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

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Abstract

This paper is an update of the on–orbit operational performance of the frequency standards on the last Block I NAVSTAR satellite (GPS–10), the complete Block II NAVSTAR satellites (GPS–13 to 21) and the Block IIA NAVSTAR (GPS–22 to 40) satellites. Since the status of the GPS constellation is now at Full Operational Capability (FOC), a minimum of twenty–four satellites are in position with all the necessary tests successfully completed. The evolution of frequency standards on board the GPS vehicles will be presented with corresponding results.

Various methods and techniques will be presented to show on–orbit life time, down time, state of health telemetry, on–orbit trending and characterization of all the frequency standards. Other topics such as reliability, stability, clock quirks and idiosyncrasies of each vehicle will be covered.

INTRODUCTION

The evaluation of the space–rated frequency standards on the GPS program started with the Block I concept validation program and the full–scale development vehicles of which only one is still functional: GPS–10 (PRN–12). The production vehicles are divided into two groups, Block II (GPS–13 through 21) and Block IIA (GPS–22 through 40). Each vehicle includes two Rubidium Frequency Standards (made by Rockwell) and two cesium Frequency Standards (made by Frequency and Time Systems as the primary source and, Kernco and Frequency Electronics Inc. as secondary sources on selected vehicles).

The cesium clocks are considered primary because of their degree of radiation hardness, their extremely low frequency drift, or aging, which does not require any Kalman filter modeling, and the shorter modeling time between turn–on and activation for GPS users.

The actual on–orbit GPS Frequency Standard operating history (shown in Figure 1 for the last Block I and all Block II satellites, and in Figure 2 for the Block IIA satellites minus the four vehicles in the Eastern Launch Site awaiting launch) illustrates the results of these hardware implementations.

The operating life history of the production models of both cesium and rubidium frequency standards will be briefly discussed. This will be reviewed in order to calm the doubting Thomas's or Henny Pennies, that the sky is not falling in regard to (1) the amount of disabled clocks that have recently been occurring, Dec 94 – July 95, (2) the reliability of the clocks and (3) the combined projected lifetime of the four clocks (7.5 years) on each of the vehicles.

A brief history of the rubidium clocks on the Block I vehicles is given in Table 1. The major problems were corrected via modifications (the final modified clock for Block II/IIA is Modification number 12). The non–generic problems were never repaired. From the sample of 30 Block I rubidiums launched, the average age was 1.5 years with a maximum of 12.5 years and a minimum of one day. The minimum acceptable hardware reliability requirement for a five–year life rubidium clock was 0.765, which equates to a 3.8 year projection life.

The history of the rubidium clocks on the Block II/IIA vehicles is given in Table 2. Of the six disabled clocks, four may be retried with possible degraded performance. The final production model #12 RFS's have not acquired much on–orbit operating time, since the cesium clocks have traditionally been preferred over the rubidiums. This is because of the advantage of cesium over rubidiums in terms of radiation hardness, lower drift rate by a factor of 100, no C–field tuning or frequency biasing needed, and a shorter warm–up time before the vehicle can be set healthy (2.6 days versus 6.4 days on the average). There have been eleven turn–ons with six powered down, for a total time of 120 months or 87,380 operational hours, as of 30 November 1995. Since the hours of operation (sample size) are so small, a point–in–time failure rate estimate must be used. If the two failures are used, then the calculated failure rate is 26.5×10^{-6} or an Mean Time Between Failure (MTBF) of 4.3 years. If the six disabled clocks are considered complete failures, then the failure rate is 79.6×10^{-6} and an MTBF of 1.4 years.

The operating history of the cesium clocks on the Block I vehicles is as follows: a total of six clocks (three pre–production models and three Model 1 production clocks) with an average life time of 5.9 years (Maximum of 9.3 years and a minimum of 3.3 years). Since five of the failures were caused by cesium depletion, the final production model (Model 2) had an increase of cesium fill (1.0 grams to 1.5 grams).

The history of the cesium clocks on Block II/IIA vehicles is given in Table 3. Of the thirty–one CFS's powered–up, nineteen are still operating, with an age range of 6.5 years to seven months. Of the twelve clocks which have been disabled, six have been labeled failures and six may be given a second chance with possible degraded performance. If the five failures, excluding one GFE clock, are used, then the calculated failure rate (via the point–in–time failure rate estimate) is 7.2×10^{-6} and the MTBF is 15.8 years. If the ten disabled clocks (excluding the two GFE clocks) are considered failures, then the failure rate is 14×10^{-6} and the MTBF is equal to 7.9 years. The manufacturer signed up for a minimum acceptable hardware reliability requirement for a 7.5 year life of 0.663, or 4.3 years per clock. Taking the reliability numbers of both rubidium and cesium clocks, plus having to meet the navigation payload reliability number of 0.934 for 7.5 year life, the number of clocks per vehicle came out to be two rubidiums and two cesiums. Another figure to remember is the mean mission duration value of six years, a specification which five vehicles have already surpassed. In summary, the complete GPS Block II/IIA clock status is included in Table 4.

ON–ORBIT PERFORMANCE

In order to acquire the exact performance characteristics of the operating on–orbit frequency standard, the L–Band signal must be evaluated. This signal is affected by the (Frequency Synthesizer Distributor Unit) FSDU (which is commanded by the NDU), atmospheric effects, ephemeris uncertainties, monitor station variations, spacecraft effects and other factors. All of these factors are fed into a Kalman filter, which is a computer algorithm for processing discrete measurement data in an optimal fashion.

There are several parameters which are instrumental in evaluating the operational performance of the frequency standards. The first two parameters are in the navigation message. One is a_1, which is the frequency offset (sec/sec). This is the filter's estimate of the frequency difference, or offset between the satellite's frequency standard and the GPS composite clock (a nominal frequency). This is a continuous absolute value. One can also take the daily average of the difference between the minimum and maximum values of a_1 as a possible trending signature. Another parameter is the frequency drift in sec/sec^2, a_2 term. This is the rate of change of the drift term.

Another parameter that is used daily to evaluate the clock's performance is the Estimated Range Deviation (ERD). An ERD is the difference between a range determined from the aposteriori state estimates during a Kalman interval and the range determined from the navigation upload data that is valid for the same time. These ERD's compare the current filter estimates each 15 minute period to the prediction made from previous filter estimates (considered to be a minimum range error either induced primarily, by clock movement or satellite positional change). Examples of these ERD's are in Figures 3 and 4. Plots of these estimates provides us one more clue of evaluating the performance of each spacecraft's clock.

Continuing the investigation of a potential clock problem, a correlation of these ERD plots to the telemetry monitor values must be examined. Along with these clock monitor values, the a_1 and a_2 terms must be observed for movement.

One important aspect of Kalman filter operation is to provide accurate continued measurement updates, every fifteen minutes. Unfortunately, there are periods when the spacecraft is not in view of a monitor station, and the filter must estimate aging through the a2 term, with no real measurement verification. Also, different monitor stations (with obvious different clock errors) contribute errors into the filter estimation and subsequently the prediction process.

An operating limit is set on the ERD value in terms of meters (eg. 10 meters or 8 meters). When the limit is exceeded, a new upload must be sent to the vehicle to correct the new terms in the navigation message. A new experimental limit has recently been defined as 5 meters, resulting in a fifteen percent improvement in the URE. This also has increased the work load on the Master Control Station (MCS) crew, which now performs approximately twelve more uploads per day on the 25 vehicles. As a rule, the MCS contacts each vehicle twice a day, once to update the navigation message. This equates to a total of 60 to 70 supports per day for the MCS crew.

Another set of parameters which appear to effect the clock's performance are environmental effects, such as prolonged radiation effects (i.e. passing through the Van Allen belts every twelve hours) and irregular solar activities. Thermal variations, either induced by delta–v maneuvers or eclipse seasons, appear to be causing the older cesium clocks (> 5 years) the most problems in terms of ERD's. Maybe aging of the electronics, resulting in a degraded temperature coefficient causes frequency changes. The eclipse season causes the cesium clock's temperature to decrease by three degrees centigrade with a $\pm$ 1° C variation. The rubidium does not have this problem since a heater (ABTCU) keeps the rubidium clock at a stable temperature, $\pm$ 0.1° C. When the satellite enters eclipse season especially during the first eclipse season, an ephemeris change could also occur, which is corrected by manual intervention from the operators.

ON–ORBIT TRENDING

The most important objective of trending analysis is to determine when a particular frequency standard is no longer useful for providing a navigation signal. Particularly elusive is the time frame – whether it be in days or months – when a clock will expire. Note that this is different than not meeting specifications. The stability specification of the clock, 2×10^{-13} at one day for the cesium clock, is so tight, that if the clock is performing at 3×10^{-13} at one day, the URE of 4.8 meters (1 s) can still be met with extra maintenance by the MCS, for the space segment. There are several vehicles now that do not meet the stability specification, but the Air Force is reluctant to switch to another clock. The Air Force will determine when a clock will be disabled by many factors. These factors include:

1. how burdensome to the MCS crew are extra daily uploads and/or Kalman maintenance in order to correct the a1 and a2 terms?
2. how old is the clock (> 5 years)?
3. how old is the vehicle (> 6 years)?
4. how many clocks are left to be tried?
5. what is the world situation (conflicts/trouble spots)?
6. what is the condition of the vehicle in terms of performance operation and other subsystems? and
7. what is the condition of the entire constellation?

The navigation signal must be made available 98% of the time with 21 spacecraft. In predicting the useful operating lifetime of the clock, the most important performance parameter is the stability of the clock. This is what most effects the user, and is the most sensitive parameter.

The next set of parameters are the a1 and a2 terms and their deterioration and/or fluctuations, and the ERD's. The last set of parameters which effect the performance of the clock and that of the navigational signal is internal to the clock. The cesium clock has 18 monitors (combination of analog and digital) and the rubidium clock has 11 monitors (combination analog and digital). Of all the telemetry monitors on the cesium clock, there are only a few that could vary and not effect the performance of the clock. The rest of the monitors will cause an upset of the performance by any detectable movement (minimum step size). One of the monitors having particular character or individuality is the cesium beam current monitor. This trending parameter is hard to interpret in the sense that each of the 19 operating clocks has a slightly different signature as seen in Figure 5. SVN–17 has the normal stair–stepping decline in beam current. Since each clock starts off at a different absolute value, each has a different rate of decline (the higher it starts, the faster it drops) and each has a different final plateau. So each drop in beam current may or may not effect the stability, a_1 or a_2 terms, or ERD's. Furthermore, each clock will degrade or age at a different rate. Even though each clock is built to the same specification and from the same set of drawings, when one compares stability performance in terms of parts in 10^{14}, there will be variations in their outputs.

The other parameter that might change without detrimental effects on the performance is the loop–control voltage, which normally will move slightly one way or another, depending on what electronic changes or aging occur in the loop in order to keep the same 10.23 MHz frequency output to the FSDU. The parameters which are catastrophic to clock performance if any movements are observed are the cesium oven temperature, RF level (power shift and or spectrum change), electron multiplier gain changes, ionizer voltage, and any input current changes to the total clock or to individual units such as the quartz oven.

The rubidium clocks have the same type of monitors and the same type of loop control voltages. The lamp voltage monitor which detects pressure changes and photo cell degradations is somewhat similar to the cesium beam current in terms of end–of–life predictions.

To predict the exact (one week) end–of–life of either type of clock is extremely hard. This was tried on SVN–20 with Cesium No. 3. After 4.5 years of operation, the stability was $> 2 \times 10^{-13}$ one–day with four to five extra uploads needed per week. Maybe two to three months of less than useful life could have been squeezed out of the clock.

Other parameters that are incorporated into the trend analysis include on–orbit temperature of the spacecraft, any FSDU – NDU influence, or L–Band effects.

SCHEDULES

The last of the Block I satellites, NAVSTAR 10 (PRN 12), launched in 1984, is scheduled to be disposed of in the June 1996 time period. The main problem is that the solar arrays have lost their efficiency (design life of five years) and can no longer support the navigation payload. On November 18, 1995, the payload was set unhealthy. Kalman filter tests, frequency standard tests, sun sensor test, etc., will be performed in February and March 1996. The two rubidium frequency standards, yet to be powered up after 12 years of on–orbit storage, will be tested for stability, temperature coefficient, VCXO and turn–on characteristics and any other tests the clock community would like to have performed.

The last Block IIA satellite launched, GPS–37, reached orbit in March 1994. This completed the 24 satellite constellation. There are four vehicles in the Eastern Launch Site in storage waiting to be launched. The next launch is planned to be positioned in "Plane C" in March 1996. There are available launch slots for summer 1996 time frame.

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 exceed 60 years of operation, while the cesium on–orbit times are more impressive with over 125 years of operation. The GPS clock utilization times in their operational sequence are shown in Figure 6.

CONCLUSION

As verified by on–orbit performance data, most of the major generic problems, especially with the rubidiums, have been corrected. I will admit that the rubidium short life times, the phase jumps that occur within the first 3 to 4 months of operation and the changing drift rate within the first 6 months are on–going problems. There have been 31 out of 48 cesium clocks activated with 19 currently operating. Of the 12 disabled clocks, half may be reactivated with possibly degraded performance. There have been eleven rubidium clocks activated with 37 remaining to be turned on. Of these eleven clocks, five are still operating and four to be reactivated for future use.

The average age of all the disabled clocks is 1.65 years. The average age of the currently operating clocks is 2.9 years. The average age of the space vehicles is 4.5 years, which equates to 60% of the design life (7.5 years). The total number of clocks turned on is 42, which equates to using only 44% of the available clocks. The usage and performance to date indicates that the number of clocks (four), originally determined in the 1982 proposal, will support both the spacecraft design life of 7.5 years and the mean mission duration of 6.0 years.

For the more quick–look–managerial type, a user–friendly smiley face chart, Figure 7, has been concocted in order to eliminate reviewing all the Kalman drift rate residuals, Allan variance stability curves, and ERD's figures. Each little quirk and idiosyncrasies of the vehicles combined with clock performance in terms of ERD's are for your (management) eyes only.

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- Naval Research Laboratory (NRL)
- National Institute of Standards & Technology (NIST)
- Aerospace

- Rockwell (RFS Manufacturer)
- Frequency and Time System (CFS Manufacturer)
- Kernco & Frequency Electronics Inc. (Second Source CFS Manufacturers)

TABLE 1 RUBIDIUM FREQUENCY STANDARDS - BLOCK I

TYPES OF PROBLEMS		NO.	AGE (YR) Hi - Low	HOW FIXED
TRANSFORMER		3	0.53 1.0 - .3	MOD. P/N 3
RUBIDIUM FILL		8	2.7 12.5 - 0.4	MOD. P/N 4
C-FIELD TUNING HITS		3	1.9 5.1 - 0.03	MOD. P/N 11
VCXO		1	2.8	NON-GENERIC
DRIFT RATE		2	0.5 0.5 - 0.5	NON-GENERIC
ATOMIC LOOP *		1	1 DAY	NON-GENERIC
		18	1.77 12.5 - .003	
OPERATIONAL TO END *		7	1.2 3.5 - 0.1	N/A
NOMINAL TURN-ON (TESTS)		2	1 MONTH	N/A
NEVER TURNED-ON *		3	-	N/A
	TOTAL	30	1.5 12.5 - .003	

* ONE STILL AVAILABLE

TABLE 2 RUBIDIUM FREQUENCY STANDARDS - BLOCK II

- **DISABLED 6 CLOCKS**

AGE (YRS.)	SYMPTOMS
1.7	ERRACTIC MONITORS
1.4	HEATER CIRCUITRY; LAMP VOLTAGE ERRACTIC
1.4	DRIFT RATE LARGE; DESERT STORM DECISION
1.1	TEMPERATURE SENSITIVE; FREQUENCY MOVEMENTS
0.2	INSIDE TEMPERATURE CONTROLLER; FREQUENCY MOVEMENTS
0.2	DRIFT RATE LARGE
AVE. = 1.0 YR.	

- **OPERATIONAL 5 CLOCKS**
  - OLDEST = 1.3 YRS.
  - AVERAGE = 0.8 YRS.

TABLE 3 CFS BLOCK II VEHICLES

No. of CFS - 19 Operating	AGE
2	> 6 YRS.
2	> 5 YRS.
2	> 4 YRS.
4	> 3 YRS.
3	> 2 YRS.
3	> 1 YR.
3	< 1 YR.

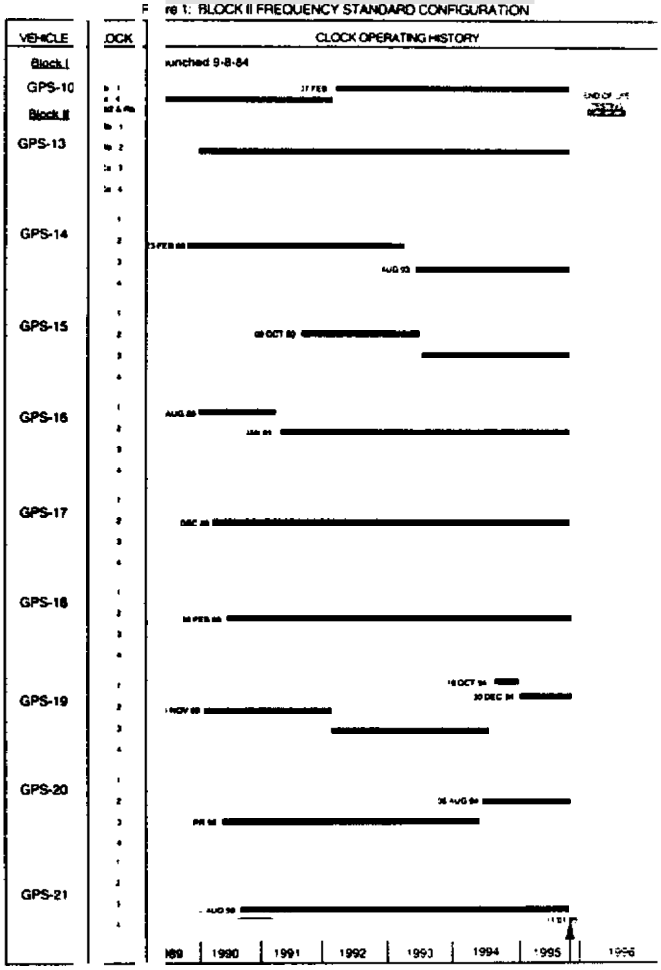
12 - DISABLED AGE	REASONS
4.3 YRS.	* $\sigma > 2$ E-13 at 1 day
3.5 YRS.	VCXO OR SERVO
2.8 YRS.	FUSE
2.5 YRS.	* VCXO; Δf
2.3 YRS.	* SECOND SOURCE - RF
2.2 YRS.	* 35 DAY CYCLIC PATTERN
2.1 YRS.	CBI LOW, HIGH BACKGROUND NOISE
1.8 YRS.	SECOND SOURCE - RF
1.1 YRS.	EMULT; Δf
.7 YRS.	VCXO, DAC, SERVO or EMULT
0.1 YRS.	* SOLAR COEFFICIENT
0.1 YRS.	* DESERT STORM; Δf

* AVAILABLE FOR POSSIBLE DEGRADED OPERATION

TABLE 4 - GPS BLOCK I / II / IIA CLOCK STATUS - NOV. 30, 1995

SVN	CLOCK	STATUS	PART	PLN/ SLT	TURN ON-OFF	NEXT IPO	RECENT COMMENTS
13	1Rb	SPARE		B/3			$\sigma = 1.4 \times 10^{-13}$ @ 10^5 S, 0.86×10^{-13} @ 10 days.
	2Rb	SPARE					Aging - 3.6×10^{-15}/day on 3/Cs.
	3Cs	OPERATING			6/17/89		
	4Cs	SPARE				MAR 96	
14	1Rb	SPARE		E/1			$\sigma = 1.1 \times 10^{-13}$ @ 10^5 S, 0.47×10^{-13} @ 10 days.
	2Rb	SPARE					Aging - 2.0×10^{-15}/day on 4/Cs.
	3Cs	DEAD			2/23/89-8/30/92	NONE	VCXO or Servo bad, not in Cesium tube on 3/Cs.
	4Cs	OPERATING			8/30/92		
15	1Rb	SPARE		D/2			$\sigma = 1.3 \times 10^{-13}$ @ 10^5 S, 0.51×10^{-13} @ 10 days.
	2Rb	SPARE					Aging - 0.3×10^{-15}/day for 4/Cs.
	3Cs	DEAD			10/9/90-11/10/92	NONE	Low beam current and high noise on 3/Cs caused turn-off
	4Cs	OPERATING			11/10/92		
16	1Rb	SPARE		E/3			$\sigma = 3.0 \times 10^{-13}$ @ 10^5 S, 1.0×10^{-13} @ 10^6 S. Aging +
	2Rb	SUSPECT			8/24/89 - 1/7/91		- 17.0×10^{-15}/day; Low Beam current < 1.1 nA on 3/Cs.
	3Cs	OPERATING	VI		1/7/91		Suspect clock with many frequency discontinuities, large drift rate,
	4Cs	SPARE				DEC 95	along with the Desert Storm time period, caused change from 2/Rb
17	1Rb	SPARE		D/3			$\sigma = 1.2 \times 10^{-13}$ @ 10^5 S, 0.47×10^{-13} @ 10 days.
	2Rb	SPARE					Aging - 0.8×10^{-15}/day on 3/Cs
	3Cs	OPERATING			12/24/89		
	4Cs	SPARE				MAR 96	
18	1Rb	SPARE		F/3			$\sigma = 1.4 \times 10^{-13}$ @ 10^5 S, 0.35×10^{-13} @ days.
	2Rb	SPARE					Aging is 3.6×10^{-15}/day on 3/Cs
	3Cs	OPERATING			2/5/90		
	4Cs	SPARE				MAY 96	
19	1Rb	SUSPECT		A/4	10/16/94-12/30/94		$\sigma = 1.8 \times 10^{-13}$ @ 1 day for 2/Rb. Freq change on 11/20/94 and
	2Rb	OPERATING			12/30/94		temperature controller instable for 1/Rb.
	3Cs	SUSPECT			11/1/89-1/2/92	AUG 96	Suspect 3/Cs had 35-day freq offset cyclic pattern with large
	4Cs	DEAD			1/2/92-10/16/94	NONE	aging of 16×10^{-15}/day. $\sigma = 1.2\ 10^{-13}$ @ 10^5 S. Instant Off on 4/Cs.
20	1Rb	SPARE		B/2			Disturbance on 8/20/94; ABTCU - Range C, $\sigma = 0.6 \times 10^{-13}$ @ 1 day.
	2Rb	OPERATING			8/6/94		Aging - 80×10^{-13}/day on 2/Rb. $\sigma = 1.9 \times 10^{-13}$ @ 10^5 S,
	3Cs	SUSPECT			4/8/90-8/6/94	JUL 96	4 extra ERD weekly; CBI < 1.6 nA on 3/Cs. Proactive move
	4Cs	SPARE				JUL 96	
21	1Rb	SPARE		E/2			$\sigma = 2.0 \times 10^{-13}$ @ 10^5 S, 1.0×10^{-13} @ 10 days; Aging 8.4×10^{-15}/day
	2Rb	SPARE					4 extra uploads needed weekly: low cesium beam current; ≈ 3.5 nA;
	3Cs	OPERATING	IV		8/14/90		LTC ≈ 136 sec, gain decrease of 11 in 4.5 years on 3/Cs.
	4Cs	SPARE				JUL 96	
22	1Rb	SPARE		B/1			$\sigma = 1.4 \times 10^{-13}$ @ 10^5 S, 0.81×10^{-13} @ 10 days; Aging - 10 x
	2Rb	SPARE					10^{-15}/day for 4/Cs. Incorrect solar coefficient in Kalman filter
	3Cs	SUSPECT			2/14/93-3/17/93	FEB 96	estimate during eclipse season, influenced 3/Cs change.
	4Cs	OPERATING	IV		3/17/93		
23	1Rb	SPARE		E/4			$\sigma = 1.2 \times 10^{-13}$ @ 10^5 S, 0.32×10^{-13} @ 10 days.
	2Rb	SPARE					Aging -1.6×10^{-15}/day for 4/Cs.
	3Cs	SUSPECT			12/5/90-1/4/91	JUL 96	Frequency jumps along with Desert Storm caused change for 3/Cs.
	4Cs	OPERATING	IV		1/4/91		
24	1Rb	DEAD/SUSPECT	III	D/1	1/24/94-7/1/95		Heathly on 7/7/95; $\sigma = 0.7 \times 10^{-13}$ @ 10^5 S, for 2/Rb; Heater
	2Rb	OPERATING			7/1/95		
	3Cs	SUSPECT			7/13/91-1/24/94	MAY 96	loop control voltage changes with Δ Freq on 1/Rb; VCXO suspect
	4Cs	SPARE				MAY 96	on 3/Cs.
25	1Rb	SPARE		A/2			$\sigma = 1.1 \times 10^{-13}$ @ 1day, aging 1.0×10^{-13} for 3/Cs.
	2Rb	DEAD			3/14/92-12/1/93		Frequency jumps occured in 11/93 with erratic lamp voltage
	3Cs	OPERATING	III		1/10/95		and control voltages on 2/Rb. EMULTV and CBI toggling
	4Cs	DEAD			12/1/93-1/10/95	NONE	after 1×10^{11} M. Large ERD cun-off for 4/Cs.
26	1Rb	SPARE		F/2			$\sigma = 1.0 \times 10^{-13}$ @ 10^5 S, 0.73×10^{-13} @ 10 days.
	2Rb	SPARE					Aging + 4.5×10^{-15}/day
	3Cs	OPERATING	II		7/17/92		
	4Cs	SPARE				JUL 96	
27	1Rb	SPARE		A/3			$\sigma = 1.2 \times 10^{-13}$ @ 10^5 S, 0.45×10^{-13} @ 10 days.
	2Rb	SPARE					Aging 0.6×10^{-15}/day
	3Cs	OPERATING	IV		9/24/92		
	4Cs	SPARE				AUG 96	
28	1Rb	SPARE		C/2			$\sigma = 1.1 \times 10^{-13}$ @ 10^5 S, 0.26×10^{-13} @ 10 days.
	2Rb	SPARE					Aging - 1.0×10^{-15}/day
	3Cs	OPERATING	I		4/18/92		
	4Cs	SPARE				MAR 96	
29	1Rb	SPARE		F/4			Second Source Cesium of Kernco.
	2Rb	SPARE					$\sigma = 0.8 \times 10^{-13}$ @ 10^5 S, 0.23×10^{-13} @ 10 days.
	3Cs	SPARE				AUG 96	Aging - 0.5×10^{-15}/day
	4Cs	OPERATING	III		12/30/92		
31	1Rb	SPARE		C/3			$\sigma = .91 \times 10^{-13}$ @ 1 day, aging -300×10^{-15}/day on 2/Rb.
	2Rb	OPERATING	III		1/18/95		Second Source Cesium of FEI. Temperature sensitive VCXO.
	3Cs	SPARE				JAN 96	SRD & P.S. variations for 4/Cs.
	4Cs	SUSPECT			4/8/93-1/18/95	JAN 96	
32	1Rb	SUSPECT	IV	F/1	3/18/95-5/8/95		Second Source Cesium of FEI; SRD problem on 4/Cs.
	2Rb	OPERATING			5/8/95		Aging 400×10^{-15}/day large ERD's and drift rate changes for
	3Cs	SPARE				MAY 96	1/Rb. Healthy on 5/12/95. $\sigma = 1.4 \times 10^{-13}$ @ 1 day for 2/Rb.
	4Cs	DEAD			12/5/92-3/18/95	NONE	
33							LAUNCH IN MARCH 1996 (C-PLANE)
34	1Rb	SPARE		D/4			Second Source Cesium of Kernco.
	2Rb	SPARE					$\sigma = 0.8 \times 10^{-13}$ @ 10^5 S, 0.6×10^{-13} @ 10 days.
	3Cs	SPARE				NOV 96	Aging 2.0×10^{-15}/day on 4/Cs.
	4Cs	OPERATING	II		11/15/93		
35	1Rb	SPARE		B/4			$\sigma = 1.5 \times 10^{-13}$ @ 10^5 S, 1.2×10^{-13} @ 10 days.
	2Rb	SPARE					Aging - 1.5×10^{-15}/day on 3/Cs.
	3Cs	OPERATING	I		9/21/93		
	4Cs	SPARE				SEP 96	
36	1Rb	SPARE		C/1			
	2Rb	SUSPECT			3/18/94 - 5/01/95		ΔV on 2/10/95, Problems on next eclipse 3/16/95. Frequency
	3Cs	SPARE				MAR 96	movements on 2/Rb. $\sigma = 0.8 \times 10^{-13}$ @ 1 day, C-field monitor
	4Cs	OPERATING	I		5/01/95		high on 4/CS. Aging -5.5×10^{-15}/day.
37	1Rb	SPARE		C/4			$\sigma = 1.1 \times 10^{-13}$ @ 10^5 S, 0.3×10^{-13} @ 10 days.
	2Rb	SPARE					Aging - 0.1×10^{-13}/day on 4/Cs.
	3Cs	DEAD			5/20/93-3/31/94	NONE	VCXO, DAC, Servo, or Multiplier suspect on 3/Cs.
	4Cs	OPERATING	III		3/31/94	*	
39	1Rb	SPARE		A/1			$\sigma = 0.8 \times 10^{-13}$ @ 10^5 S, 0.42×10^{-13} @ 10 days.
	2Rb	SPARE					Aging + 3.0×10^{-15}/day on 3/Cs.
	3Cs	OPERATING	III		7/4/93		
	4Cs	SPARE				JUN 96	

F re 1: BLOCK II FREQUENCY STANDARD CONFIGURATION



F 2: BLOCK IIA FREQUENCY STANDARD CONFIGURATION

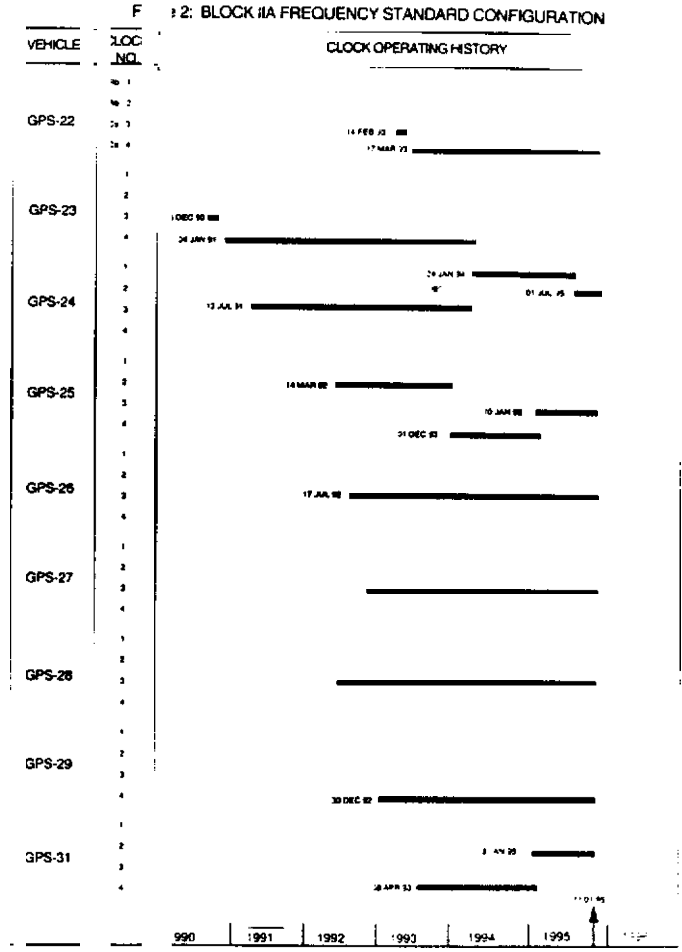
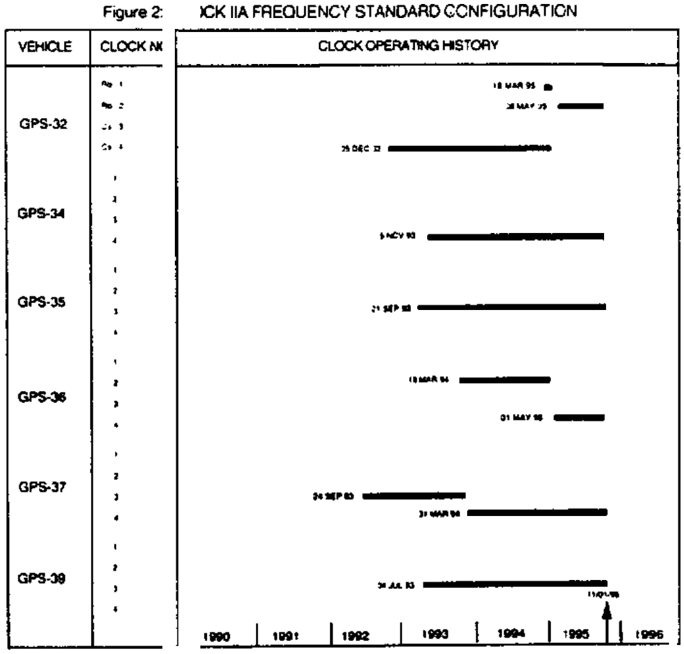
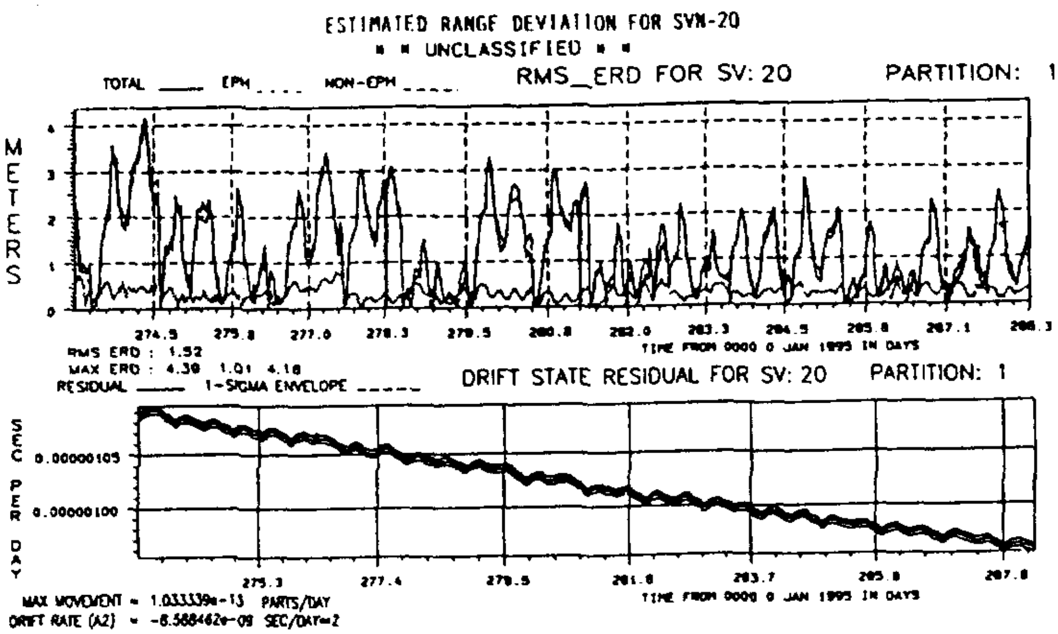


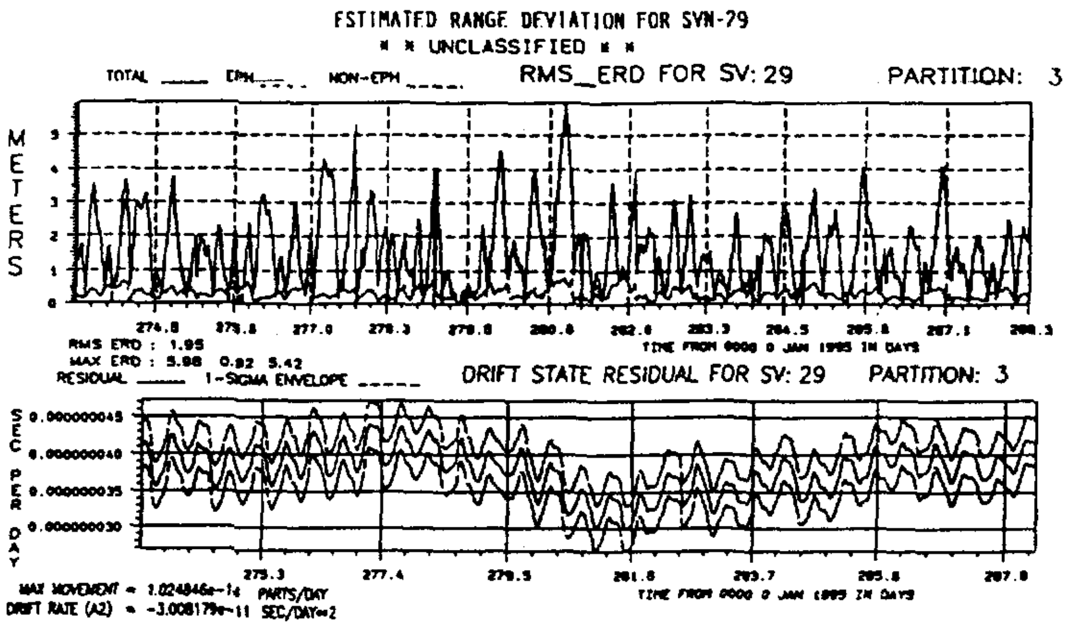
Figure 2: CK IIA FREQUENCY STANDARD CONFIGURATION





Plot 009 of 052

* * UNCLASSIFIED * *
FIGURE 3



Plot 018 of 052

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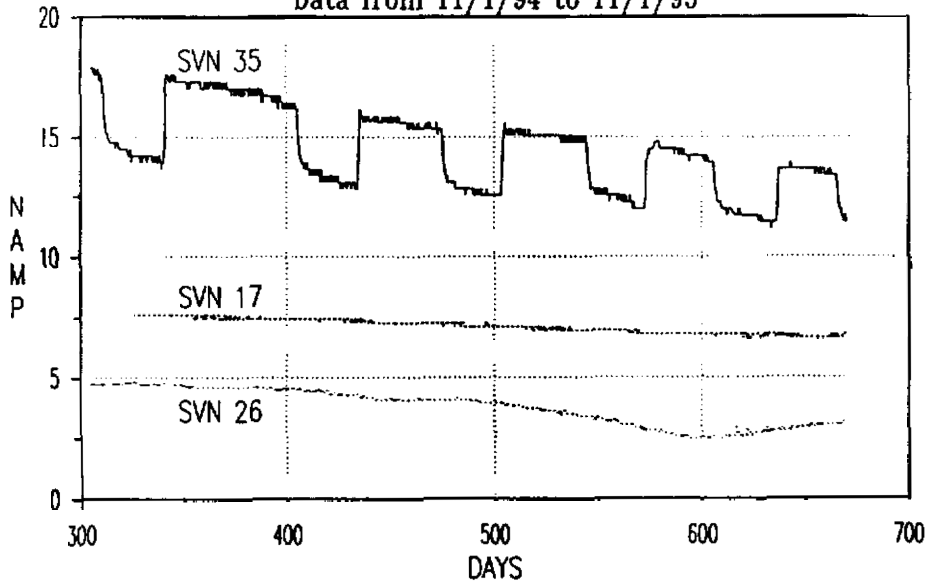
FIGURE 4

FIGURE 5

Cesium Beam Current for Three Different Clocks

Data from 11/1/94 to 11/1/95



Rockwell GPS Operations, Falcon AFB, Colorado

GPS CLOCK UTILIZATION IN OPERATIONAL SEQUENCE

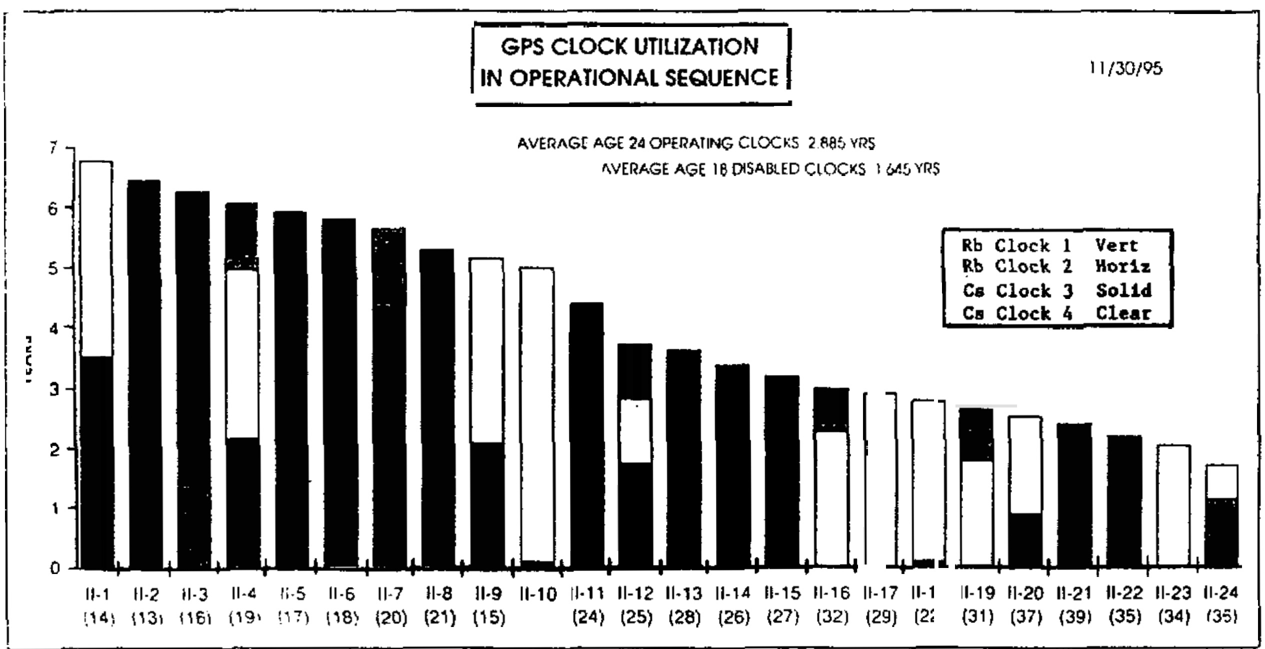


FIGURE 6

ROCKWELL Aerospace
NAVSTAR GPS Operations
November 01, 1995

CLOCK OPERATIONAL PERFORMANCE October, 1995

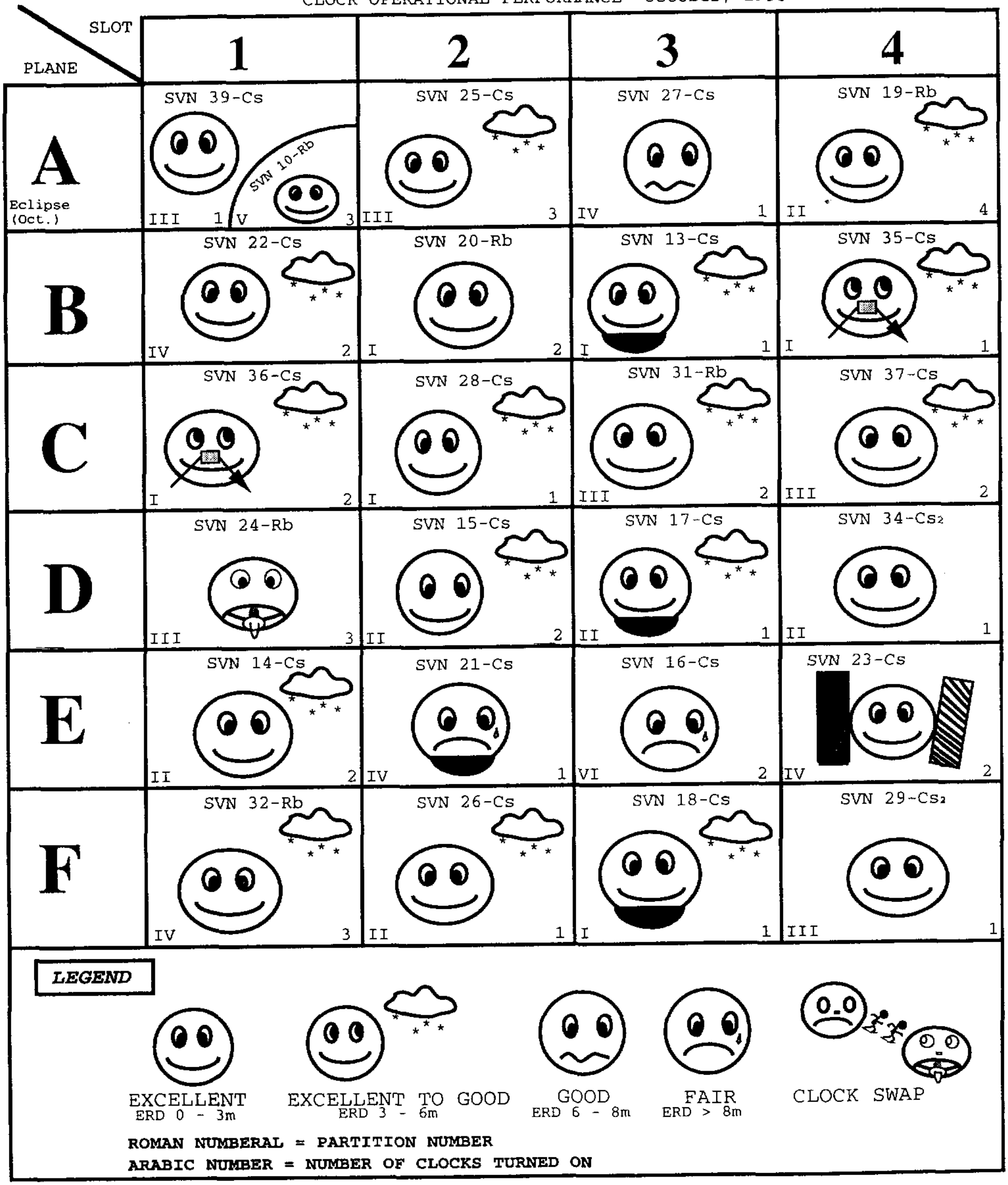


FIGURE 7

Questions and Answers

DAVID ALLAN (ALLAN'S TIME): Given our opening talk by Captain Foster and work that Dr. Winkler did some years ago on measuring lifetimes of clocks, I wonder, given the importance of the lifetime of this system, why we're still using MTBF rather than half-life, as was recommended by Dr. Winkler. That was a very excellent piece of work, and it's a much better measure of lifetime than MTBF.

M.J. VAN MELLE (ROCKWELL SPACE AND OPERATION CENTER): Right, I still don't – this is a reliability person that I gave all the data to who said that all I can figure out was that it seemed to be was a little high. Plus, I think most of the problems that we had may be workmanship. I don't know how hard it is. Remember, this is the first production vehicle we've ever had with production rubidium and cesium clocks on board. To me, it's still in the infant stages.

But to answer your question, I don't know. It probably would be a little better the way you're suggesting.

DAVID ALLAN (ALLAN'S TIME): Well it's the work that Dr. Winkler did on those clocks some years ago, and it's a very excellent measure. Perhaps, in terms of this being a PTTI planning meeting, it's something we should think about for some future representation. I don't know whether we can do anything here, but it certainly is an issue.

M.J. VAN MELLE (ROCKWELL SPACE AND OPERATION CENTER): Sounds good to me.

MARTIN BLOCH (FEI): Van, we've discussed this many times. You say workmanship, but something bothers me. If you take a look at the performance of similar clocks that were made by the same manufacturers on the ground, they outperform the space segments significantly, where life is over 10 years on the cesium and the same on the rubidium. I'm wondering if there's some other reason that we're overlooking on what is happening in space – it just sounds that the number of failures, with all the care that space hardware is supposed to take, that workmanship doesn't sound to me is a good excuse; unless what you're implying is that we do worse for space hardware than we do for military or commercial hardware.

M.J. VAN MELLE (ROCKWELL SPACE AND OPERATION CENTER): Well with the rubidium, you know, Rockwell made it, Rockwell is not a clock manufacturer. They took Efratom's physics package and they took your oscillator, and we just packaged it up and put it together; and tested it only like three or four months on the ground. Then we launched it. Maybe during the six-month period, it would have a failure on the ground. Maybe the launches affected it, but we still do a lot of fault testing with vibration and so forth. We only vibrated it once; you know, maybe the second vibration killed it.

But, the FTDS's are production clocks made by the cesium manufacturers, and they seem to have a little longer lifetime. I can't explain why the Block-I's are lasting more than the Block-II's. But then, we only had a sample of six; and here we had a sample of 19; maybe the sample size was too small compared to the complexity of the standards themselves.

MARTIN BLOCH (FEI): I wonder if anybody else has some thoughts as to the other effects that influence the life performance.

M.J. VAN MELLE (ROCKWELL SPACE AND OPERATION CENTER): And we're talking about if it goes to 5×10^{-13}, it's no good.