REFINING MONITOR STATION WEIGHTING IN THE GPS COMPOSITE CLOCK

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Abstract

The two closely linked missions of the Global Positioning System (GPS) are precise positioning for navigation accuracy and precise time transfer. Positioning has typically received the most attention; however, the ability to derive a precise position depends on having a stable and reliable time scale as a starting point. Throughout the history of GPS, its time scale has slowly evolved through many phases. The most significant change came with the introduction of the Composite Clock in 1990. Additionally, in recent years the 2d Space Operations Squadron (2 SOPS) has tuned the Composite Clock to take better advantage of its contributing timing sources. In addition to reviewing the Composite Clock's tuning history, the authors will discuss the recent implementation of unique tuning for each of the GPS monitor station frequency standards.

As pointed out in a previous paper regarding satellite clock-unique tuning[1], no two satellite frequency standards exhibit the same performance. This also holds true for monitor station frequency standards. However, other factors must be considered when deriving process noise values (tuning parameters) for ground system contributors to the Composite Clock. Mainly because the values chosen for each clock determine the size of its vote in contributing to GPS time, one must look not only at clock performance, but environmental factors as well. An excellent clock placed in an environment with significant temperature and humidity fluctuations can be very detrimental to GPS time if that clock is weighted heavily in the Composite.

This newly adopted concept of representing monitor station clocks based on individual performance and environmental history has significantly improved the stability and reliability of GPS Time. The authors discuss several examples that reveal the robustness of the new tuning as well as the current implicit long-term weighting given to each frequency standard that contributes to the Composite Clock.

INTRODUCTION

Throughout the history of the Global Positioning System (GPS) the 2d Space Operations Squadron (2 SOPS), Department of Defense (DoD) agencies, and contractors have been striving to improve the performance to users. Both position and time solutions produced by GPS have dramatically improved since its inception. As the system evolved and a greater understanding of the science of the control system of GPS became available, the system has undergone many refining stages. These enhancements are due to the ingenuity of dedicated individuals using practical ideas and the flexibility (data base parameters) offered by the original system. The most popular improvements are those which enhance the position solutions for users. However, the heartbeat of the GPS service relies on the ability to produce and maintain a reliable and stable time scale. Since initial operational capability the GPS program has made several advancements in the area of establishing and maintaining its time scale. After several years of evolution and coordinated efforts amongst various agencies, the current GPS system has greatly matured.

EVOLUTION OF GPS TIME

The Master Clock

In the beginning years of the GPS program a single reference clock known as a master clock [not to be confused with the United States Naval Observatory (USNO) Master Clock] represented GPS time. This arrangement simply meant that one clock in the GPS control network was deemed as the closest to an ideal clock or "truth" source. All other clock offsets were then measured against this reference clock. The GPS master clock approach worked sufficiently as long as the one clock chosen as master performed well. Unfortunately, if this one clock failed or experienced instability then the GPS time scale suffered as well. Despite its drawbacks the GPS master clock served as a starting point in the development of GPS time.

The Composite Clock

Fortunately, in 1987, Mr. Ken Brown of IBM proposed using a majority of the estimated clocks in the GPS system as contributors into what is essentially a Kalman filter-based time scale. His idea of creating a "Composite Clock" came to fruition when employed operationally in 1990. The Composite Clock theory, described in detail in [2], provided the platform for GPS time as we know it today. In short, the Composite Clock is an implicit ensemble mean of corrected clocks residing within the Master Control Station (MCS) Kalman filter. In the Composite design, all clocks whose offsets are estimated within the Kalman filter can contribute to the GPS time scale. The amount that each clock contributes to the final Composite Clock is implicitly represented by the relative variances associated with that particular clock. In the initial employment of the Composite Clock all satellite and Monitor Station (MS) clocks had the same process noise values (or qs). GPS time operated under this philosophy for several years.

The transition from a single master clock to a Composite Clock philosophy has probably been the single most valuable advancement in the evolution of GPS time. It provided a more stable time scale, in that with more clocks contributing, the failure or instability of a single clock has a much smaller impact to GPS time and thus to users, compared to the impact of problems with a single master clock. This impact due to the instability of a single clock is roughly proportional to 1/n, where n is the number of contributing clocks. Therefore, the more clocks allowed to contribute, the more robust the Composite time scale. Also, a system of n clocks should theoretically demonstrate stability roughly proportional to $n^{-1/2}$. Thus more clocks equate to greater stability. However, as with any new idea, there was still room for improvement in order to make the most of this new operational philosophy.

Tuning the Composite Clock

As previously mentioned, the original implementation of the Composite Clock theory used an approach that assumed all clocks exhibited similar stability performance. This assumption, of course, is not true and in fact all clocks do exhibit unique noise characteristics. To determine what *q*s best represent each clock's performance one must obtain empirical performance of the GPS clocks. Thankfully, agencies like the National Imagery and Mapping Agency (NIMA) and the Naval Research Lab (NRL) have developed the capabilities to monitor, track, and trend clock performance data for all vehicle and MS clocks within GPS. Their analyses provide the tools necessary to enhance the operational Composite Clock.

In 1994 2 SOPS began the initial effort to fine tune the Composite Clock. At first, 2 SOPS addressed the rubidium process noise values,[3] and subsequently evaluated and modified the *q*s for the entire satellite clock constellation[1] . This successful tuning effort brought the GPS time scale another step closer towards optimum utilization. The only other contributing timing sources to GPS time not optimally tuned until recently were those residing at the MSs.

RECENT EFFORTS IN MONITOR STATION TUNING

The remote MS clocks previously each contributed equal weights in long-term weighting to GPS time. For years the MS *q*s were representative of normal HP 5061 Frequency Standard (FS) performance in a stable environment. However, historically MS environmental problems have in many instances caused severe degradation to the stability of the GPS time scale.[4] With most of the ground system clocks located in facilities susceptible to severe temperature, humidity, and mechanical disturbances, performance problems can occur. Also, much like orbiting clocks, no two ground FSs exhibit the same stability. Thus, having equal process noise values for all ground clocks did not make optimal use of their contributions to GPS time. For these reasons, in late 1996 2 SOPS began implementing monitor station-unique *q*s on a quarterly basis along with the satellite-unique *q*s.

Initial Derivation of the MS qs

Derivation of the MS qs follows nearly the same methodology as that used for deriving the satellite qs. By using the following equation[1]

$$\text{Allan deviation } (\tau) = [(q_1/\tau) + (q_2*\tau)/3]^{1/2} \qquad (1)$$

one can plot the theoretical Allan deviations from a predetermined set of process noise values (q_1 and q_2) for each MS clock. The resulting plots can then be compared to empirical plots produced by NRL similar to that in Figure 1[5]. These plots are possible due to the analysis capability recently developed by NRL in Linked Common View Time Transfer (LCVTT)[6]. MCS operators can adjust the noise parameters q_1 and q_2 to match empirical MS clock performance. This process is repeated for each monitor station clock to derive an initial set of qs.

Environmental Considerations

MS clocks operate in environments different from orbiting clocks as mentioned earlier, and therefore must be subjected to other considerations when deciding on the implementation of unique qs. For example, the MS frequency standards at Hawaii reside in a room that is usually occupied with people coming and going quite often. Contrary to that situation, the frequency source for the Colorado Springs MS is the USNO Alternate Master Clock (AMC), which is operated in a controlled environment. Additionally, the Colorado Springs timing source is much more stable than those at all other MSs, due primarily to the AMC's use of a hydrogen maser reference, which is steered via two-way satellite time transfer to the DoD Master Clock at USNO, Washington D.C.[7] Given such inherent differences between MSs, using equal q values, and thus equal implicit weighting, is intuitively not the best choice.

Tuning the Backup MS FS

With two frequency standards located at each site, one must determine what qs to use for the backup, should the operational fail. The phase and frequency offsets and associated variances for the operational FSs at each site are estimated through the Kalman filter process, and therefore contribute to GPS time. Unfortunately, since the MCS only estimates the "site" phase and frequency offsets, one only has insight to the current operational FS. Because HP 5061 FSs have non-trivial environmental sensitivities[8] the differences in noise characteristics, simply due to the physics of each clock being unique, are overshadowed by the noise characteristics due to environmental changes. For this reason one may assume that the long-term performance of two clocks in the exact same environment will be very similar. Based on this assumption, 2 SOPS currently uses the same q values for the operational and backup FSs at each remote site. The only exception to this practice is for the Colorado Springs MS. Though the primary timing source for this site is the USNO AMC, the backup FS at this site is a single HP 5061, and therefore uses the process noise values more suited to its performance.

Operational Considerations

During planned maintenance periods, the 2 SOPS operators may evaluate and modify the process noise values to effectively de-weight MS clock contributions as necessary. During February of 1997, the Air Force physically relocated the Diego MS equipment into a newly constructed facility. During this move, the operational HP 5061 FS remained powered on but still experienced a period of environmental instability inherent to any construction project. Starting at the time of the move and for several months afterwards, the 2 SOPS operators chose to effectively de-weight the Diego MS clock's contribution to the GPS time scale by increasing the process noise values. With a different noise signature expected in the new facility, increasing the q values initially helped to protect the GPS time scale from potential corruption during the stabilization period. In this circumstance, 2 SOPS operators proactively modified MCS Kalman filter qs to help maintain a reliable and stable time source during a period of instability in the GPS system.

MCS Partitioning Considerations

Due to system processing limitations, the contributing clocks in GPS are dispersed throughout three separate estimating partitions. Each of these partitions contains the states of up to six different satellite clocks and all five MS clocks. Each partition is integrated into GPS time through a MCS process known as partition reconciliation. Because each partition contains its own estimate of each MS clock, the weight implicitly given to each ground clock in GPS time is effectively tripled. In order to compensate for this inherent weighting increase, 2 SOPS multiplies the q values derived from the NRL plots by a factor of three (or the current number of estimating partitions)[9]. These modified values are then implemented by updating the operational database of the GPS control segment.

With the considerations discussed above, the current philosophy employed by the 2 SOPS for MS tuning is to examine the current and previous two to three quarterly reports provided by NRL, in order to analyze any MS-specific trends. Typically, the worst case deviation plot from all the available NRL plots for each MS is used to derive the tuning qs for each MS in question. Exceptions are taken when known maintenance or anomalies have occurred or are planned to occur in the future, as discussed earlier.

RELATIVE CLOCK WEIGHTING IN GPS TIME

Once the new q values are updated on the operational system, one can view the implicit long-term weighting given to each contributing clock towards GPS time. The long-term weighting can be thought of as being inversely proportional to the long-term steady state frequency variances produced from the Kalman filter process for each of the clocks, taking into account the effective tripling of MS weighting. That is, the relative long-term weighting of clock x (W_x) with respect to an n-clock ensemble can be represented by:

$$W_x = \frac{1/Var_x}{1/Var_1 + 1/Var_2 + \ldots + 1/Var_x + \ldots + 1/Var_n} \qquad (2)$$

where Var_x = the long-term variance of clock x

Following a settling out period after *q* changes, one can observe the steady state frequency variances from the operational display NPARCOV as shown in Figure 2. Examples of the various weightings in GPS time as described by the above equation are shown in Figures 3 and 4.

The weighting now applied to all the operational clocks within GPS, which represents each clock uniquely according to its actual historical behavior, serves to better optimize the true benefits of the Composite Clock. Clock-unique weighting allows excellent performing FSs to contribute more to GPS time, while allowing other FSs to still contribute. Our MS tuning efforts have contributed to the best ever synchronization and stability of GPS with respect to UTC as demonstrated in Figures 5 and 6 respectively.

Allowing more clocks to contribute increases the robustness of the system, as mentioned earlier. Currently, the MCS utilizes three estimating partitions with six vehicles and five estimating ground states each, resulting in a maximum of twenty-three GPS clocks that can contribute to GPS time at any instance. Typically, 2 SOPS maintains this configuration and only modifies the partitioning layout as necessary for maintenance or anomalous/troubleshooting periods.[3]

FUTURE IMPROVEMENTS

The frequency of the tuning of MCS clock state estimation is currently limited by the data collection analysis and distribution processes required between NIMA, NRL, and 2 SOPS. Additionally, the overall system performance is limited by the environmental sensitivity of the HP 5061 FSs, which could be significantly alleviated with a simple upgrade to HP 5071 FSs at the Air Force remote MSs. This would significantly reduce the environmental sensitivity and add many more stable clocks for higher weighting in the GPS time scale. The stability difference between the two frequency standards is clearly visible by looking at the Allan deviation plots in NRL's quarterly reports. NIMA MS HP 5071 FSs demonstrate an average stability of 3×10^{-14} at one day, which is better than typical HP 5061 FS performance at the Air Force MSs, which can be as poor as 1×10^{-13} at one day.[5]

Several system changes planned for the near future should also serve to improve the performance of the GPS time scale. For example, under the new Architecture Evolution Plan (AEP), the control segment will have the capability to operate with all satellite vehicles in a single estimating partition. This capability will alleviate the need for artificially multiplying the process noise due to the multiple partitioning used in today's system, but it will also permit better flexibility to allow more satellite clocks to contribute to GPS time. Also, the Accuracy Improvement Initiative (AII) will allow the addition of more ground system clocks to contribute to GPS time by incorporating the NIMA MSs into the control segment of GPS. As mentioned earlier, the HP 5071s at the NIMA sites already demonstrate excellent stability characteristics. Both the AEP and AII projects are currently funded and scheduled to be operational by late 1999 to mid 2000. Lastly, very encouraging initial on-orbit performance of recently activated Block IIR rubidium FSs paints an optimistic picture in terms of the quality of future on-orbit clocks contributing to GPS time.

CONCLUSION

The most significant step in the evolution of GPS time came with the implementation of the Composite Clock in 1990. Following this new idea, 2 SOPS, alongside other DoD agencies, has worked to accurately tune the system to optimize the robustness and stability offered by a Composite Clock. The authors have described the most recent step in this process, MS clock unique tuning, and have shown the resulting implicit long-term weighting for all the clocks currently contributing to GPS time. To complement the quarterly tuning philosophy adopted by 2 SOPS, plans for further improvements mentioned in this paper should also contribute to better performance of the GPS time scale for the user community.

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REFERENCES

[1] S. T. Hutsell, 1995, *Fine Tuning GPS Clock Estimation in the MCS,* Proceedings of the 26th Annual Precise Time and Time Interval (PTTI) Meeting, 6-8 December 1994, pp. 63-74.

[2] K. R. Brown, 1992, *The Theory of the GPS Composite Clock,* Proceedings of ION GPS-91, 11-13 September 1991, pp. 223-242.

[3] S. T. Hutsell, 1995, *Recent MCS Improvements to GPS Timing,* Proceedings of ION GPS-94, 20-23 September 1994, pp. 261-273.

[4] S. T. Hutsell, 1996, *Ideas for Future GPS Timing Improvements*, Proceedings of the 27th Annual Precise Time and Time Interval (PTTI) Meeting, 29 November – 1 December 1995, pp. 63-73.

[5] W. G. Reid, and J. A. Buisson, NRL Analysis Updates No. 96-1 through 97-2.

[6] W. G. Reid, T. B. McCaskill, and O.J. Oaks, J. A. Bussion, and H. E. Warren, 1996, *Common View Time Transfer Using Worldwide GPS and DMA Monitor Stations*, Proceedings of the 27th Annual Precise Time and Time Interval (PTTI) Meeting, 29 November – 1 December 1995, pp. 145–155.

[7] W. V. Bollwerk, 1997, *The Alternate Master Clock and Precise Time Requirements; Why an Alternate Master Clock?*, Proceedings of the 28th Annual Precise Time and Time Interval (PTTI) Meeting, 3-5 December 1996, pp. 141-145.

[8] R. L. Sydnor, T. K. Tucker, C. A. Greenhall, W. A. Diener, and L. Maleki, 1990, *Environmental Tests of Cesium Beam Frequency Standards at the Frequency Standards Laboratory of the Jet Propulsion Laboratory*, Proceedings of the 21st Annual Precise Time and Time Interval (PTTI) Meeting, 28-30 November 1989, pp. 409-420.

[9] K. R. Brown, private communications, March 1994.

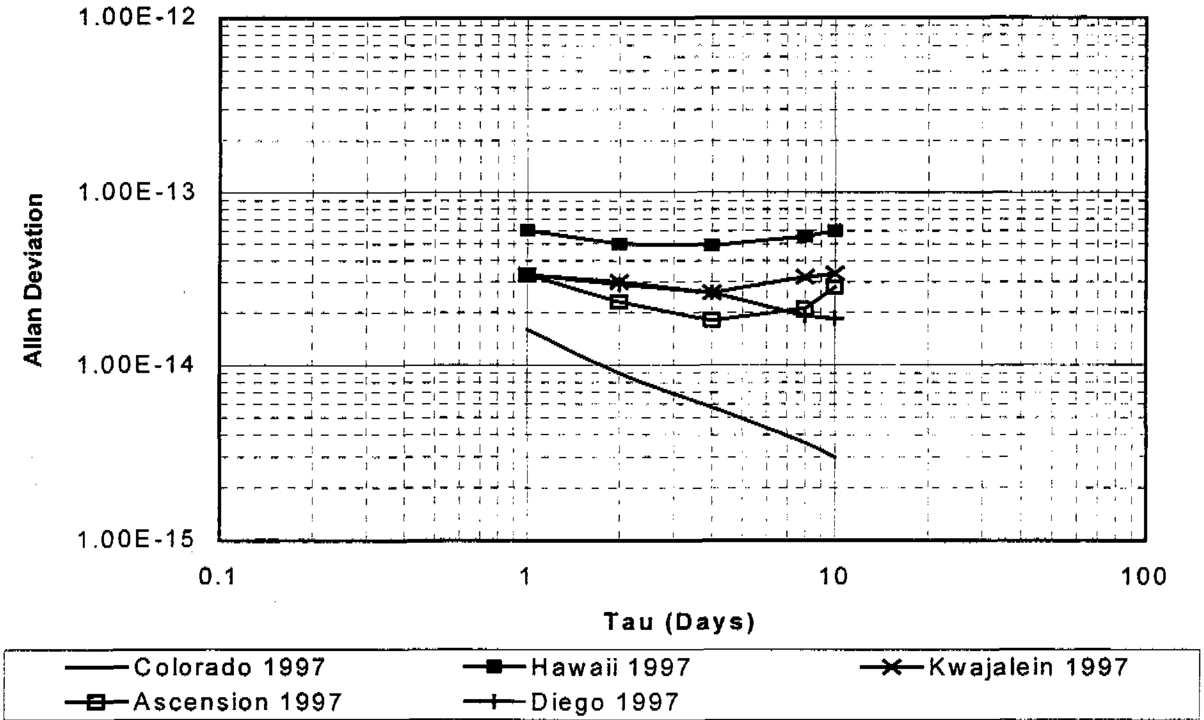

Figure 1. Air Force MS HP 5061 FS Allan Deviation Plots Produced by NRL

PARTITION COVARIANCE PARTID: 1 TIME: 230/01:15:00

SVID	B4/35	E2/21	B3/13	A1/39	D4/34	A2/25
EPH EPOCH TIME	203/00:00:00	203/00:00:00	203/00:00:00	203/00:00:00	203/00:00:00	203/00:00:00
X-REF (m2)	8.93E+04	5.46E+03	7.85E+03	2.37E+05	1.13E+04	2.31E+04
Y-REF (m2)	2.23E+03	1.90E+05	2.37E+05	3.14E+04	1.16E+05	1.45E+05
Z-REF (m2)	1.72E+05	5.85E+03	1.51E+04	2.25E+04	1.11E+05	1.18E+05
VX-REF (m2/s2)	2.58E-05	1.29E-03	1.73E-03	9.58E-07	3.81E-03	4.59E-03
VY-REF (m2/s2)	5.56E-03	2.18E-04	4.51E-04	2.59E-03	1.89E-04	6.07E-05
VZ-REF (m2/s2)	2.96E-05	2.78E-03	3.27E-03	3.63E-03	1.09E-03	1.39E-03
K1-RES	6.89E-06	4.68E-06	6.38E-06	8.36E-06	5.48E-06	8.02E-06
K2-RES (m2/s4)	5.57E-21	8.17E-21	5.52E-21	4.97E-21	6.11E-21	5.00E-21
B-RES (s2)	1.59E-17	1.21E-17	1.37E-17	1.27E-17	1.32E-17	1.21E-17
D-RES (s2/s2)	5.81E-27	2.85E-27	3.09E-27	2.97E-27	1.34E-27	1.32E-27
DR-RES (s2/s4)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
MS STATES	--ASCNM--	--DIEGOM--	--KWAJM--	--HAWAIM--	--COSPM--	
B-RES (s2)	1.19E-17	1.33E-17	1.38E-17	1.57E-17	1.06E-17	
D-RES (s2/s2)	2.91E-27	1.56E-26	3.00E-27	1.58E-26	1.12E-27	
TROPO RES (m2)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	

Figure 2. NPARCOV Display from Partition One

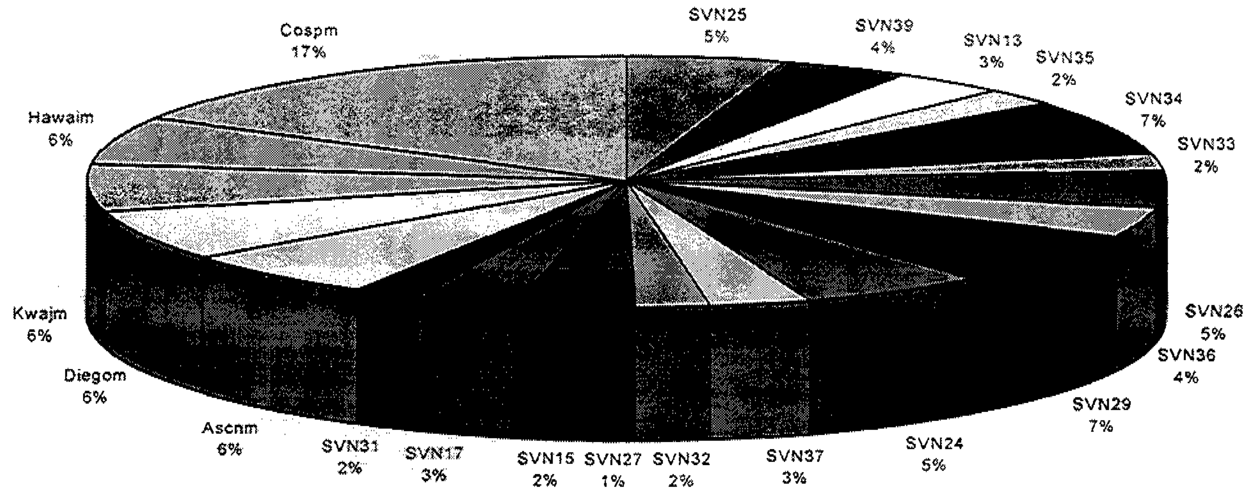

Figure 3. Implicit Long Term Weighting of GPS Time 1 December 1996

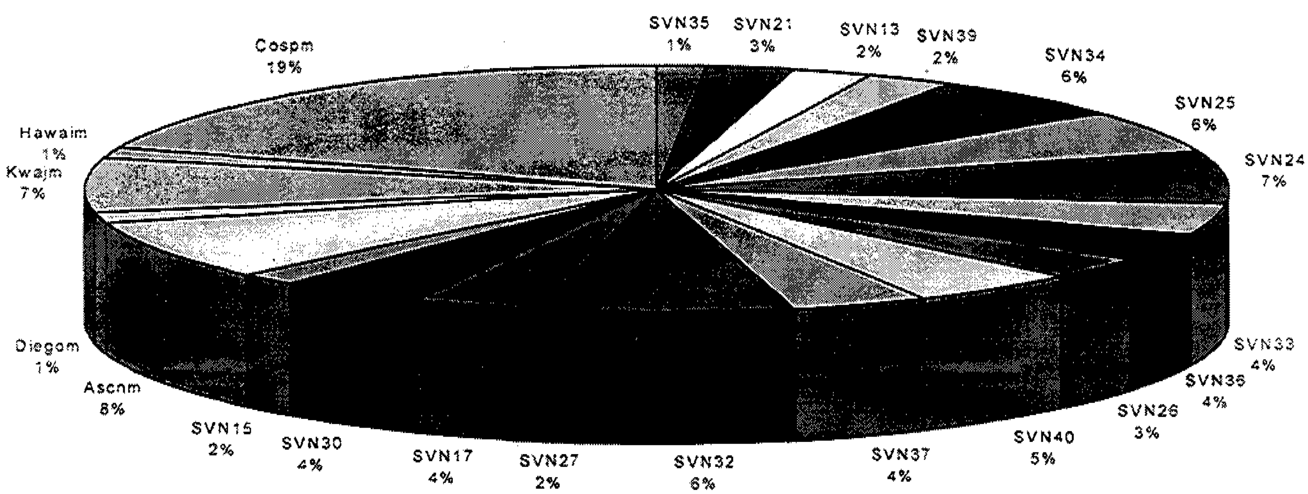

Figure 4. Implicit Long Term Weighting of GPS Time 18 August 1997

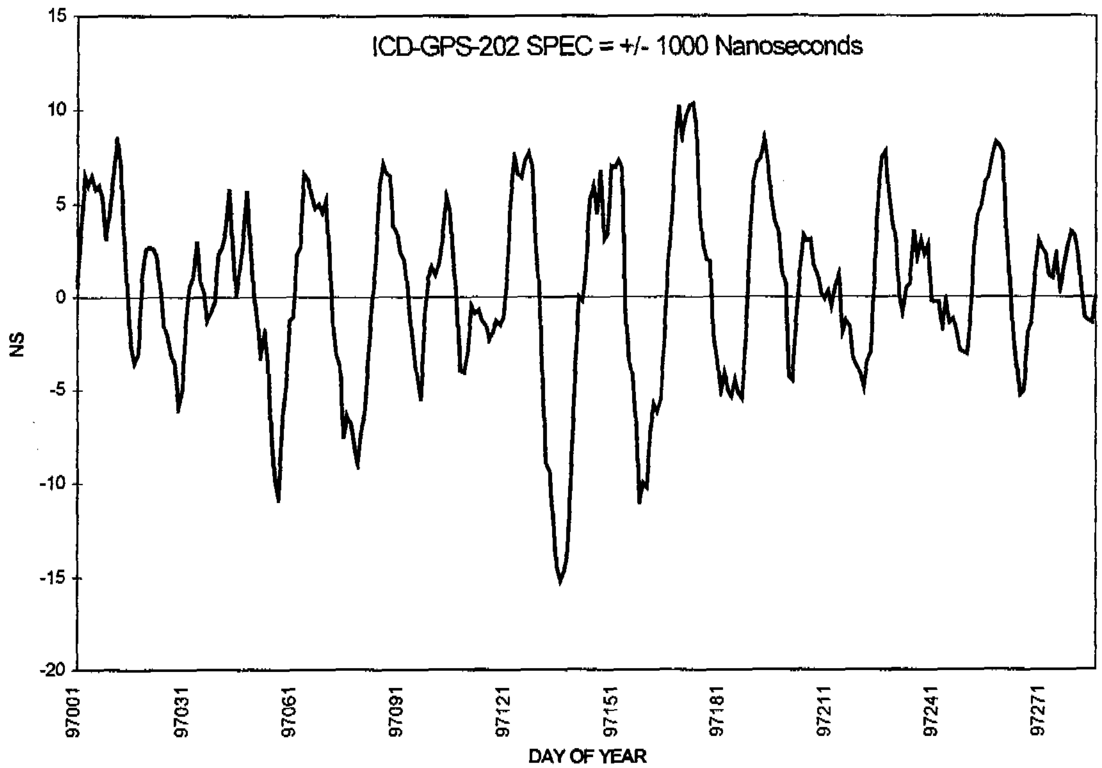

Figure 5. 1997 Daily GPS – UTC(USNO)

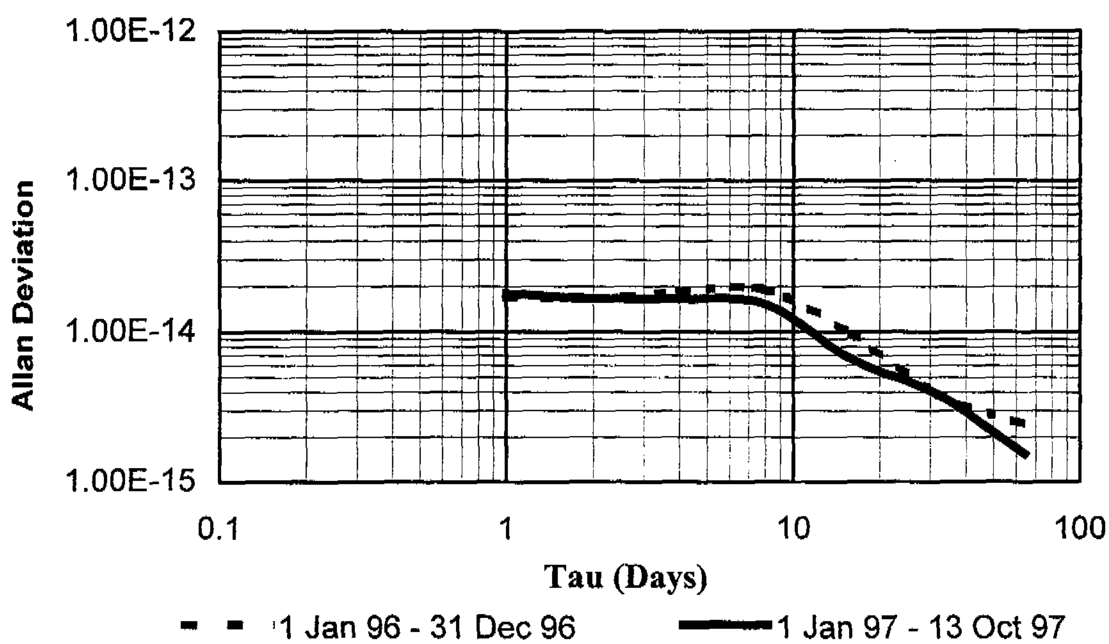

Figure 6. GPS-UTC(USNO) Stability for 1996 and 1997