N92-33353

Evaluation of GPS/UTC Steering Performance

W. A. Feess, H. Holtz, A. L. Satin, C. H. Yinger
The Aerospace Corporation, El Segundo, CA

Abstract

The Global Positioning System (GPS) is required to maintain GPS time to UTC to an accuracy of one microsecond and broadcast to the user the offset between GPS and UTC to an accuracy of 100 nanoseconds (1 sigma). On June 25, 1990, an automatic steering algorithm was implemented to control GPS time to synchronize it with UTC. The description of the steering laws and predicted performance results were presented at the 1989 PTTI conference, while preliminary performance results were presented at the 1990 PTTI conference. The initial performance was not as predicted, resulting in an in-depth analysis of the observed performance and a more thorough sensitivity analysis. In addition, responses to anomalies were investigated. This paper will describe these analyses and results, and evaluate actual steering performance from June 1990 to November 1991. Although anomalies were observed during the initial phase of steering, recent experience is more in line with expectations.

1.0 Introduction

The Global Positioning System (GPS) is a Department of Defense space-based navigation and time dissemination system. When fully deployed it will consist of a constellation of 21 operational satellites (Blk II/IIA) plus three active spares. The current constellation consists of nine Blk II and two Blk IIA satellites. In addition, five Blk I development satellites are still functioning.

As a navigation system, each satellite is required to deliver to a user a timing signal and information relative to the satellite vehicle (SV) position and time offset with respect to system time (GPS time) to an accuracy of six meters (20 nanoseconds) one sigma. Given this accuracy of time signals to four SV's with appropriate geometry, an authorized dual frequency user can navigate in three dimensions to an accuracy of 16 m SEP. A user who knows his location in the reference coordinate system of GPS (WGS84), can synchronize his time to GPS time. The accuracy of this time transfer is also dependent on the user's ability to remove propagation effects (ionospheric and tropospheric) and when applicable the effects of selective availability (SA).

GPS is also required to synchronize GPS time to Universal Coordinated Time (UTC) maintained by the U.S. Naval Observatory (USNO) and to broadcast to the user the time difference between these two timing systems. The requirement is to synchronize to one microsecond (1000 ns) and to broadcast the difference to an accuracy of 100 nanoseconds (one sigma). This paper evaluates the performance of these functions.

2.0 Steering Performance

To meet these requirements, USNO is equipped with GPS receivers to monitor GPS time and the broadcasted GPS-UTC time difference. Reference 1 describes in detail the equipment and tracking schedules used to perform these functions. The data collected is processed by USNO and available for transmission to the Operational Control Segment (OCS) daily via secure telephone lines. The OCS operates with this data to control GPS time. This operation is pictorially and schematically presented in Figure 1. Early in the program, the control was manual in that the operator would observe the time history of the timing difference and periodically effect a magnitude and time duration command to steer the GPS time offset towards zero. The command is a frequency drift command (second derivative of time) whose magnitude is limited. The limit was set to protect the navigation user in the event the OCS was rendered inoperable due to hostile or natural causes. More recently (June of 1990) steering was automated to ease the operator function and to improve performance. Several control laws were considered for automation of the control function. Reference 2 described and analyzed these control laws, and presented predicted performance. In addition to steering, the GPS time reference was changed from a GPS master clock to a GPS clock ensemble configuration (composite clock). Reference 3 presented the preliminary performance of these changes after initial turn on. To put steering performance in prospective, Figure 2 shows the time history over the past five years.

The steering law implemented is that designed by the Control Segment contractor (IBM) which is described in Reference 2. It is a three state controller, i.e., plus, minus or zero command. The command rate is the limiter value of 2E−19 s/s^2 ($\approx$ 1.5 ns/day^2). The anticipated steady state performance after initial transients have subsided was 10 ns one sigma (Reference 2). Automatic steering was initiated June 25, 1990 (MJD=48067). Figure 3 presents the GPS/UTC time difference and steering command from turn on to November 1, 1991 (48561). The initial overshoot was expected, however the large undershoot was much larger than expected and the magnitude of the second overshoot was not anticipated at all. Concern was raised with the initial undershoot and analyses were initiated after the second overshoot. Automatic steering was turned off for 9 days following the initial undershoot (48120 to 48129) and turned off from 48160 to the end of 1990 (MJD 48256). Occasional manual steers were introduced during this later period.

The observed performance was of particular concern to us, because the concepts for steering here are being applied to a more difficult task for the Blk IIR SV's currently being designed. The task there will be to synchronize two GPS clock ensembles, the Blk IIR SVs ensemble operating in their autonomous navigation mode and the current OCS clock ensemble of all SV's and monitor stations. The GPS/UTC synchronization will also be required.

To investigate the situation, a set of OCS filter data covering the first 22 days of October, 1990 (MJD 48165 to 48187) were obtained and analyzed. At this point in time, it was not known whether the problem existed with the steering or the GPS clock ensemble since both were initiated about the same time. Prior to this analysis the steering algorithm was checked and found to be producing the correct steering commands for the phase and frequency offsets observed by USNO. Two major phenomenon were observed from the filter data. First, estimates of aging on two of the SV's with rubidium frequency standards (PRN's 3 and 16) had large estimation errors. Second, it was observed that Nav 16 had a large uncompensated frequency jump ($\Delta f/f \approx$ 4E-12) causing a change in frequency estimates of the other clocks in the ensemble of opposite polarity and about one fifteenth the size. During this period, the frequency standard at the Colorado Springs monitoring station was switched to the NRL's hardware ensemble (48167). Although the frequency of the two standards were considerably different, the transition was handled correctly by the filter with no detectable changes in ensemble frequency.

Simulations of the steering loop to aging and frequency jumps led to the conclusion that the first undershoot problem was due to the filter mismodeled aging and the second overshoot was a combined effect of NAV 16 frequency jump and a change in aging. Based on these findings it was concluded that the problem was in the clock ensembling process and not in the steering loop design. It was therefore recommended that all SV rubiduim clocks and any other SV which was experiencing estimation problems of clock or ephemeris be removed from the GPS ensemble process. This was done in December and automatic steering was again initiated January 1, 1991.

The performance since January 1 still reflects spurious responses which can be associated with monitoring station clock problems. It should also be noted here that it is not necessary that SV rubiduim clocks be excluded from the GPS ensembling process; however, it is necessary that the filter be tuned properly to estimate the aging state.

3.0 Stability of GPS Time

The common measure of time stability is the Allan Variance of the sample function. This is presented in Figure 4 for the time history of the GPS time offset presented in Figure 3. This represents the composite of the GPS time ensemble and the steering function. When the steering command is integrated twice and removed from the sample function of Figure 3, a measure of the GPS ensemble time is obtained. This is also presented in Figure 4. These are rather complex functions to make any quantitative statements; however, certain qualitative observations can be made. The one day value ($\approx$ 2.8 E-14) is a reasonable assessment of the GPS ensemble time since its value is not affected by the contribution of steering. Also included in this number is the accuracy of the measuring system which includes the SV clocks, therefore it can be concluded the GPS ensemble is performing better than 2.8 E-14 at one day. In the interval of 1 to 100 days, the GPS time ensemble response suggests a significant component of aging noise. Beyond 25 days, the steering loop significantly removes the effects of this noise as evidence by the intersection of the open and closed loop curves.

4.0 Time Dissemination Performance

The time dissemination relates to how well a GPS user can determine his time offset with respect to UTC. USNO monitors this function by correcting the observed GPS time offset by the offset broadcast by GPS in subframe 4. The phase, computed frequency and reference time received from USNO for steering is also used at the OCS to prepare the subframe 4 data. USNO then uses what it receives in the message to arrive at the GPS (UTC) error. What is computed by USNO and presented here in Figure 5 is the daily mean and the one sigma value about the mean for the interval when steering was turned on to November 1, 1991. Observing Figure 5 it is seen that early in the steering interval, June to October 1990 (MJD 48067 to 48165), the pattern and magnitude of error was larger than the rest of the interval. Initially a three day least squares polynomial fit was done at the OCS using a subset of the total data collected by USNO. Problems associated with this procedure resulted in the change to the current procedure (see Section 5) and associated improved performance.

The RSS value of the mean and sigma is more the intent of the 100 ns requirement. Table I summarizes the performance of these quantities over the total interval and over the interval covering this year.

Table 1. Disseminated Time Accuracy RMS Statistics over each interval (ns)

Interval	Mean	Sigma	RSS	Max RSS
June 25 '90 to Nov 1 '91	8.3	11.8	14.5	52.6
Jan 1 '91 to Nov 1 '91	4.9	10.9	12.0	23.6

5.0 Sensitivity Study

Because of the anomalous performance initially experienced, a re-examination of the steering loop was initiated. The new simulation depicted more closely the USNO to OCS interface and the OCS to satellite interface system than was used in the original study (Reference 2). Figure 6 presents the new simulation diagram. As in the original study the OCS Ephemeris and Clock Kalman filter is represented as a simple two stage clock model. In the simulation, the steering command is integrated twice to reflect schematically the response while in the OCS the steering command is fed directly to the Kalman filter and the filter performs the integration. This schematic representation has the advantages that more realistic representations of the Kalman filter could be implemented without changing the steering diagram. The difference of these two outputs (filter and steering) represents GPS time and is used as the reference for uploads to the satellite system. Each SV in the constellation of N satellites is also modeled as a two stage clock with phase and frequency outputs being reset daily to represent the upload function. For most studies, N was set to 12 and the rotary switch would reset a different SV clock every two hours. On the other end of the SV simulation is another rotary switch sampling one of the SV's in the constellation every 15 min representing the operation at the USNO. Noise is added to these samples to represent errors in the USNO caused by receiver and correction errors. The current procedure since Oct 1990 has been for USNO to collect 38 hours of data (0 hrs GMT to 14 hrs the next day) and to perform a least squares linear fit on the data to produce a phase and frequency offset of GPS time to USNO time. The time tag for this data is 24 hour into the fit interval. For our simulation, an hour delay is incorporated to allow time for transmitting and entering the data into the OCS system. The OCS uses the first difference of the daily phase error data to represent frequency error. This output is fed daily to the steering law. The IBM steering law operates on this command every 15 minutes to determine an output steering command. The steering law is described in Reference 2 with a change to the TOL value (error tolerance from 1 to 10 ns) which was recommended by IBM. For comparison, the linear law of Reference 2 was also simulated where steering commands are computed once per day subject to the output limit.

The main inputs to this simulation for steady-state performance analysis are the performance parameters of the ground ensemble, the performance of the SV clocks, and the noise level of the measurement process. Figure 7 presents Allan Variance curves for the clock models and defines the nominal values used for stochastic parameters in this study. Other inputs of initial conditions, ensemble aging and/or frequency jumps, limiter level, data dropouts, number of SV clocks simulated, measurement filtering intervals, and delay variations were also investigated but not reported here.

One of the characteristics noted in this simulation was the non-repeatability of statistical results with changes in the seed to the random number generator. It was initially thought that simulation intervals of 3 to 5 time constants (100 to 200 days) would be adequate to portray performance for a particular set of inputs. However, it was found that significant changes in results occur even for simulation intervals of 1000 days. Figure 8 is a typical example where the first 300 days exhibits large excursions (parasitic oscillations) with a significant change in apparent performance over the remainder of the interval. For the same input conditions (except for a change in the random number seed) a completely different response results. Similarly for the same seed, but a change in the magnitude of one of the input noise levels, results in a complete change in apparent performance over time. For this reason, it is difficult to conduct a sensitivity analysis on a non-linear controller. To a lesser extent, the linear controller also suffers when noise levels are sufficient to cause frequent limiting action. The nonlinearity violates laws of superposition and stationarity enjoyed by linear systems and makes the analysis for stochastic inputs more difficult to predict.

With this characteristic noted, a sensitivity study was run simulating both the current controller and a linear controller. Table II defines the parameters and values used and presents results in terms of RMS phase and frequency errors for each case. Figure 9 graphically summarizes the phase errors for each class of input and variation used.

It is seen from these results that the loop performance is most sensitive to the performance of the ground clock ensemble and relatively insensitive to measurement noise at USNO or to individual SV clock performance.

Table II Sensitivity Study Parameters and Results

Input							RMS Results			
	Noise Seed	Ground Clock		SV Clocks		Meas. Noise (ns)	IBM		Linear	
Symbol	REP	W1E	W2E	W1S	W2S	MNZ	Phase (ns)	Freq (ns/day)	Phase (ns)	Freq (ns/day)
Nominal	3	3	1	9	3	10	22.1	4.6	14.7	3.3
Seed	1	”	”	”	”	”	15.9	4.0	12.7	3.0
	2	”	”	”	”	”	12.3	3.8	11.1	3.0
	4	”	”	”	”	”	15.5	3.7	14.5	3.1
	5	”	”	”	”	”	20.4	4.2	15.1	3.2
Grd Clk	3	6	”	”	”	”	36.1	6.0	27.1	4.9
	”	1.5	”	”	”	”	17.0	3.6	11.9	7.6
	”	3	2	”	”	”	56.8	7.1	53.2	6.8
	”	”	.5	”	”	”	10.2	3.1	9.8	2.5
SV Clk	”	”	1	27	”	”	20.0	4.3	19.8	3.8
	”	”	”	3	”	”	14.2	3.7	13.8	3.1
	”	”	”	9	9	”	21.8	4.5	14.9	3.3
	”	”	”	”	1.5	”	19.2	4.2	14.7	3.3
Meas.	”	”	”	”	3	20	21.8	4.4	16.0	3.4
Noise	”	”	”	”	”	5	18.8	4.3	14.4	3.2

6.0 Performance Improvements

Although the current performance (both in control of GPS time and dissemination of the GPS/UTC time difference) are well within required accuracies, improvements are always possible. The major perturbation to control accuracy is detection of and compensation for individual clock anomalies. To this end, an enhancement to the control segment software, called Performance Visibility, is currently in the design stage by IBM (Reference 4). This enhancement will examine the Kalman filter products to automatically detect anomalous magnitudes, trends, etc. so that operator intervention and correction can be applied before anomalies spread into the GPS system and the constellation of satellites.

Currently, the clocks contributing to ensemble time are all equally weighted. The Colorado Springs monitor station has the NRL hardware ensemble as its reference and could be weighted so as to enhance stability of GPS time with corresponding improvement in control of GPS time. This requires no software changes. Converting to a linear controller in contrast to the IBM controller offers some improvement, particularly if the limits were increased so higher gains could be used.

Time dissemination improvement is harder to achieve. The accuracy is primarily dictated by the SV clock performance in prediction and the update rates involved. Update rates, e.g., twice a day could offer perhaps a factor of two improvement and perhaps would not be that difficult to implement. Relative to SV clocks, our experience with Blk II rubiduim clocks (NAV 16) is limited and its performance plagued with frequency jumps not necessarily inherent in the standard design. In the absence of frequency jumps and with proper modeling of aging in the Kalman filter, the stability of Nav 16 standard over one day was excellent. The Blk IIR rubiduim clocks could offer improved performance, while the autonomous navigation feature will offer enhanced accuracy of SV broadcast time.

7.0 Conclusions

Both control and dissemination of GPS time with respect to USNO time have been demonstrated to exceed performances requirements by at least an order of magnitude. The performance of the GPS Composite clock demonstrates an accuracy better than 3E-14 frequency stability at one day. Every indication is that this will improve with enhanced anomaly detection and filter tuning. The lesson learned is to evaluate system design under anomalous performance as well as nominal performance. Also, not all clocks perform equally and should not be weighted equally. For questionable clocks, zero weights are much preferred to equal weights. Finally, the techniques to evaluate performance are valid and should carry through to designs of the Blk IIR constellation synchronization and GPS/USNO control and dissemination. Anomaly studies of the Blk IIR has been an integral part of the design activity and experience here reinforces the need for anomaly analysis during the design phase.

References

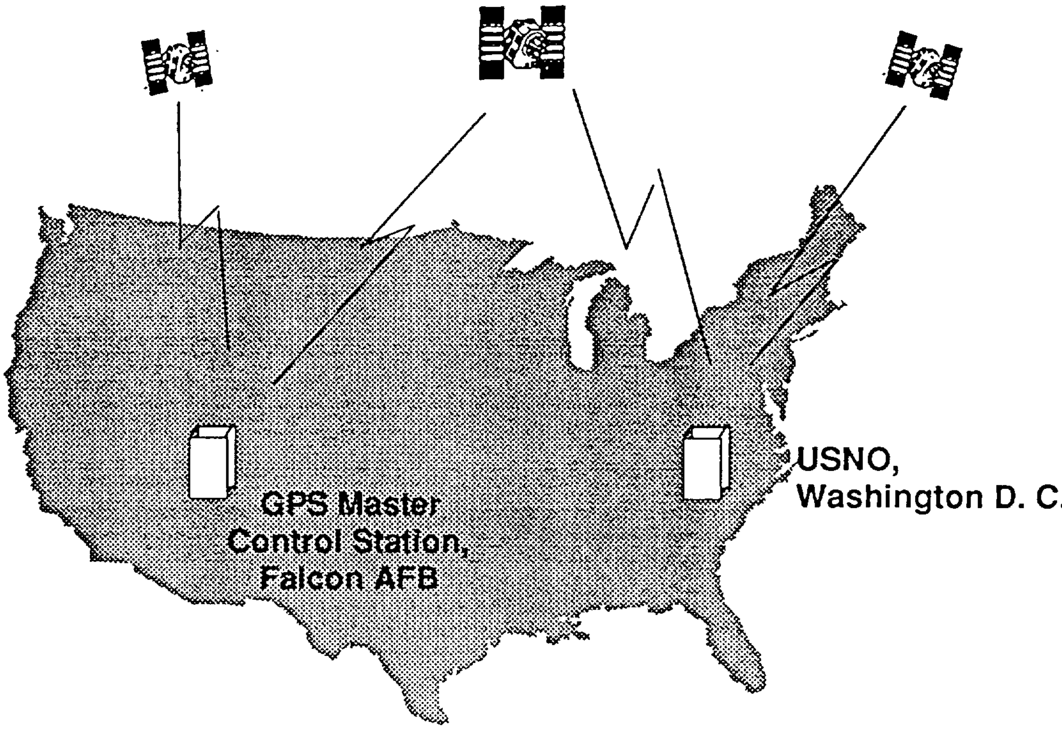
1. M. Miranian and W. J. Klepczynski, *"Time Transfer Via GPS at USNO"*, ION GPS-91 ION Satellite Division's 4th International Technical Meeting, September, 1991.

2. C. H. McKenzie, et al., *"GPS-UTC Time Synchronization"*, Proceedings of the 21st Annual PTTI Applications and Planning Meeting, November 1989.

3. A. L. Satin, W. A. Feess, H. F. Fliegel, C. H. Yinger, *"GPS Composite Clock Software Performance"*, 22nd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, Vienna, Virginia, December 4-6, 1990.

4. K. R. Brown, *"Navigation Performance Visibility Study Report for the NAVSTAR Global Positioning System (GPS) Operational Control Segment (OCS) Residual Development"*, IBM, Gaithersburg, Maryland, July 8, 1991.

Figure 1. GPS/UTC Steering Diagram



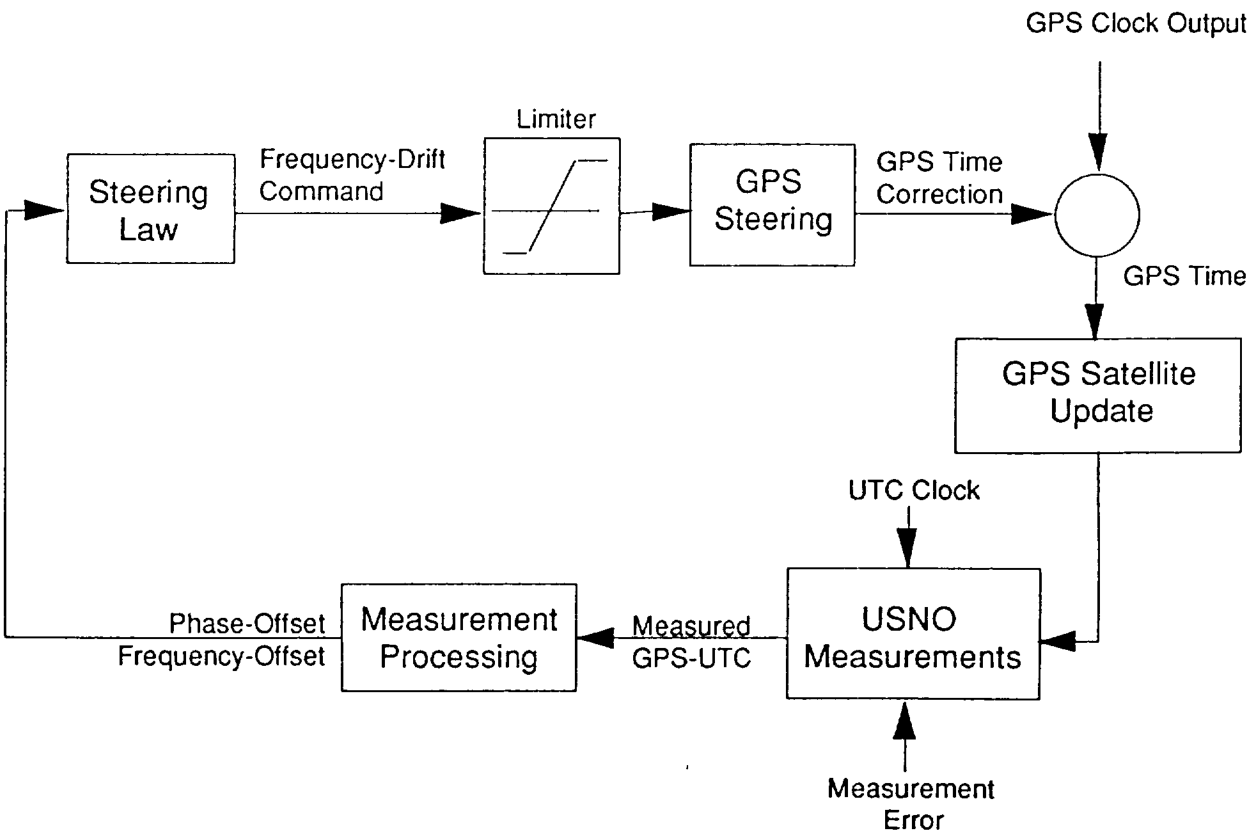


Figure 2. GPS-UTC Steering Performance

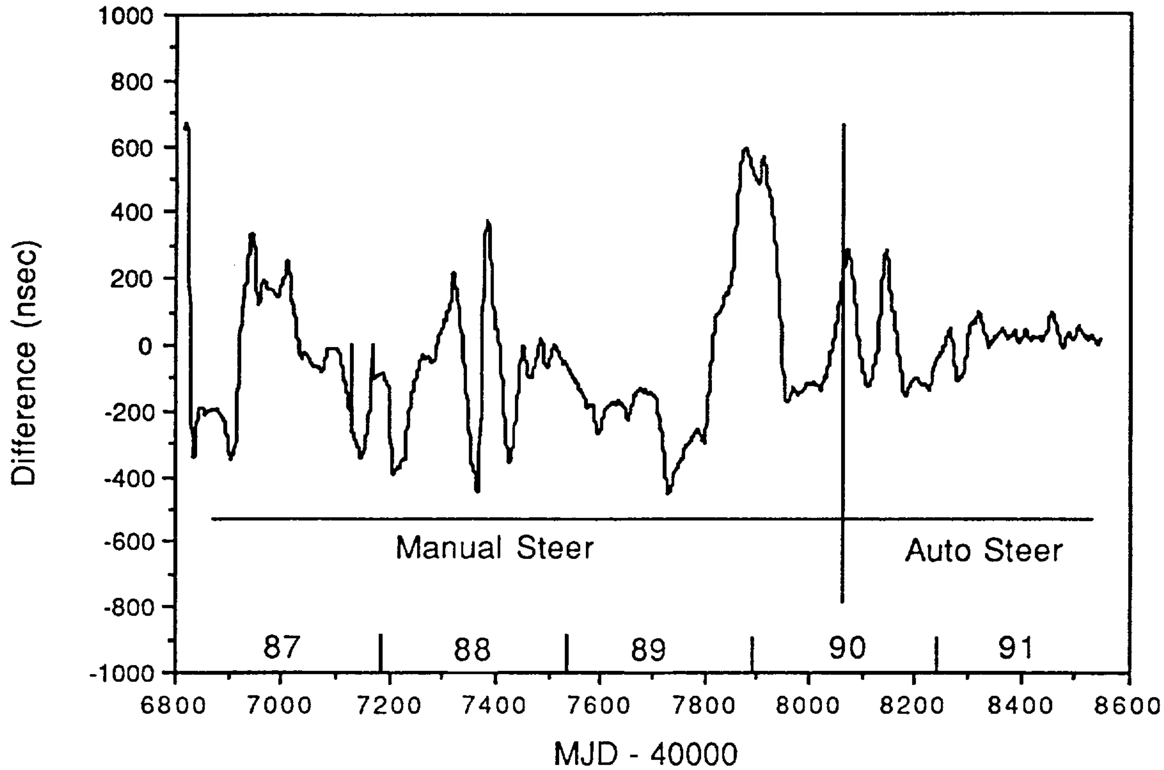


Figure 3. GPS-UTC Performance (Auto Steer)

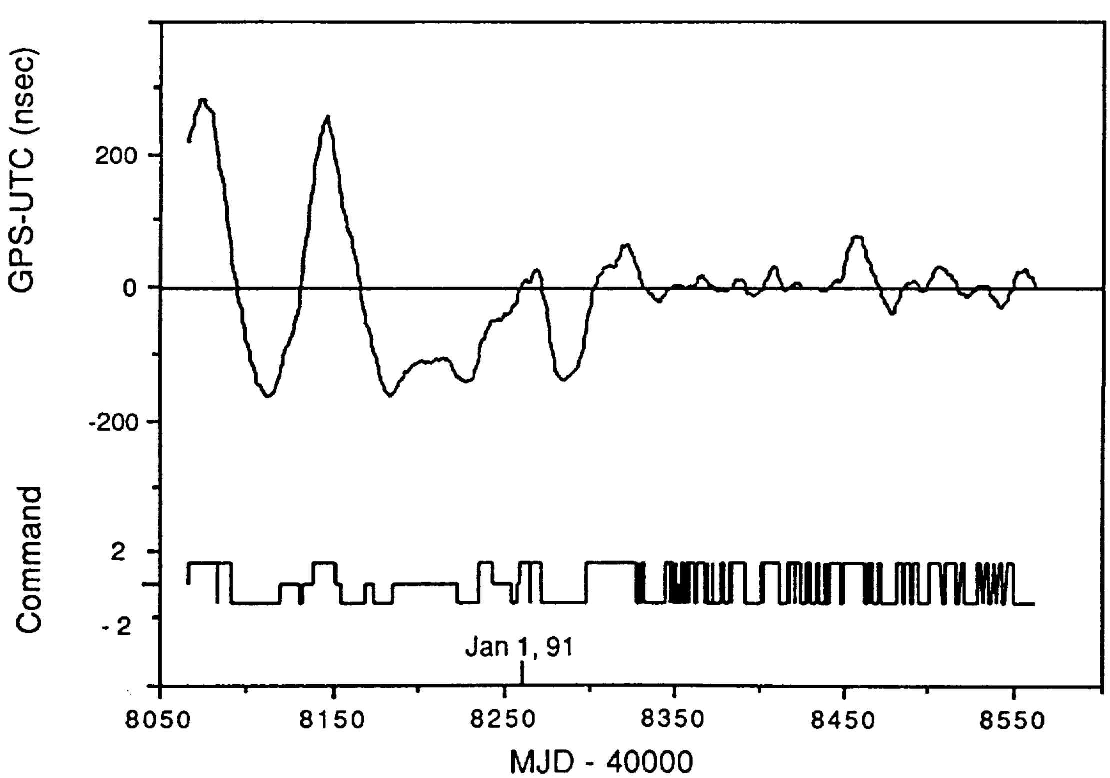


Figure 4. Allan Variance of GPS Time

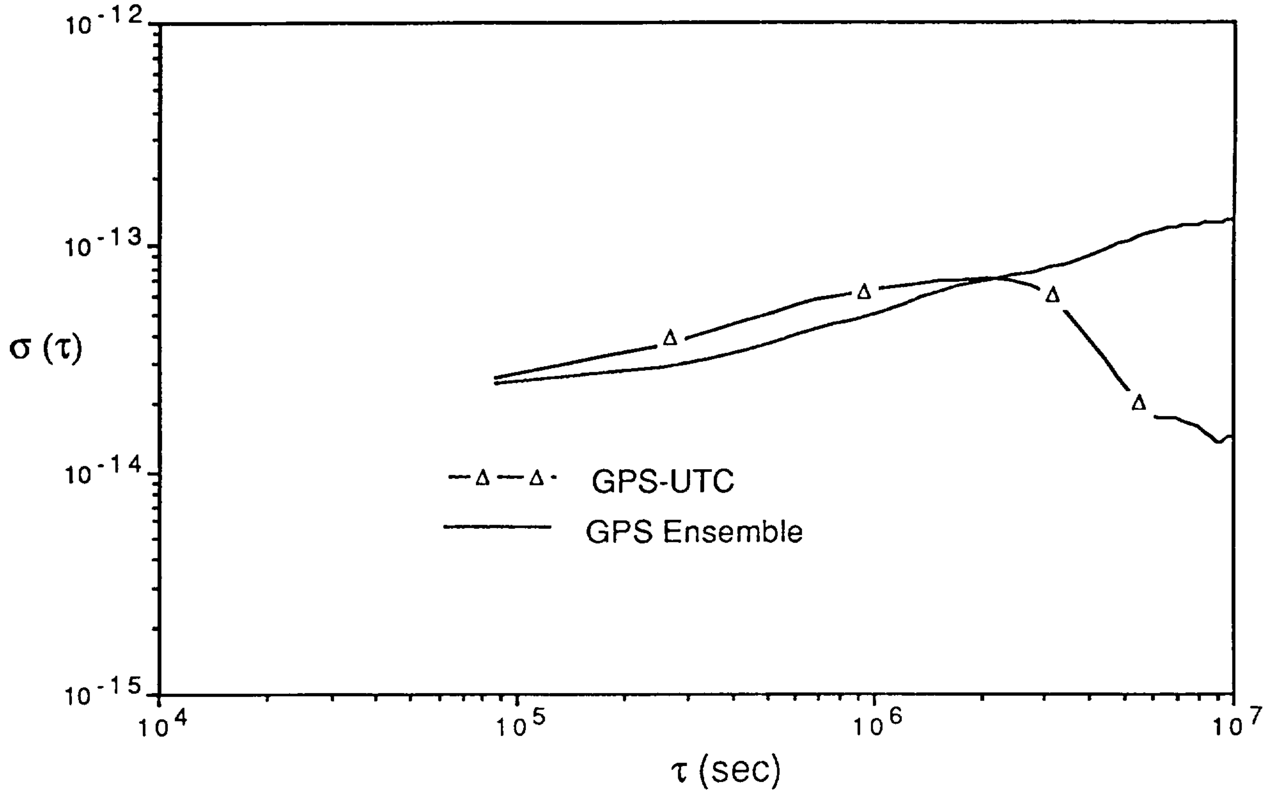


Figure 5. GPS (UTC) Performance

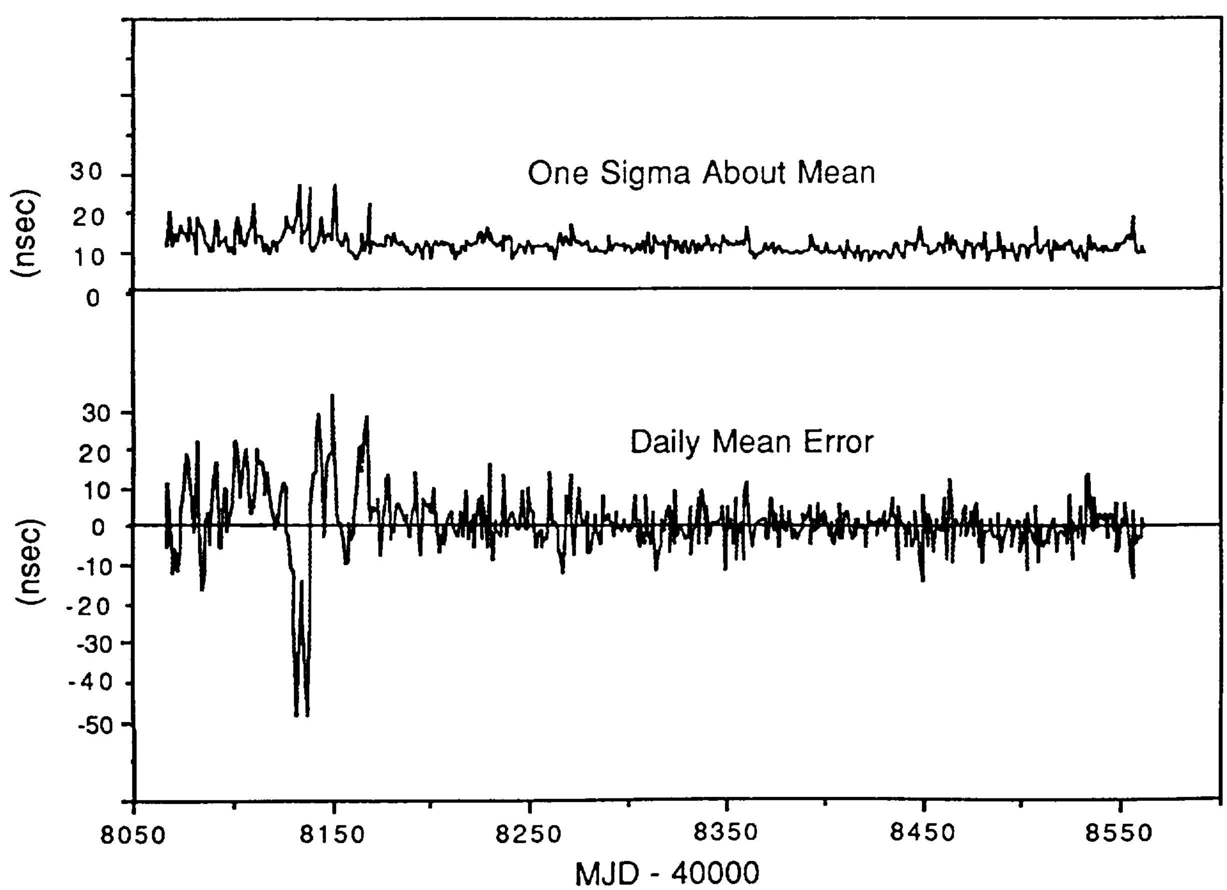


Figure 6. GPS-UTC Steering Model

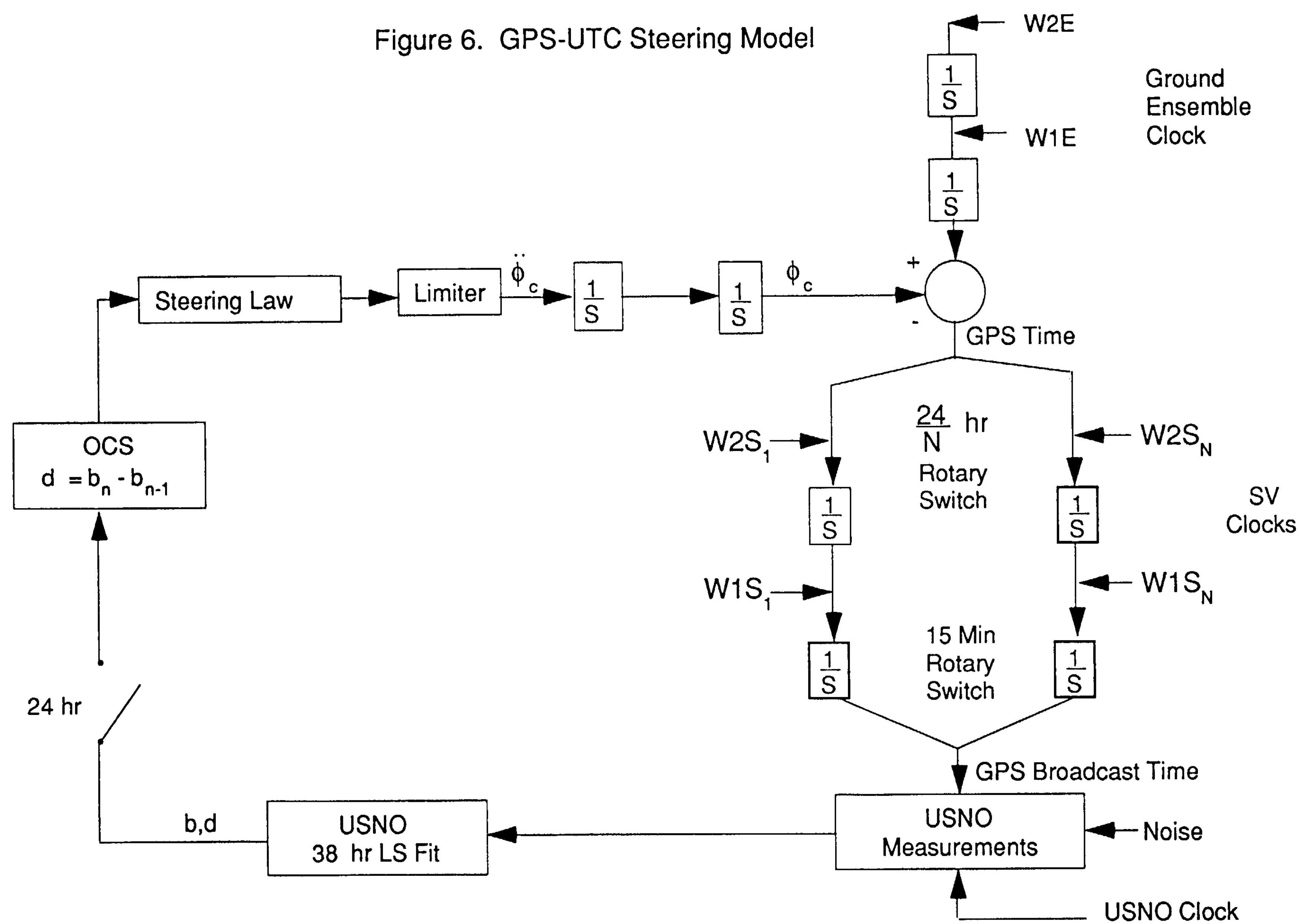
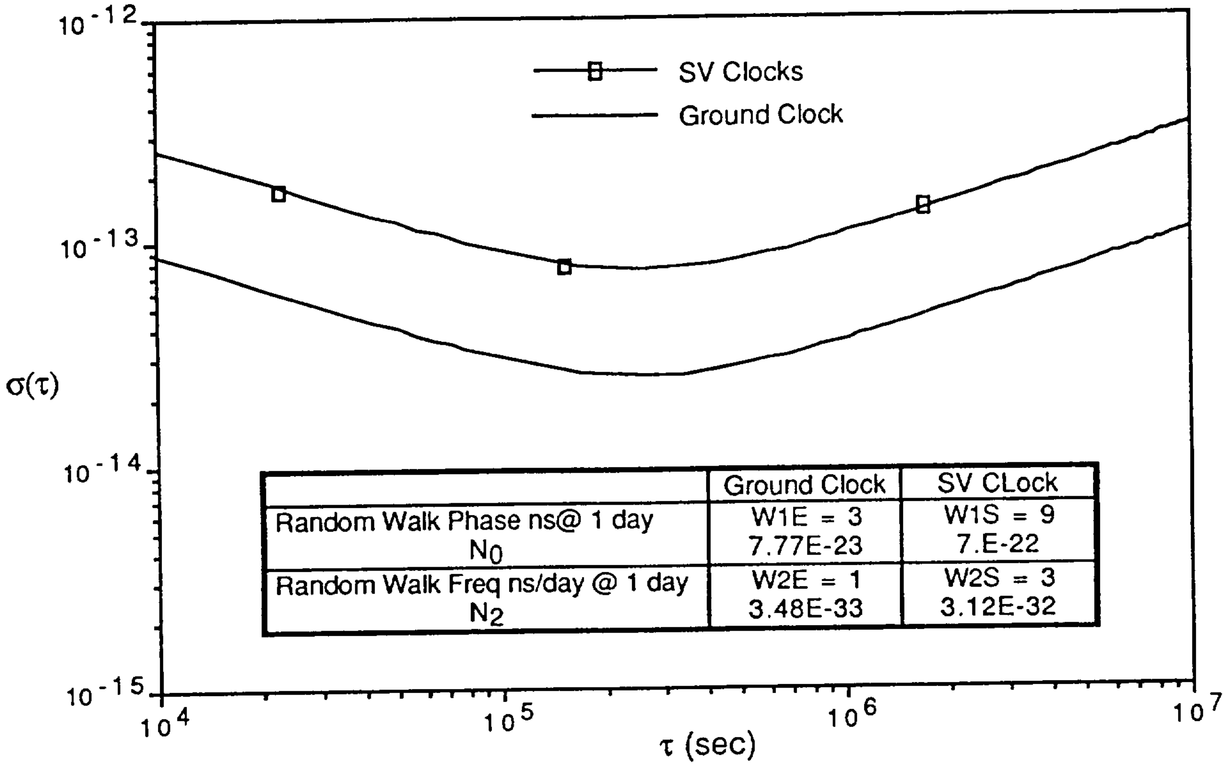


Figure 7. Allan Variance Clock Models



	Ground Clock	SV CLock
Random Walk Phase ns@ 1 day N_0	W1E = 3 7.77E-23	W1S = 9 7.E-22
Random Walk Freq ns/day @ 1 day N_2	W2E = 1 3.48E-33	W2S = 3 3.12E-32

Figure 8. Typical Simulated Sample Function

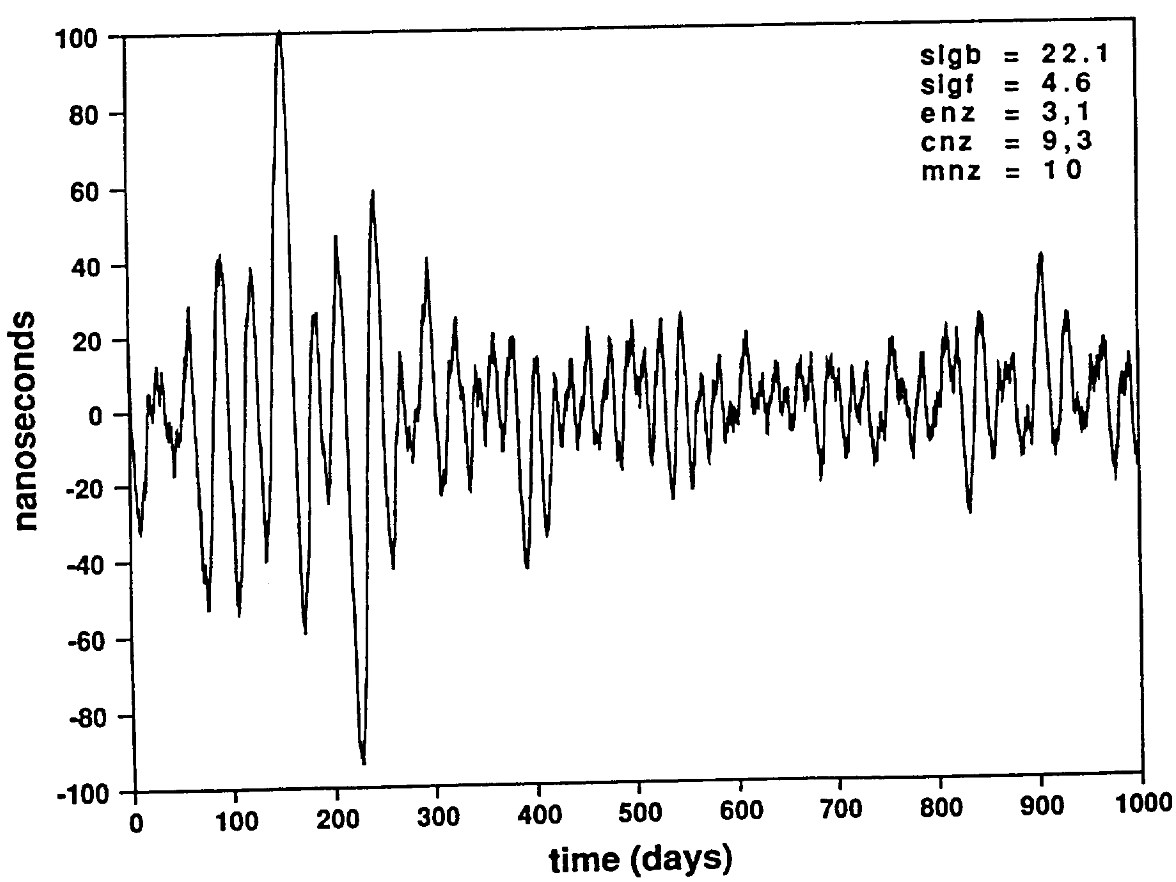
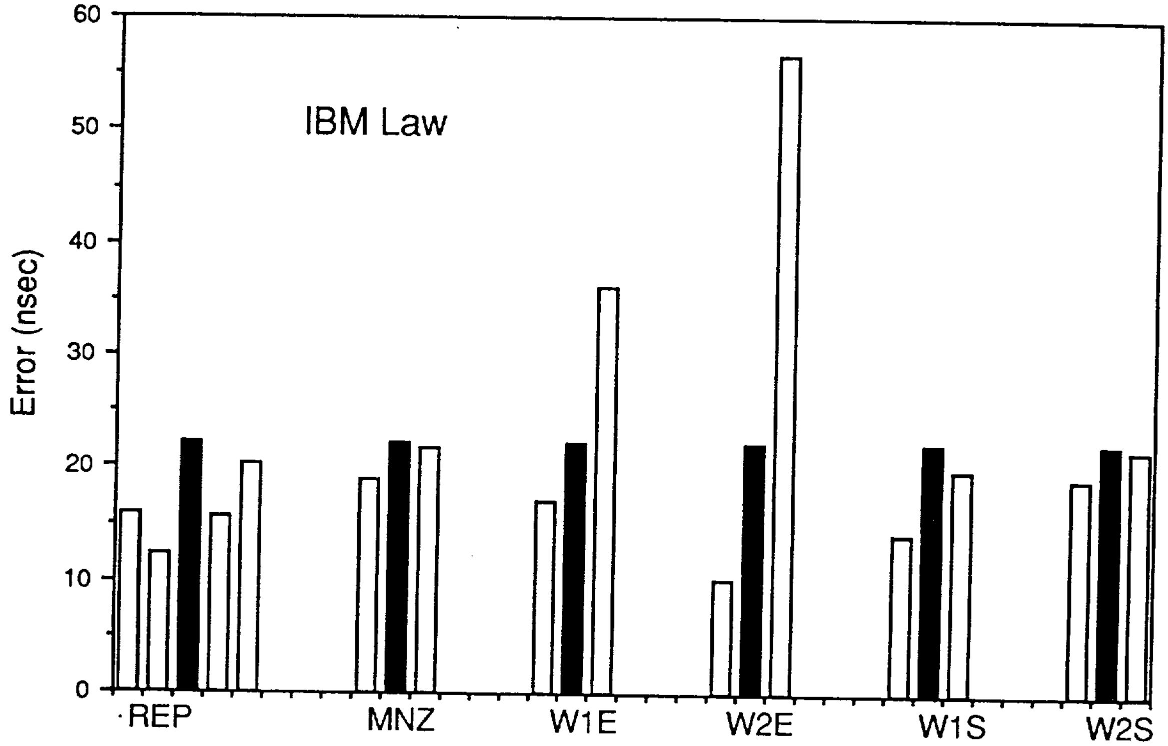
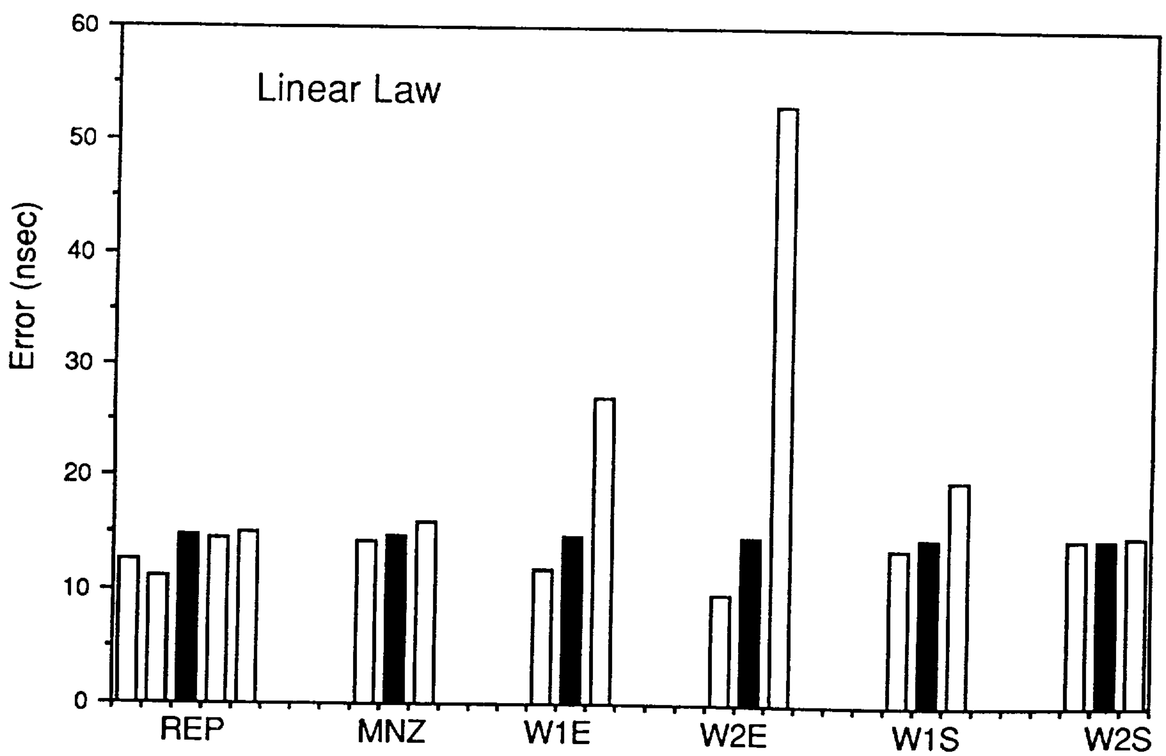


Figure 9. Sensitivity Study Summary





QUESTIONS AND ANSWERS

David Allan, NIST: In your previous chart, where you showed the state of the steering law, plus or minus or zero, during the period where it was operating well, it was almost never at zero. Where it was operating poorly, it was often at zero. Intuitively, one would say that, since it is almost never at zero during that last period, there could be something done to make it work even better, even though it is as good as you need. Statistics says that it should be often at zero, rather than always at the limit.

Mr. Feess: If the two are synchronized, and have no driving force, that is true. Simulation shows that it is usually in this state, unless you are responding to some transient. The system is essentially driven by random processes. It would be nice if we didn't have random processes, because then we would expect it to remain at zero.

Mr. Allan: Intuitively it seems that, with improved digital design, one could spend part of the states at zero, instead of at the hard limit.

Mr. Feess: That is the way that it is designed, to be either plus or minus. If you used a linear law, you would operate most often at one-half or one-quarter of this level, but never at zero during the active steering mode.

Dr. Gernot Winkler, USNO: I share David Allan's concern. In other words, we are constantly steering, and that is the consequence of the principal of bang-bang steering. A three-state control...

Mr. Feess: It is a three-state controller with zero, but it very seldom stays at the zero point.

Dr. Winkler: I think that this can be incorporated by allowing for a dead-band. Then, when you are in the dead-band, you are not steering. I have another comment; in your chart where you showed the assumed Allan Variance for the ground clocks as compared to the space clocks, the space clocks are about three dB above the ground clocks. My question is: is that a result of the Kalman filter which puts all sorts of errors into the clock states, which would, of course, be erroneous. Why are they higher by three dB?

Mr. Feess: The space clocks were assumed to be three dB higher than the ground clocks because the specifications are higher.

Dr. Winkler: Yes, but that is not necessarily realistic in terms of performance. David Allan has shown repeatedly that the satellite clocks are performing very well, and in fact may be better than the ground clocks.

Mr. Feess: The satellite clocks that we have assumed here are better than specification by a factor of two to four. We know that the clocks are performing better than specification. The specification on the ground clocks is better, but are they really performing to specification? We think that they are not, and probably are performing no better than the satellite clocks, except for the one at Colorado Springs. We have measures that indicate that it is performing much better, and we should weight that clock more if we really wanted to optimize the system.

David Allan, NIST: I think that one of the problems with the Kalman Queuing is that they have only one set of queues distributed uniformly across all clocks.

Mr. Feess: No, there is a separate queue for each clock in the system.

Mr. Allan: Appropriate to its performance?

Mr. Feess: No, it is set by an operator.

Mr. Allan: There is the problem because the statistics that we observe on the clocks are different than what is queued in.

Mr. Feess: Right. That is one of the things that could improve the performance. We could tune the clocks for better timing performance.

Mr. Allan: An ensemble would work much better.

Mr. Feess: The system is designed more for the NAV user than the timing user and there is some reluctance to change anything. If it ain't broke, don't fix it.

Dr. Claudine Thomas, BIPM: I would like to make one comment: what you are doing is steering on UTC(USNO) and not on UTC.

Mr. Feess: That is true. We regard USNO as UTC. That is our requirement. Whether Dr. Winkler agrees with that...

Dr. Winkler: Let me comment on that. You are absolutely correct. Of course, UTC(USNO) is steered, in very long term, with respect to UTC. At the moment the offset is somewhat like eight nanoseconds. It is our intent to keep that as small as possible within the constraints: the delay of 45 to 70 days to receive BIPM information, and additionally you do not want steering changes that exceed one part in 10^{14} maximum, you do not want to make changes frequently–there are a number of boundary conditions within which you want to follow the principle that, in the long run, the offset should be as small as possible. That is our policy and therefore we must take reference to one physical clock and in fact, it is also dictated by the regulations of the DoD, that that clock should be used as an operational reference. In the interest of international coordination, we have to be as close to BIPM as we can.

We do **not** have a bang-bang controller!

Mr. Feess: I am not recommending the bang-bang, in fact I would recommend not the bang-bang.

Dr. Henry Fliegel, Aerospace: We have long considered the effect of the bang-bang steering and have in fact discussed the possibility of introducing a dead-band. Obviously, there is a trade off between maintaining frequency stability and timing stability. As you can clearly see from Bill's graphs, what we have opted for is the smallest mean offset of GPS minus UTC in time. We realize that makes a very busy situation in frequency. The frequencies are continually going up and down. We would appreciate any response from actual users who may want more in the way of frequency stability even at the cost of having larger swings in the time domain. We are open for suggestions at this point, at least at Aerospace, and we will try to convince our Airforce colleagues accordingly.