TIME TRANSFER WITH THE NAVSTAR GLOBAL POSITIONING SYSTEM

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ABSTRACT

The Navstar Global Positioning System (GPS) is a space-based, radio positioning, navigation system which was authorized for development by DoD in December, 1973. The system will provide extremely accurate, three dimensional position and velocity information, together with system time, to suitably equipped users anywhere on or near the earth. Concept validation field tests were completed in the Spring of 1979. One of the objectives of these tests was to evaluate the performance by measuring the precision and accuracy of the transfer of GPS time to the static user.

INTRODUCTION

The Navstar Global Positioning System (GPS) is a space-based, Radio Frequency (RF), Navigation System that provides extremely accurate, three-dimensional position, velocity and system time information to properly equipped users anywhere on or near the earth. It is a Joint Services Program, managed by the Air Force, with deputies from the Navy, Army, Marines, Defense Mapping Agency, Coast Guard and NATO.

Concept validation, Phase I of the program, was completed in the summer of 1979. This phase of the program included extensive testing that was conducted at Yuma Proving Grounds (YPG), Ariz. The objectives of these tests were to address a variety of operational and technical issues which characterize the performance of the system. One of these issues was the ability of GPS to provide a properly equipped user with accurate system time.

Objectives

The objectives of the Phase I Navstar GPS Time Transfer Tests were: to evaluate the performance, to measure the precision and accuracy of the transfer of GPS time to the static user and to develop a base of information that would support and expediate the United States Naval Observatory's (USNO's) efforts to develop and evaluate specialized user equipment to exhibit the operational GPS's precision timing characteristics.

System Description

GPS comprises three distinct segments: (1) the Control Segment (CS), (2) the Space Segment (SS), and (3) the User Segment (US). An inherent design property of the system is its precise and internally accurate time.

The CS comprises Monitor Stations (MS) and the Master Control Station (MCS) that are all very closely related in time (within a few nanoseconds). For the Phase I GPS there were four MS located at Guam, Hawaii, Alaska and Vandenberg Air Force Base, Calif., with the MCS at the same location as the Vandenberg MS. The function of the CS is to monitor the SS (GPS satellites) via measures of pseudorange, delta range (integrated Doppler) and satellite health. This information is processed in near real-time by the MCS to provide best estimates of each GPS satellite's ephemerides and clock performance. Using these estimates, very accurate predictions of the satellites' ephemerides and clock models are generated and uploaded to the satellites daily by the MCS.

The SS of the operational GPS comprises 24 satellites whose orbits are nearly circular, with 12-hour period and radii of 20,200 kilometers. These satellites will be configured into three equally spaced orbit planes that are inclined 63 degrees from the earth's equatorial plane. There will be eight equally spaced satellites in each plane. This configuration will provide continuous visibility to at least four satellites from any place on or near the earth. Each satellite will carry a system of redundant, high precision and highly predictable time and frequency standards. These standards will be used to generate the RF spread spectrum, Pseudo Random Noise (PRN), signals to the user segment. For the Phase I GPS there were four development model satellites that were equipped with redundant, precision, rubidium time and frequency standards, in orbit, for testing. These satellites were configured in operational orbit slots so that testers at YPG were able to observe them simultaneously for up to 1.5 hours per day. Just prior to this visibility at YPG, the satellites were uploaded with the newest ephemerides and clock prediction models by the MCS. In addition, if required, the satellites' standards were adjusted in phase and/or frequency so that they provided the user segment with the necessary coherent navigation signals that are processed by the user equipment to obtain position, velocity and system time.

The user segment comprises a variety of User Equipments (UE's) and their associated host vehicles. The UE's are sets which are composed of PRN receivers and data processors. These sets are designed to meet the specialized operational requirements of the user which are generally characterized by the dynamics of the host vehicle. For the Phase I GPS there were four classes of UE: (1) high dynamic sets for fighter/bomber applications, (2) low dynamic sets for air transport applications, (3) low cost prototype sets for commercial aviation applications, and (4) man-vehicle sets for ground applications. In general, these sets all perform the navigation mission of GPS in the same manner. The receiver obtains measurements of pseudorange and delta range (integrated Doppler) to four satellites. These measurements are handed over to the data processor which computes the user's position, velocity and time, using a Kalman filtering technique. The rate of these measurements/computations is related to the dynamics of the host vehicle.

Test Description

The data for time transfer testing were collected in conjunction with static (point) positioning tests. These tests were conducted from January through March 1979 at YPG, Ariz. by Defense Mapping Agency personnel using the Mobile Test Van (MTV).

The MTV is a one-ton step van which provides an approved operational environment for an electronics pallet which contains a high dynamics user equipment (Magnavox X-Set) and instrumentation to monitor and record user equipment performance, measurements and navigation solutions. The X-Set comprises a four-channel, dual-frequency receiver, power supply and battery pack, navigation data processor (NAV DP), Control Display Unit (CDU), preamplifier and omnidirectional (volute) antenna. The instrumentation comprises a data processor, input/output extender, nine-track tape recorder with buffer forematter, cassette tape transport (memory loader), engineering display (CRT) unit and engineering control (keyboard) unit, power supply, power distribution unit, line filter, high performance cesium beam time/frequency standard with power supply and IRIG time code generator. Figure 1 provides a block diagram of the X-Set/ Instrumentation.

The GPS satellites continuously broadcast PRN RF (L-band) signals at 1575.42 (L1) and 1227.60 (L2) MHz. Essentially, the process is as follows: the carrier frequency is combined with the PRN code and the low rate data stream, which contains the satellite's ephemerides and clock model to produce a modulated carrier frequency. To measure the range from the user to a satellite, the X-Set internally generates a PRN code which is identical to that of the satellite. This code is shifted until it is correlated with the received code and the amount that it is shifted can be interpreted as the difference in time between the X-Set's clock and that of the satellite. If the two clocks are synchronized, this time difference is the range to the satellite from the user, when multiplied by the speed of light and corrected for atmospheric effects. In reality, the two clocks are never synchronized exactly. This situation produces a pseudorange measurement which can be expressed by the following equation:

$$\bar{R} = R + c\Delta t_a + c\Delta t_o, \tag{1}$$

where

$\bar{R}$ = pseudorange measurement from the user to the satellite,.

R = true range from the user to the satellite,

c = speed of light,

Δt_a = propagation delays due to the atmosphere,

Δt_o = the user's clock offset from the satellite clock.

The X-Set's receiver is a four-channel, two-freqeuncy unit which is implemented with internal process control software (firmware). The receiver is integrated with a high speed navigation data processor to provide a high dynamic user with navigation solutions at a 1.7 second rate. These solutions are obtained by processing the simultaneous measurements of pseudorange and include a first order ionospheric correction, 0.5 second duration delta ranges to four satellites, and a Kalman filter estimation process whose eight element state vector contains three dimensional position and velocity, and user clock offset and rate. In the context of the static user, the Kalman filter is cued so that the velocity state only reflects the noise of the delta range measurements. To clarify this process, the determination of position and user clock offset can be determined in general mathematical terms as follows:

$$\overline{R}_i = R_i + c\Delta t_o, \tag{2}$$

where

$i = 1,\ldots,4$ and identifies measurements to the four satellites,

$R_i = [(X_u - X_i)^2 + (Y_u - Y_i)^2 + Z_u - Z_i)^2]^{\frac{1}{2}}$ are the true ranges from the user at X_u, Y_u, Z_u to the four satellites at X_i, Y_i, Z_i,

$\overline{R}_i$ = the X-Set's simultaneous measurements of pseudorange to the four satellites,

Δt_o = the user's clock offset from satellite's clocks. Notice, this assumes that all of the satellites' clocks are synchronized. In reality, the satellites' clocks are not exactly synchronized in terms of their pulse trains but the broadcast navigation messages contain the predicted clock models that are generated by the MCS, which mathematically synchronize the satellite clocks to the GPS Master clock, which resides in the Vandenberg MS. In the X-Set's computational process, the pseudorange measurements are corrected with these clock models prior to their entry into the estimation process so that one must solve for only the common clock offset.

In the above system of four equations there are four unknowns to be determined: three for the user's position (X_u, Y_u, Z_u) and one for the user's clock offset (Δt_o). Notice that the satellites' positions (X_i, Y_i, Z_i) are provided via the broadcasted navigation message which contains the predicted ephemerides that are generated by the MCS. For the testing, real time solutions of the user's clock offset were obtained as a part of the navigation solution. In addition, postprocessed solutions of the clock offset were obtained by assuming the users' position and this results in a one equation system with one unknown.

In order to maximize the precision of the pseudorange measurements and to provide a test configuration which would support time transfer tests, the X-Set was implemented as follows: the receiver's oscillator was synchronized in a phaselock loop to the 5 MHz output of the instrumentation's cesium standard via a hardware upgrade in the receiver, and the receiver's clock phase was synchronized to the one pulse per second (PPS) output of the cesium standard by implementing specialized navigation software. This use of the cesium standard actually makes it the receiver's clock. Thus, the internally generated PRN code is equally or more precise than the satellite generated code.

To provide an independent monitor for the cesium and system redundancy, two additonal cesium standards were installed in the MTV and the three cesium standards were integrated into an ensemble which was monitored hourly using a computer controlled time interval counter which measured the difference in time between the one pulse per second outputs of the cesium standards. These differences were automatically recorded on magnetic tape in a small cassette. The instrumentation cesium standard was considered the master for all testing. Figure 2 illustrates the timing ensemble.

The test site at YPG was located in the immediate vicinity of the Inverted Range Control Center (IRCC) and the antenna was precisely referenced to a permanent survey station mark. The position of the mark was determined in the WGS 72 earth centered/earth fixed coordinate system by the Defense Mapping Agency (DMA), using precise conventional and Geoceiver-Transit satellite surveys. The MS's have been positioned in the WGS 72 system by DMA, using the same methods, and their locations form the reference frame for GPS. Given the above, it is clear that we can use the position of the station mark as the user's position to implement the single satellite time transfer.

Up to this point, time transfer has not been defined explicitly, but it is now possible to provide this definition. Time transfer is the process whereby GPS time is transferred to a user's clock. In these tests, the transfer of time is to the instrumentation's high performance, cesium, time/frequency standard. To realize the transfer, the navigation (real-time) solution of the user's clock offset, error in clock phase (ECP), is applied to the user's clock time so that, effectively, the user's clock is in synchronization with GPS time. In the case of the postprocessed solution, the clock offset is determined and applied to the user's clock time to provide a GPS time scale for the user's clock.

Results

For the time transfer tests, the time reference was provided by the United States Naval Observatory flying clock trips, which established the difference in time between the GPS Master Clock at the Vandenberg MS and the MTV clock ensemble.

During the period from early January to early March 1979, the USNO flying clock made five trips from Washington DC to YPG and Vandenberg. Each of these trips consisted of flying a high performance, cesium beam, time/frequency standard and time interval counter from the USNO, Washington, D. C. to YPG, to the Vandenberg MS to YPG and back to Washington in approximately two days. Prior to the clock's departure and after its return to Washington, it was calibrated with the USNO ensemble of more than 20 high performance cesium standards. When the clock was at YPG and the MS, the time interval counter was used to measure the time difference between the flying clock and the local clock. The calibrations and the time difference measurements were processed at USNO to provide the relationship between the clocks at the Vandenberg MS, YPG, and the USNO. Figure 3 and Table I provide the results for these flying clocks.

For the period of 1 February through 1 March 1979, real time, time transfer, test data were collected at YPG. During this period, 14 days of data were collected. Each day's data consisted of approximately six samples which were collected over 20-minute time periods after the satellites were uploaded by the MCS with appropriate ephemerides and clock models. Each sample was the real time, Kalman Filter solution of the error in the X-Set's clock phase. This error in clock phase (ECP) is the difference between the user's local time and GPS time, and in this case the user's local time is obtained from the MTV instrumentation's high performance, cesium, time/frequency standard. To obtain values for the accuracy and precision of real time, time transfer, the ECP was compared with the accepted true difference in time between the MTV and GPS as determined by the flying clock and USNO's analysis of the MTV clock ensemble data. Before the comparisons were made, the ECP was corrected for hardware delays. These delays are due to the length of the X-Set's receiver calibration cable and to the difference between the six-second pulse offset of the Vandenberg MS and that of the MTV X-Set receiver from their respective time/frequency standards' one pulse per second references. The values for these delays are listed and explained in Appendix A and B. Table II contains the ECP/

USNO comparisons.

To provide additional checks of the time transfer and to look at the case in which the user's position is known, the MTV magnetic data tapes containing the pseudorange measurements, satellite broadcast ephemerides and Kalman Filter solutions for February 5-7 were post processed by the Aerospace Corporation. The results of these efforts are presented below.

Case I is a four satellite solution of the ECP which used the broadcast ephemerides/clock models and the Geoceiver/Transit determined WGS 72 position of the X-Set's antenna. The ECP was determined by differencing the measured pseudoranges and the given ranges and then fitting these differences to a second order polynomial with a constant (bias) term, drift term and aging term. This polynomial was then used to generate the ECP for the same times that real time ECP data were obtained during MTV operations.

Date	Polynomial:	$Ao + A_1 \cdot (t-to) + A_2 \cdot (t-to)^2$
		$Ao = 8952.753$ mtrs
5 Feb 79		$A_1 = -0.00042236$ mtrs/sec
		$A_2 = 0.00000023$ mtrs/sec^2
		$to = 50519.25$ sec

Time (sec)	Real-Time ECP (mtrs)	Post Processed ECP (mtrs)	Real-Post (mtrs)
50700	8951	8952.684	-1.684
50820	8951	8952.647	-1.647
51000	8952	8952.603	-0.603
51300	8954	8952.563	+1.437
51600	8951	8952.565	-1.565
51900	8949	8952.608	-3.608
		Mn	-1.278
			(-4 nanoseconds)
		S	1.652

Date	Polynomial:
6 Feb 79	$A_o + A_1 \cdot (t-t_o) + A_2 \cdot (t-t_o)^2$ A_o = 8991.612 mtrs A_1 = 0.00376515 mtrs/sec A_2 = 0.00000042 mtrs/sec^2 t_o = 52256.48 sec

Time (sec)	Real-Time ECP (mtrs)	Post Processed ECP (mtrs)	Real-Post (mtrs)
52500	8992	8990.963	+1.037
52800	8991	8990.901	+1.099
53100	8990	8991.652	-1.652
53400	8991	8993.219	-2.216
		Mn	-0.433
			(-1 nanosecond)
		S	1.749

Date	Polynomial:
7 Feb 79	$A_o + A_1 \cdot (t-t_o) + A_2 \cdot (t-t_o)^2$ A_o = 9042.962 mtrs A_1 = 0.00148212 mtrs/sec A_2 = 0.00000042 mtrs/sec^2 t_o = 50509.02 sec

Time (sec)	Real-Time ECP (mtrs)	Post Processed ECP (mtrs)	Real-Post (mtrs)
50700	9044	9043.260	0.740
51000	9044	9043.791	0.209
51300	9044	9044.397	-0.397
51600	9041	9045.079	-4.079
51900	9040	9045.836	-5.836
52200	9040	9046.669	-6.669
52500	9040	9047.598	-7.578
			-3.373
		Mn	(-11 nanoseconds)
		S	3.505

Case II, is a single satellite (Navstar 4/PRN Code 8) solution which was obtained using the same technique as in Case I.

Date	Polynomial:	$Ao + A_1 \cdot (t-to) + A_2 \cdot (t-to)^2$
		$Ao = 9044.438$ mtrs
7 Feb 79		$A_1 = 0.00162105$ mtrs/sec
		$A_2 = 0.00000003$ mtrs/sec^2
		$to = 50449.12$ sec

Time (sec)	Real-Time ECP (mtrs)	Post Processed ECP (mtrs) 4 Satellite	1 Satellite	Real-Post (mtrs) 1 Satellite
50700	9044	9043.260	9044.847	-0.847
51000	9044	9043.791	9045.340	-1.340
51300	9044	9044.397	9045.839	-1.839
51600	9041	9045.079	9046.304	-5.304
51900	9040	9046.836	9046.853	-6.853
52200	9040	9046.669	9047.368	-7.368
52500	9040	9047.578	9047.889	-7.889
				-4.491
			Mn	(-15 nanoseconds)
			S	3.063

Case III, is a combined solution of the three days' data from Case I. In this case, Aerospace Corporation generated post flight empherides and satellite clock models for the four satellites by post processing MS measurement data, which covered the period of 29 January to 12 February. These ephemerides and clock models were then processed with the MTV measurements in a batch, least squares process which provided solutions for the MTV's position, clock offset and rate. In addition, solutions were obtained by using the MTV measurements without applying first order, ionospheric corrections.

Date & Time (sec)	Real-Time ECP (mtrs)	Post Processed ECP (mtrs)		Real-Post (mtrs)
5 Feb @ 51000	8952	8953.4	(8961.4*)	-1.4
6 Feb @ 52500	8992	8993.4	(9000.o*)	-1.4
7 Feb @ 51000	9044	9044.9	(9050.9*)	-0.9

*These are the ECPs determined without using the 1st order ionospheric ocrrections.

Review of the Results

The Case I data verify the real time solution data and indicate only marginal (approximately 10 nanoseconds) improvement is obtained when the pseudoranging data is post processed.

The single satellite results illustrated in Case II and and ECPs determined without ionospheric corrections in Case III provide an indication that a single satellite time transfer without ionospheric correction would degrade the result by approximately 30 nanoseconds, depending on the individual satellites' broadcast ephemeris and clock model quality.

The Case III data indicate that processing with post fit ephemerides does not significantly improve the real time results except in terms of confirmation and greater statistical significance due to the amount of data employed to obtain the results, that is, the confidence level is greatly increased.

Conclusions

The comparisons of the real time and post processed ECPs show that GPS will be able to provide better than 20 nanosecond time transfers in real time, but the real time ECPs which were corrected for X-Set synchronization errors and calibration delay line errors indicate that there are hardware delays which must be accounted for if the user actually is to obtain a physical transfer of time in terms of his UE's clock output pulse. In this context, tests are now in progress that have been designed to address the delay issues so that the Phase II GPS UE will provide the user with a time transfer capability that is more in conformance with the system's real capability which has been demonstrated via the real time/post proccessed ECP comparisons.

Table I

USNO Master Clock - MTV Clock

11 January to 1 March 1979

The offsets are determined from USNO's adjustment of flying clock trip and MTV timing ensemble data.

Date	Time	Offset (μs)
1 Feb	1445	-8.210
2 Feb	1425	-8.298
3 Feb	1355	-8.366
5 Feb	1412	-8.482
6 Feb	1442	-8.535
7 Feb	1420	-8.591
8 Feb	1425	-8.646
9 Feb	1415	-8.705
12 Feb	1318	-8.890
13 Feb	1328	-8.951
15 Feb	1310	-9.078
21 Feb	1252	-9.452
28 Feb	1220	-10.014
1 Mar	1212	-10.086

Table II

Time Transfer at Yuma Proving Ground AZ
Mobile Test Van w/Magnavox X-Set

all data in nanoseconds

Date	Time (UT)	ECP	Correc-tion	ECP'	USNO TR†	ECP'-TR†
1 Feb	1430-1500 (7)*	29351±3	177	29528	29596	-68
2 Feb	1345-1505 (8)	29505±13	211	29716	29741	-25
3 Feb	1345-1405 (10)	29579±5	165	29744	29866	-122
5 Feb	1400-1425 (7)	29859±5	185	30044	30094	-50
6 Feb	1435-1450 (4)	29991±3	161	30152	30203	-51
7 Feb	1400-1440 (9)	30160±6	219	30379	30315	+64
8 Feb	1420-1430 (3)	30193±5	185	30378	30425	-47
9 Feb	1400-1430 (7)	30338±7	205	30543	30539	+4
12 Feb	1300-1335 (8)	30708±6	197	30905	30886	+19
13 Feb	1320-1335 (4)	30808±8	197	31005	31001	+4
15 Feb	1300-1320 (5)	30959±4	241	31100	31234	-134
21 Feb	1240-1305 (6)	31750±7	161	31911	31917	-6
28 Feb	1205-1235 (7)	32700±3	163	32863	32825	+38
1 Mar	1200-1225 (6)	32784±3	163	32947	32945	+2

†Time Reference

* these are the number of samples obtained during the time period.
ECP, is the mean of samples and is characterized by its standard deviation.
Corrections are derived from the material presented in Appendix A and B.
ECP' is the ECP with corrections applied.
USNO Time Reference, these values were obtained from the data presented in figure 3 and Table I.
ECP'-Time Reference are the errors in the time transfer.

Analysis, investigations of clock trips, timing ensemble and the synchronization suggest that the quality of each test is ±50 nanoseconds (one sigma). The mean of the 14 tests: -27 ± 56 nanoseconds confirms this and suggests that the major source of error is the nominal value of 170 nanoseconds of VMS synchronization delay.

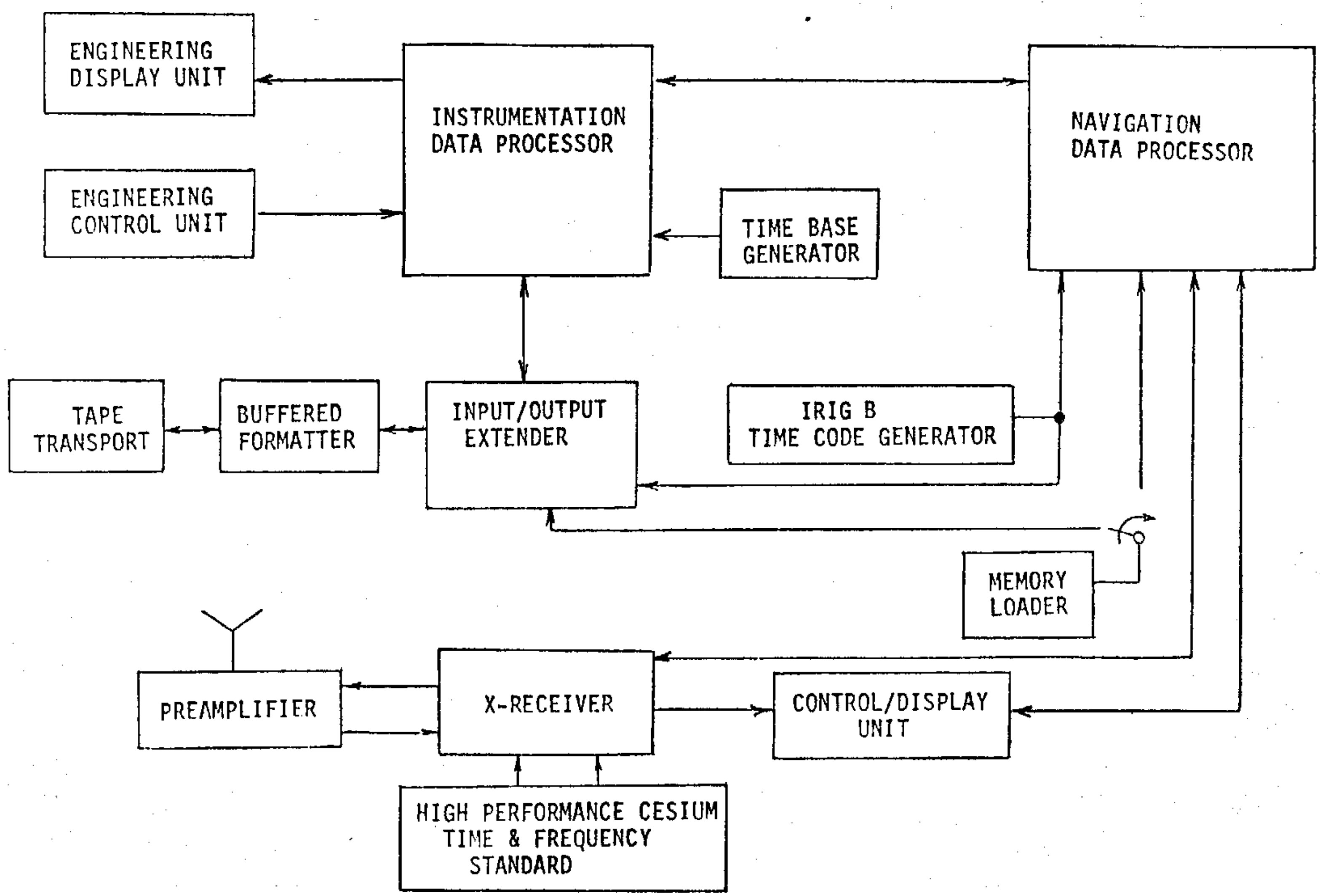
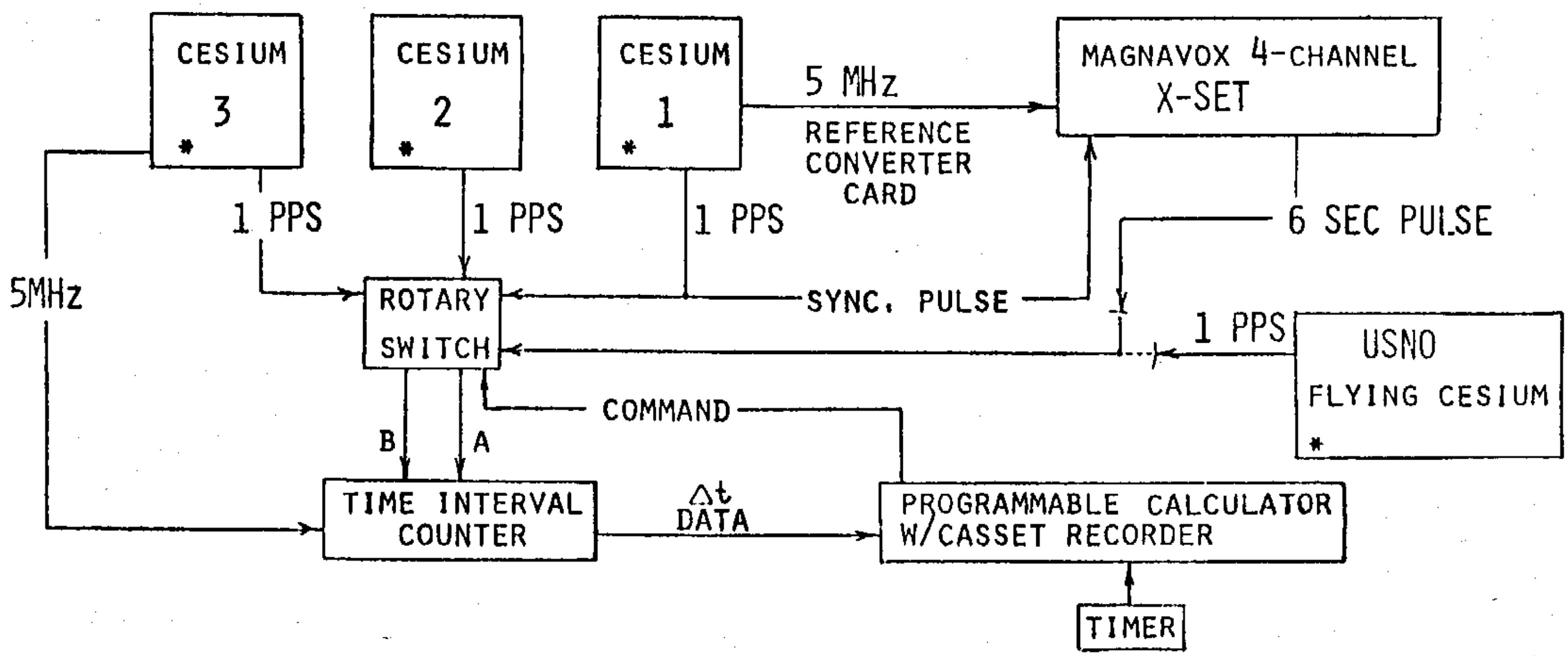


Figure 1. X-Set/Instrumentation



*ALL CESIUMS ARE HIGH PERFORMANCE TIME & FREQUENCY STANDARDS.

Figure 2. Time Transfer MTV's Timing Ensemble

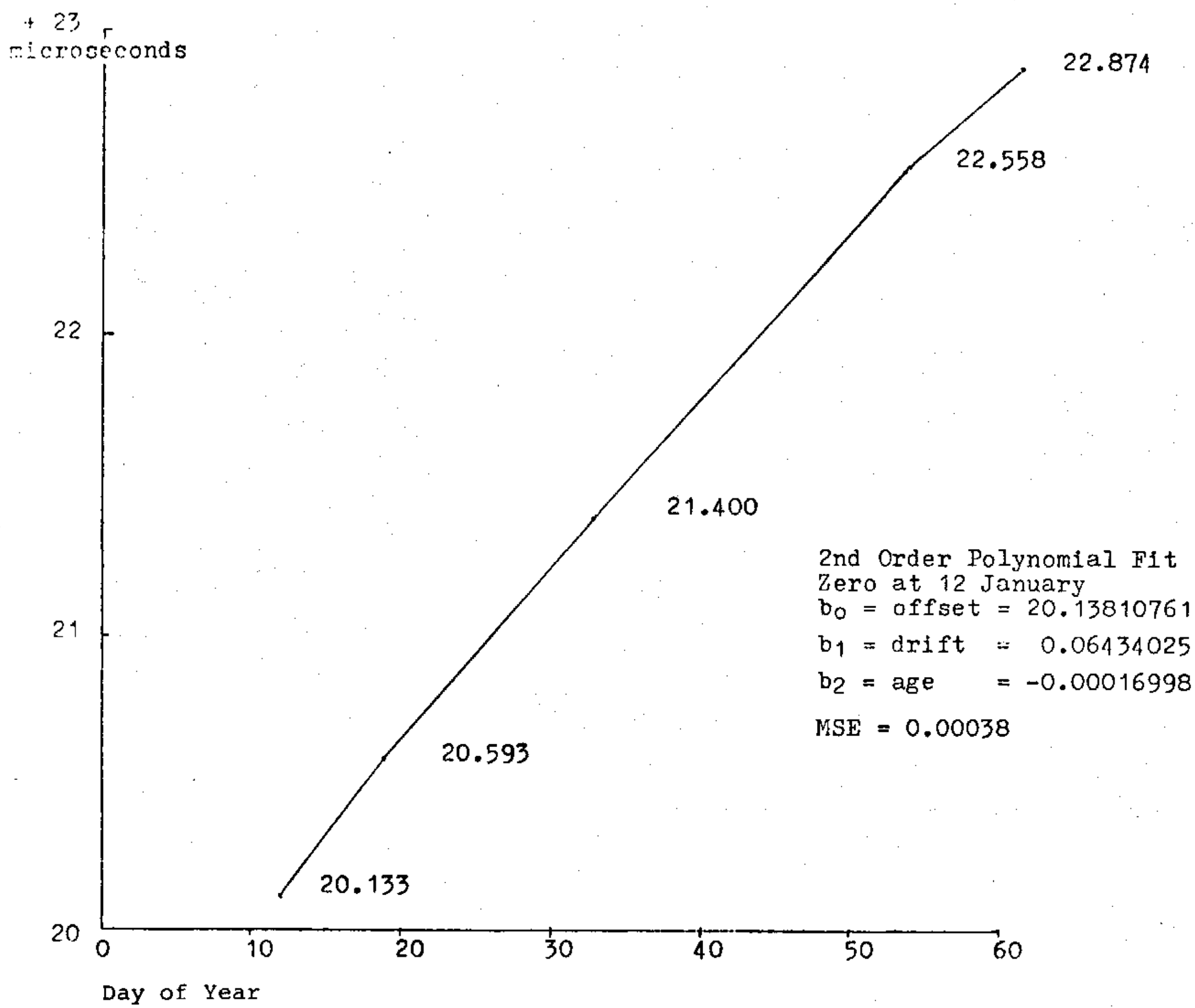
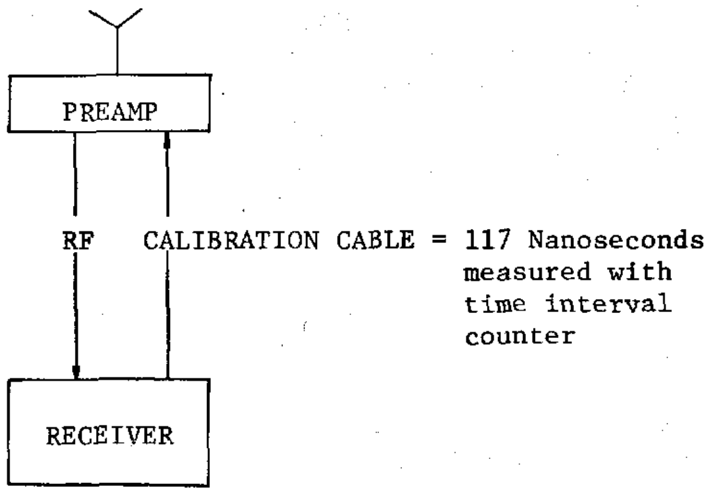


Figure 3. USNO Master Clock – GPS Master Clock, 11 January to 1 March, 1979

Appendix A

MTV X-Set
Calibration Delay

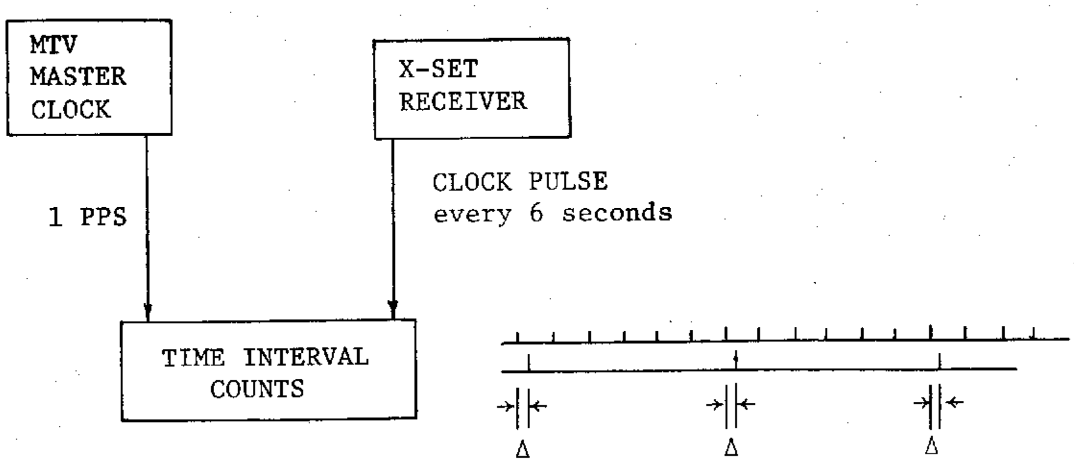


The X-Set's calibration procedure sends a signal out via a cable to its preamplifier and back to the receiver via the RF cable. The receiver measures the time it takes and the equivalent range is subtracted from the pseudorange measurements. This results in a measurement which is too short by the length of the calibration cable delay time. The calibration cable's delay was measured several times with a two-nanosecond resolution, time interval counter and found to be 117 nanoseconds. This delay is a plus correction and is added to the ECPs. Notice, MS's correct the pseudoranging for this effect so this timing bias is not introduced into the SS. Further, the MTV's X-Set does not correct for this because the navigation solution is transparent to common timing biases and navigation was the primary test goal of the set.

APPENDIX B

X-Set Synchronization Delay

The X-Set's clock is synchronized to an external 1 PPS with software control of hardware. The procedure is as follows: the operator inputs the time which will be set via the CDU plus an estimate of the reference clock's (MTV Master Clock) offset from GPS time; this sets a gate in the receiver and the X-Set's clock to the time while freezing the epoch update of the clock; just prior to the Master Clock's epoch (1 PPS) of the set time the operator implements the time set with a CDU input command, which tells the receiver that the next 1 PPS it sees will be the synchronization pulse; when the receiver sees the 1 PPS at the gate it starts the epoch update of its clock carrying the set time. To determine the quality of the MTV synchronization, the difference between the reference 1 PPS and the X-Set's clock output pulse were measured during each test with a two nanosecond resolution time interval counter. Notice, the MS's use X-Sets for data collection and their clocks are set to an external reference. In the case of the VMS, this is accomplished similarly to the MTV while the other MS clocks are set from the MCS via the satellites. For the time transfer test it is important to know the offsets of the VMS and MTV synchronizations. In the case of the VMS, a nominal value of 170 nanoseconds has been determined. For the MTV, measurements were obtained and are listed on the following page.



Δ = X-Set's pulse lag

Notice, if the VMS and MTV synchronzation errors were equal, the errors would cancel. In this case, the VMS at 170 nanoseconds and the MTV at a lower level introduce a bias in the time transfer. The effect of this bias is to make the ECP smaller as the MTV clock is slightly ahead of the VMS clock. To correct for this, the measurements of the MTV synchronization error for each test are subtracted from VMS nominal value and the resultant value is added to the ECP. In terms of the VMS nominal value, we can characterize its quality by the statistics provided by the MTV measurements, which give us a nominal value of 170 ± 25 nanoseconds (one sigma).

Table B.1

Differences between Cesium 1 PPS and X-Set (Serial #12) 6 second pulse after synchronization. Measurements were obtained with the HP 5345A Time Interval Counter (2 nanosecond resolution).

Date	Value (nanoseconds)	Date	Value (nanoseconds)
1 Feb 79	110	1 Mar 79	124
2 Feb 79	76	2 Mar 79	140
3 Feb 79	122	5 Mar 79	100
5 Feb 79	102	6 Mar 79	114
6 Feb 79	126	9 Mar 79	138
7 Feb 79	68	12 Mar 79	94
8 Feb 79	102	13 Mar 79	132
9 Feb 79	82	14 Mar 79	54
12 Feb 79	90	15 Mar 79	134
13 Feb 79	90	16 Mar 79	124
14 Feb 79	140	19 Mar 79	140
15 Feb 79	146	20 Mar 79	92
16 Feb 79	112	22 Mar 79	90
19 Feb 79	86	23 Mar 79	134
20 Feb 79	66		
21 Feb 79	126		
28 Feb 79	124		

Mn = 109 ± 25   31 samples
3σ = (34, 184) all values within this interval