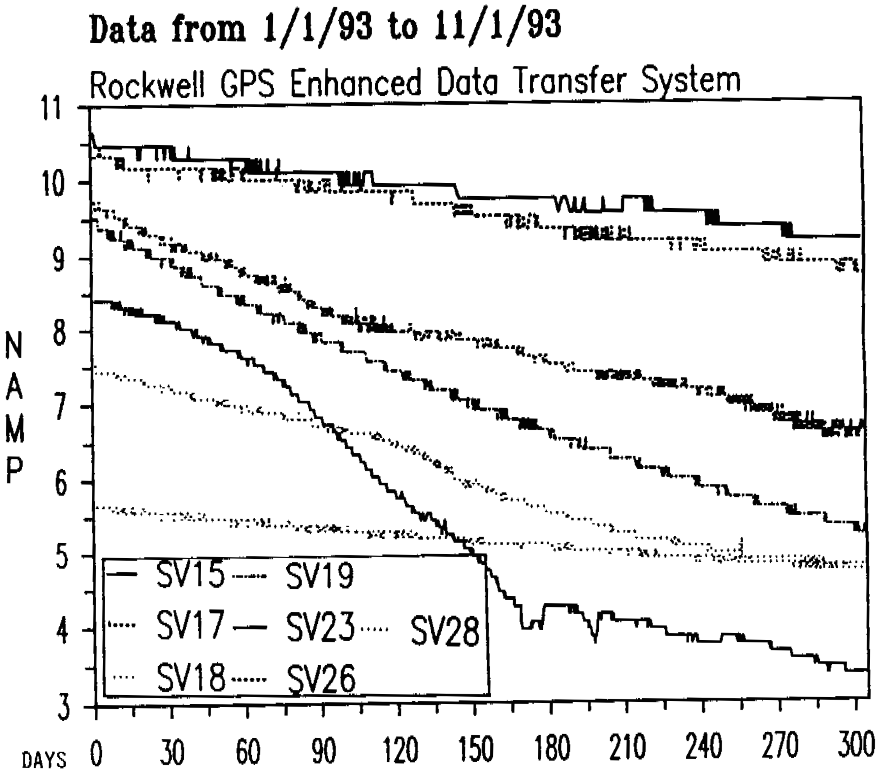

FIGURE 13: MEDIUM CESIUM BEAM CURRENT VALUE

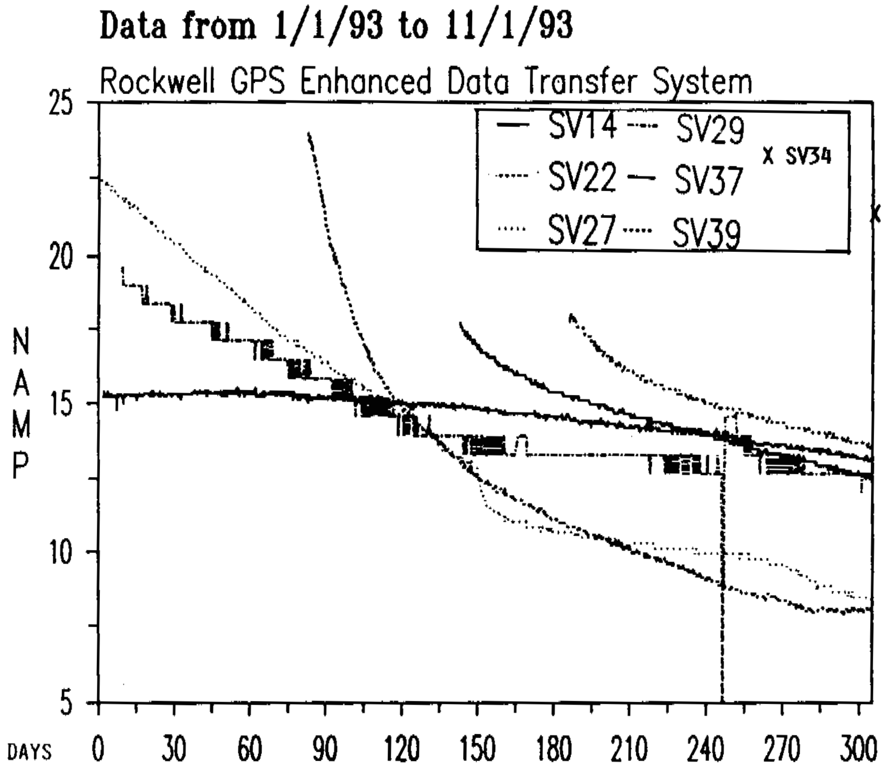

FIGURE 14: HIGH CESIUM BEAM CURRENT VALUES

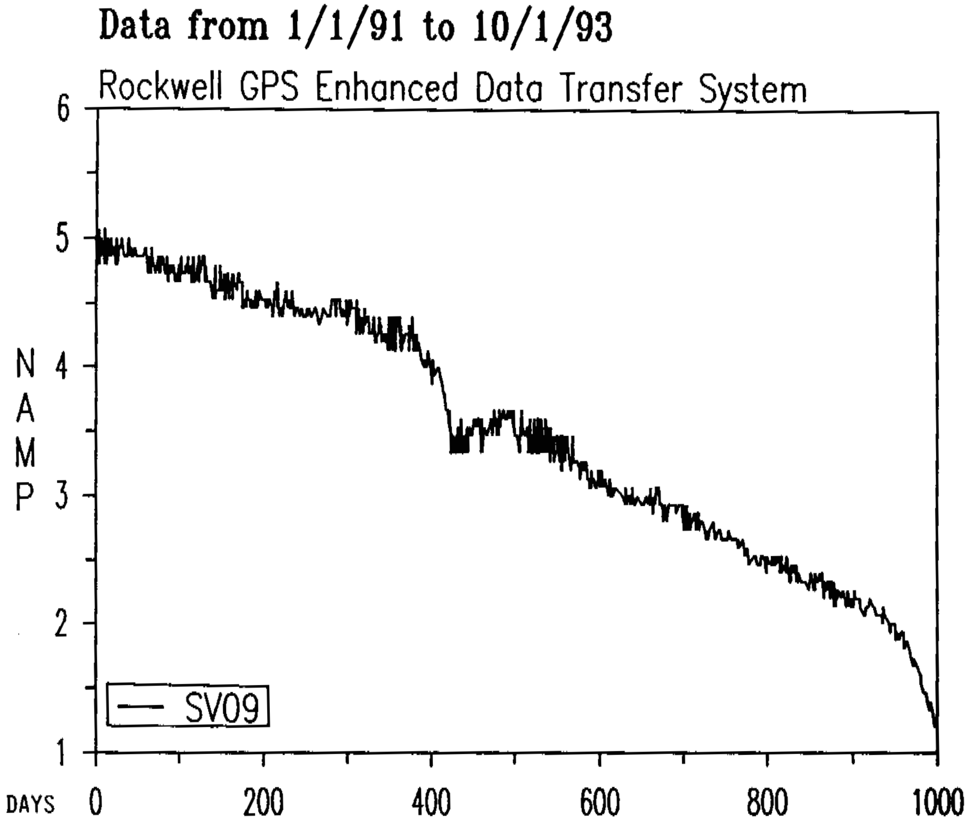

FIGURE 15: SVN 9 CESIUM BEAM CURRENT

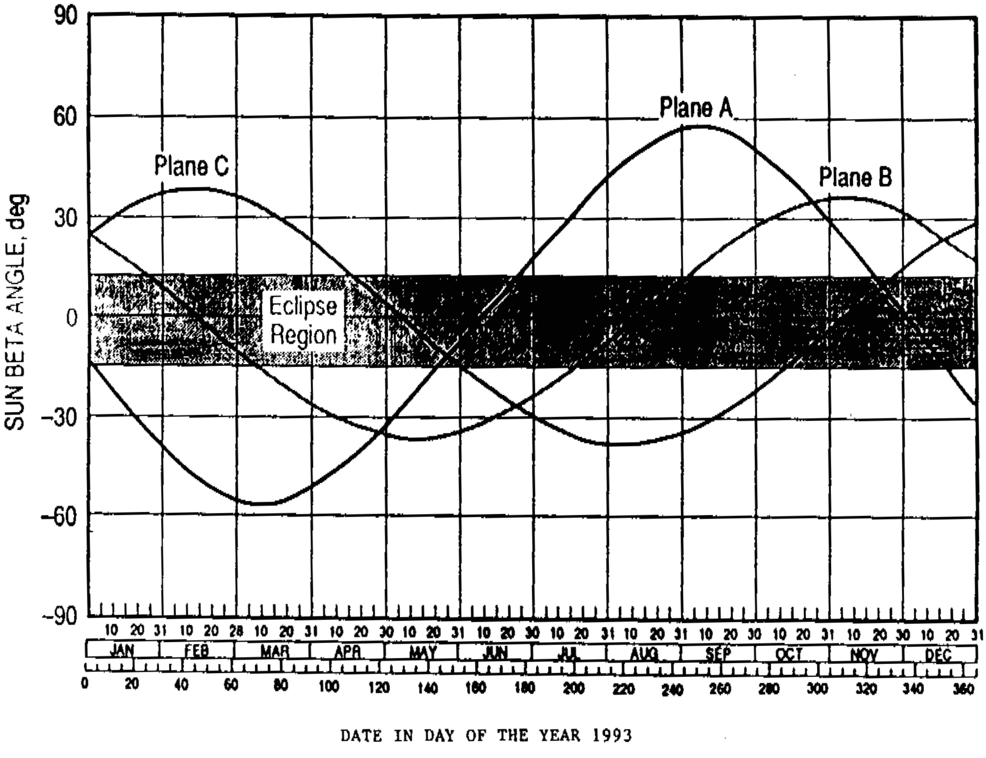

FIGURE 16: BLK II SUN BETA ANGLES AND ECLIPSE REGION

TABLE 5: TOTAL OPERATION HOURS OF BLOCK II/IIA CLOCKS

HOURS OF OPERATION

GPS VEHICLE	CESIUM		RUBIDIUM	
	3	4	1	2
13	39054			
14	*30806*	109499		
15	*18396*	5270		
16	25403			*11972**
17	34528			
18	33506			
19	*18980***	16789		
20	31973			
21	27907			
22	*744***	6280		
23	*730**	25476		
24	20877			
25				15037
26	12044			
27	11365			
28	14234			
29		8056		
31		5728		
32		8680		
34		340		
35	1704			
37	4720			
39	3624			
SUBTOTAL	394943	91568		27009
TOTAL	486511 (55.54 Yrs.)		27009 (3.1 Yrs.)	

LEGEND:

00000 = Mortified Clock

* = Powered down for Desert Storm; will power up after all clocks have failed

** = Suitable for degraded operation

8760 Hours = One year

TABLE 6: NAVSTAR MISSION OPERATIONS STATUS

On-Orbit Vehicles

DECEMBER 1, 1993

Clock Operational Performance Oct. - Nov., 1993