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MULTI-CHANNEL GPS/GLONASS COMMON-VIEW BETWEEN NIST AND USNO*

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Abstract

Both National Institute of Standards and Technology (NIST) and United States Naval Observatory (USNO) now operate a commercial 12-channel common-view receiver. The receiver tracks the GPS (Global Positioning System) satellites and the GLONASS (Global Navigation Satellite System) satellites. In this paper, we evaluate the receiver's performance using the common-clock, common-view calibration data. We also study the performance of multi-channel GPS/GLONASS common-view between NIST and USNO. The common-clock, common-views using multi-channel GLONASS C/A (Coarse/Acquisition) code and single-channel GLONASS P-code (precise code) contained very little transfer noise. A diurnal effect was noticed in the multi-channel GPS C/A code common-clock, common-view calibration. For the common-view comparison between NIST and USNO, the increased number of daily common-view tracks and the more precise measurements with GLONASS P-code reduced the transfer noise in short term. The multi-channel GPS/GLONASS common-view was influenced by some periodic systematic errors in long term.

1. Introduction

Since its introduction in the early 1980's, the NBS-type single-channel GPS C/A code common-view receiver has been used by the international timing community to achieve precise time and frequency comparisons of remote atomic frequency standards [1]. A single-channel GPS C/A code common-view receiver makes up to 48 common-view tracks each day according to a track schedule. The track schedule is published by the BIPM (Bureau International des Poids et Measures) twice a year. A standard common-view observation is 13 minutes long. To track the same satellite in approximately the same position every day, the track start time is advanced by 4 minutes after each track is completed. In typical applications, the uncertainty of single-channel, GPS C/A code common-view time transfer is on the order of a few nanoseconds when averaged over one day, which corresponds to a few parts in 10^{14} in terms of frequency transfer. While this performance satisfies the needs of many applications, it is certainly not up to the challenge of comparing state-of-the-art primary frequency standards whose frequency uncertainty is on the order of a few parts in 10^{15}.

The GPS system has been developed over the past 20 years. There are now 28 satellites in the constellation. The receiver technology has also matured with many multi-channel GPS receivers available on the market. Some are designed specifically for time and frequency applications. Although its future is uncertain at this time, Russia's GLONASS system offers something the civilian user cannot get from GPS, namely, the availability of the GLONASS P-code. The clock rate of the GLONASS P-code is about 5 times higher than that of the GPS C/A code. Consequently, the pseudo-range obtained from GLONASS P-code measurements should be more precise than that obtained from GPS C/A code measurements. The GLONASS P-code is modulated on both L1 and L2 frequencies, which allows high-precision ionospheric delay measurements. However, because different GLONASS satellites transmit the same code at different frequencies, using GLONASS for time and frequency transfer requires a calibration of receiver delay at each frequency. The BIPM started the coordination of GLONASS common-views in January 1996. In December 1997, a multi-channel GPS/GLONASS common-view scheme was adopted by the CGGTTS (Consultative Committee for Time and Frequency sub-group on GPS and GLONASS Time Transfer Standards) [2, 3]. A multi-channel receiver tracks all the satellites in view. It measures the pseudo-range every second for each satellite tracked. The measurements are grouped into 89 of the daily 90 16-minute intervals starting at 0 hour UTC of a reference date (October 1, 1997). The measurements are then processed to generate the REF–GPS or REF–GLONASS in the standard 13-minute format. The 16-minute interval is selected to give the receiver 2 minutes to lock on the satellite signal, 13

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minutes of common-view measurements, and 1 minute separation between tracks. The 90th 16-minute interval is not used in order to handle the 4-minute track start time shift. According to this scheme, the multi-channel common-view data set contains that of the single-channel common-view as a sub-set. For a 12-channel GPS+GLONASS receiver, it can have up to 1068 13-minute common-view tracks each day, which is about 22 times more tracks than a single-channel GPS receiver can take each day. If the common-view time transfer is dominated by white phase noise, the stability of the time transfer should be improved by a factor of 4.7.

Among other efforts to improve the performance of time and frequency transfer, both NIST and USNO now operate a commercial 12-channel GPS+GLONASS common-view receiver. The receiver consists of an antenna, an RF/IF unit, and a host computer. The computer contains two digital signal-processor cards, a GPS/GLONASS C/A code expansion card, and a time interval counter. The receiver at USNO is equipped with a temperature-stabilized antenna (TSA). Although the receiver tracks GLONASS satellites at both L1 and L2 frequencies, it does not compute the actual ionospheric delay. The receiver uses the modeled ionospheric delay correction from GPS system in both GPS and GLONASS measurements. The receiver at NIST uses the 10 MHz and 1 PPS derived from UTC (NIST) as the reference signals for time and frequency transfer. At USNO, the 5 MHz and 1 PPS reference signals for the receiver are derived from the Master Clock (MC), which is UTC (USNO).

In this work, we used the common-clock, common-view calibration data to study the performance of the 12-channel GPS+GLONASS receiver. We also studied the performance of multi-channel GPS C/A code, multi-channel GLONASS C/A code, and single-channel GLONASS P-code common-view between NIST and USNO.

2. Performance of the Multi-channel GPS+GLONASS Receiver

Both NIST and USNO participated in the multi-channel GPS+GLONASS receiver calibration organized by the BIPM in May 1999. A portable BIPM multi-channel GPS+GLONASS receiver traveled to each participating laboratory. The BIPM receiver was set up in each laboratory in a common-clock, common-view configuration alongside a local GPS+GLONASS receiver for a period of ten or more days. A block diagram of the calibration setup is depicted in Figure 1.

The purpose of the calibration was to determine the relative receiver delays of the local GPS+GLONASS receiver with respect to the BIPM receiver. The common-clock, common-view comparison of two receivers of the same type with the same operating software cancels all the common systematic errors, such as the ephemerides error, error in the ionospheric delay correction, and the common antenna coordinates error. The local reference clock also drops out in the common-clock, common-view comparison. After removing the calibrated delays, the residual of the common-view difference indicates the noise introduced by the receiver in a particular laboratory's environment. Therefore, the analysis of the common-clock, common-view calibration data allows us to evaluate the receiver's best performance. The comparisons of multi-channel GPS C/A code, multi-channel GLONASS C/A code and single-channel GLONASS P-code common-view methods are presented in Figures 2 through 5.

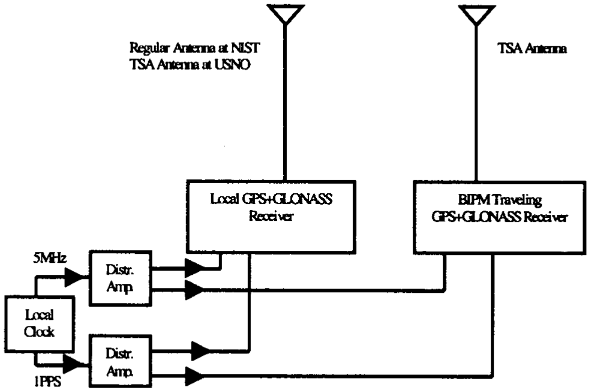

Figure 1. Block Diagram of Common-clock, Common-view Calibration Setup

To evaluate the improvement of using multi-channel common-view, we include the common-clock, common-view of two NBS-type single-channel GPS C/A code receivers in the NIST comparison (Figure 2 and Figure 3). For multi-channel GPS C/A code, we first compute the difference for each individual common-view track, and then average the differences in the same 16-minute interval to obtain the multi-channel GPS common-view difference. On average, each 16-minute interval contains 5 individual common-view differences. The GLONASS common-view differences contain the receiver delay biases for tracking different GLONASS satellites [4]. To obtain the GLONASS common-view differences, we first compute the difference for each individual track. To remove the delay biases, we use the delay of frequency No. 9 as the reference and correct the delay biases of other frequencies in the common-view differences. After removing the delay biases, we separate the common-view differences of tracking the P-code at L1 and L2 frequencies and the differences of tracking C/A code at L1 frequency. The individual C/A code common-view differences in the same 16-minute interval are averaged to obtain the multi-channel GLONASS C/A code common-view results. Each multi-channel GLONASS C/A code common-view difference is an average of 2 or more individual differences. The L2 P-code common-view difference is not used in the analysis because it contains the same information as that of the L1 P-code but with at least 6 dB less signal power. In Figure 2 and Figure 4, the common-view differences of different methods are intentionally offset for demonstration purposes. Table 1 summarizes the statistics of the common-view differences shown in Figure 2 and Figure 4.

Table 1. Statistics of Different Common-view Methods

Method	Average number of daily common-views		Standard deviation. of common-view over the period of calibration (ns)	
	NIST	USNO	NIST	USNO
Single-channel GPS C/A code	44		1.9	
Multi-channel GPS C/A code	440	420	1.7	1.3
Multi-channel GLONASS C/A code	174	154	1.7	1.3
Single-channel GLONASS P code	85	76	0.86	0.79

The comparison shows both the multi-channel GLONASS C/A code method and the single-channel GLONASS P-code method outperform the traditional single-channel GPS C/A code method. The multi-channel GPS C/A code method appeared to be the best in short term, but suffered diurnal variations in long term. The diurnal variation seems to have strong correlation with the outside temperature on both NIST and USNO sites, as shown in Figure 6 and Figure 7, but there are exceptions. The diurnal variation quieted down in the middle and came up again during the calibration at NIST. At USNO, the diurnal variation went away at the end of the calibration. On both sites, no changes were made in the setups during the calibrations. Furthermore, Figure 2 and Figure 4 show no visible diurnal variation in the GLONASS C/A code and P-code common-views. The NIST receiver is not equipped with the TSA but both the BIPM traveling receiver and USNO receiver used the TSA throughout the calibration. At NIST, the antenna's delay change due to the daily temperature variation certainly introduced the diurnal effect into the time transfer measurements. This explains why the common-view differences of all the methods at NIST were slightly noisier than that at USNO. However, it does not explain why the large diurnal variation appeared in the multi-channel GPS common-view but not in the GLONASS common-views. The diurnal variation in the multi-channel GPS common-view could be caused by the change of multi-path reflection in the antenna cable due to the daily temperature variation [5, 6]. The multi-path reflection is a function of the cable length, the RF signal frequency and the code's clock rate. A small change of the cable length changes the multi-path reflection pattern, which could introduce a large error in the measurements. Because all of the GPS satellites transmit different C/A code at the same L1 frequency, the multi-path reflection has the same effect on all the GPS signals. On the other hand, different GLONASS satellites transmit the same C/A or P-code at different frequencies. Measuring the GLONASS signals at different frequencies may reduce the effect of the change of the multi-path reflection. The diurnal variation on the multi-channel GPS common-view could also come from the error in the ionospheric delay correction of the GPS measurements. We found the software version in the BIPM traveling receiver was different from that in the NIST receiver and the USNO receiver. Because the GPS expansion card is controlled by the secondary CPU of the receiver's host PC, it is also possible that the secondary CPU was not initialized properly during the receiver start up. We believe the diurnal structure on the multi-channel GPS common-view differences was caused by a combination of systematic errors. However, we were not able to identify the exact cause of the problem. From Figure 3 and Figure 5, we also notice the multi-channel GPS common-view method contains more noise than the other methods for an averaging time longer than one day.

3. Multi-channel GPS/GLONASS Common-view between NIST and USNO

At present, both NIST and USNO still use single-channel GPS common-view and two-way satellite time transfer on a regular basis to compare each laboratory's clocks. On average, there are 40 daily single-channel GPS common-view tracks between NIST and USNO. The baseline between NIST and USNO is about 2405 km. With a baseline of this length, the ephemerides error, error in the ionospheric delay correction and the change of receiver delay due to the daily temperature variation cannot be cancelled completely by simply differencing the two sets of common-view measurements. Without post processing the common-view difference using the precise ephemerides and the measured ionospheric delay, the uncertainty of the single-channel GPS common-view between NIST and USNO is about 1.5 ns when averaged over 1 day. With good clocks (maser ensembles) at both ends, transfer noise can be seen out to about 10 days.

With the single-channel GPS C/A code common-view as the reference, we study the performance of the multi-channel GPS/GLONASS common-view between NIST and USNO using the commercial GPS+GLONASS receivers. In this study, we used data collected by both receivers from April 1, 1999 to May 12, 2000. The common-view differences for the multi-channel GPS C/A code, multi-channel GLONASS C/A code and single-channel GLONASS P-code methods were computed in the same way as described in the last section.

On average, each 16-minute interval contained 5 individual GPS C/A code common-views, and there were

80 averaged GPS common-views between NIST and USNO each day. For the GLONASS common-view, we have 60 daily single-channel GLONASS P-code common-views. There were 2 individual C/A code common-views in a 16-minute interval and a total of 71 daily averaged GLONASS C/A code common-views. Samples of the common-view differences for different methods are shown in Figure 8. The common-view differences for different methods are offset vertically for the illustration purposes.

The time deviations for each common-view method are shown in Figure 9. The time deviations were computed using the "All Tau" approach, which uses all possible averaging intervals and provides more information about the transfer noise. From Figure 9, we see the multi-channel GPS C/A code, multi-channel GLONASS C/A code and single-channel GLONASS P-code common-views all contained less transfer noise than that of the single-channel GPS common-view in short term. The multi-channel GPS common-view showed the lowest noise level when the averaging time is less than a few hours. All the common-view methods were affected by a diurnal event that peaked at about a half day. When averaging beyond one day, the single-channel GPS common-view showed the least transfer noise. The time deviation of the single-channel GPS common-view reached 800 ps at about 4 or 5 days, while the time deviation of the other methods stayed between 1 to 2 ns. All the GLONASS common-view methods were also influenced by a periodic error peaked at about 4 days due to the fact that the GLONASS constellation repeats itself every 8 days. After averaging past 10 days, the time deviation starts to show the characteristics of the two clocks.

The diurnal in Figure 9 is caused by a combination of systematic errors. These errors include ephemerides errors, errors in the ionospheric and tropospheric delay corrections, receiver coordinate errors, multi-path variations in receiving satellite signals, change of receiver delays and change of multi-path reflections in antenna cable due to the daily temperature variation. The effect of ephemerides error, antenna coordinates error and multi-path in receiving satellite signals is satellite-position dependent. Because the same satellite is tracked at about the same position every sidereal day, by displaying the daily common-view difference vertically according to the sidereal day, the effect of the position dependent errors will line up along the y-axis. The idea is illustrated in Figure 10 and Figure 11. Figure 10 contains ten consecutive daily common-view differences obtained by the single-channel GPS receivers. The daily common-view differences are offset vertically for illustration. We start with the time series of the common-view difference for MJD 51370 on the bottom of the plot. To compensate for the sidereal day, the time series of the common-view difference for MJD 51371 is shifted to the right by 4 minutes, the time series of the common-view difference for MJD 51372 is shifted to the right by 8 minutes, and so on. Figure 10 shows a clear pattern due to the position dependent errors. Besides the diurnal structure due to the position dependent errors, we see another structure that slowly rises and falls over the 24-hour period. We believe the error in the ionospheric delay correction and the effect of daily temperature variation are the main causes of this diurnal structure. Figure 11 shows the diurnal structure with the multi-channel GPS common-view data over the same period as in Figure 10. The daily common-view differences are displayed in the same way as in Figure 10. From Figure 11, we see the diurnal structure due to the position dependent errors is much smaller than that in the single-channel GPS common-view. However, there is no significant change of the slowly varying diurnal structure. This means multi-channel common-view can reduce the effect of the position dependent errors, but not the diurnal structure related to the error in the ionospheric delay correction and the effect of daily temperature variation. Because the time deviation for multi-channel GPS common-view is only about 100 ps better than that for single-channel GPS common-view around the half day region, we conclude the error in the ionospheric delay correction and the effect of the daily temperature variation are the main causes of the diurnal structure in the common-view between NIST and USNO.

4. Conclusion

The 12-channel GPS+GLONASS receiver showed a very impressive common-clock, common-view performance with the single-channel GLONASS P-code and multi-channel GLONASS C/A code methods. The time deviation is about 160 ps when averaged over one day. However, the multi-channel GPS common-clock, common-view was degraded by a strong diurnal effect with an unknown cause.

Using the multi-channel receiver greatly increases the number of daily common-views between NIST and USNO. For the multi-channel GPS method alone, the number of daily common-views is almost 10 times more than that of the single-channel common-view.

The increased number of common-views and the more precise measurement with GLONASS P-code reduce the transfer noise in short term. These two facts also reduce the effect of the position dependent errors in the common-view results.

The multi-channel common-view with the 12-channel GPS+GLONASS receivers is influenced by a strong diurnal effect at about the same level as the single-channel GPS common-view with the NBS-type receivers. We believe the diurnal effect in the common-view between NIST and USNO is dominated by the error in the ionospheric delay correction and the effect of the daily temperature variation on the receiver delay change and the change of multi-path reflection in the antenna cable.

When averaged past one day, the time deviation of the multi-channel common-views remains between 1 to 2 ns, while the noise of the single-channel GPS common-view drops below 1 ns for averaging longer than 2 days.

The GLONASS common-view is influenced by the 8-day periodicity of the GLONASS constellation.

The long term performance of the multi-channel common-view between NIST and USNO with this particular type of 12-channel GPS+GLONASS receiver needs to be improved. We plan to study the outcome of post processing the common-view data using precise ephemerides data and measured ionospheric delays, and study the improvement of minimizing the effect of daily temperature variation on the change of receiver delay and the multi-path reflection in the antenna cable

5. Reference

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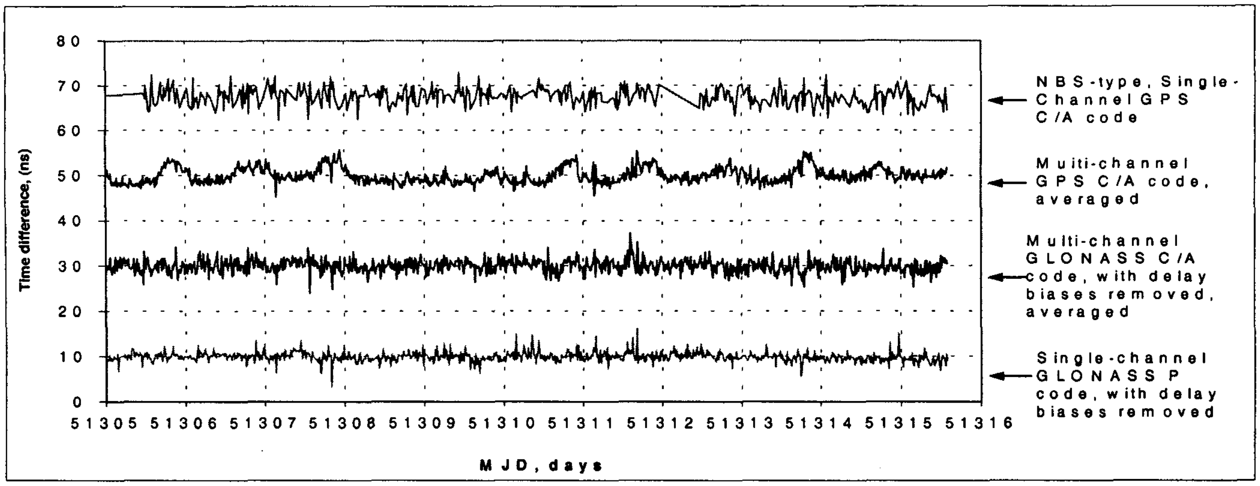

Figure 2. Comparison of GPS/GLONASS Time Transfer Methods Via Common-clock, Common-view at NIST

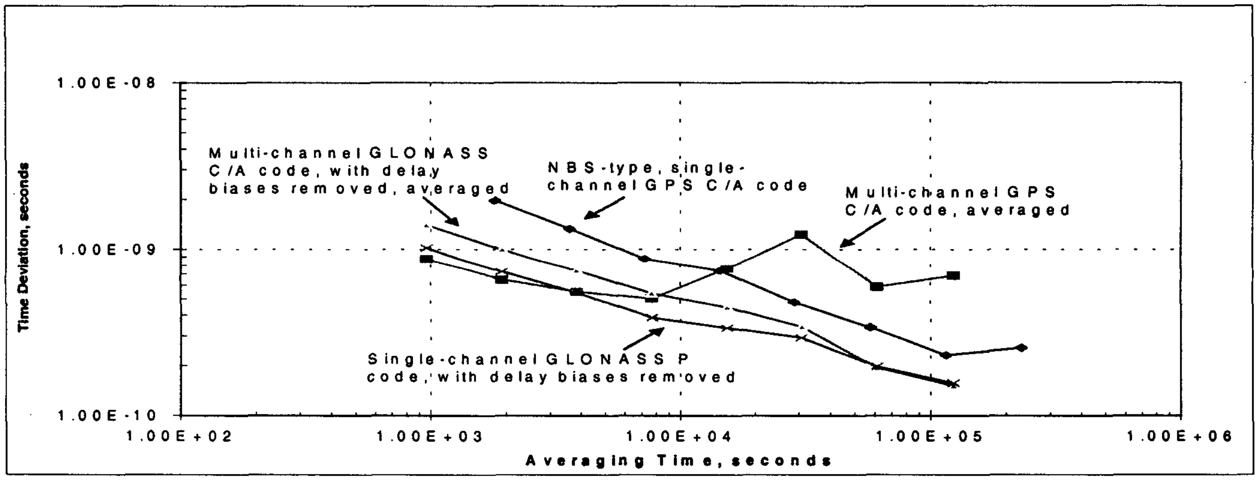

Figure 3. Time Deviation of Common-clock, Common-view GPS and GLONASS Time Transfer at NIST

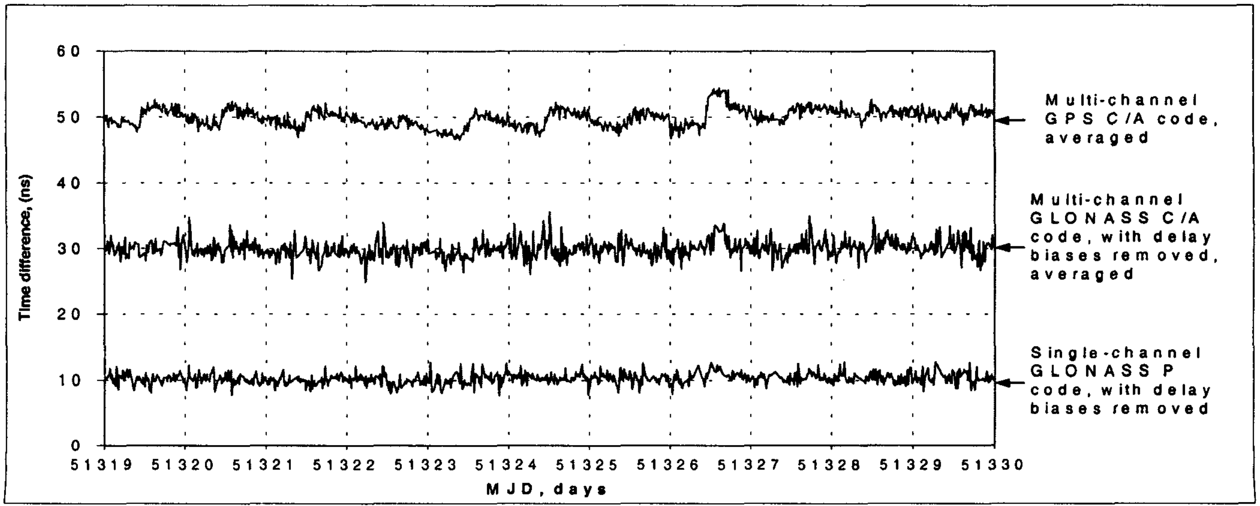

Figure 4. Comparison of GPS/GLONASS Time Transfer Methods Via Common-clock, Common-view at USNO

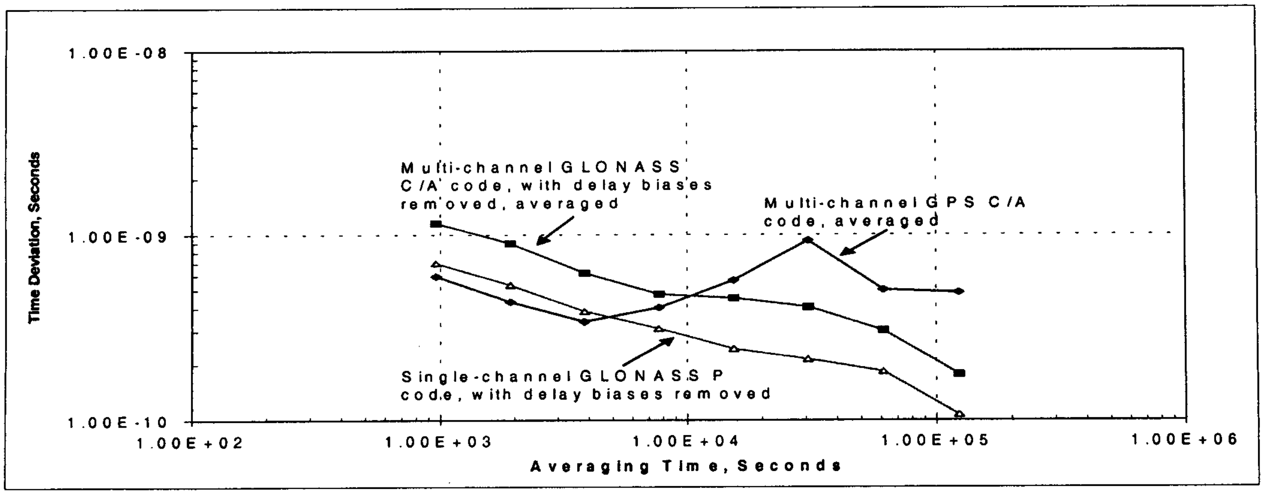

Figure 5. Time Deviation of Common-clock, Common-view GPS and GLONASS Time Transfer at USNO

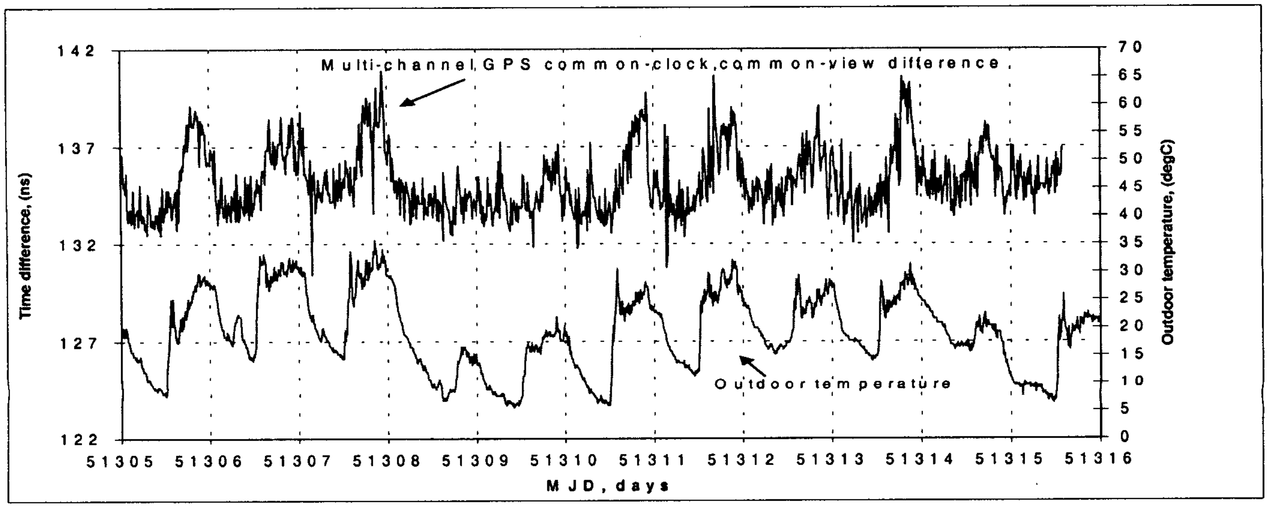

Figure 6. Correlation between Multi-channel GPS Common-view and Outdoor Temperature at NIST

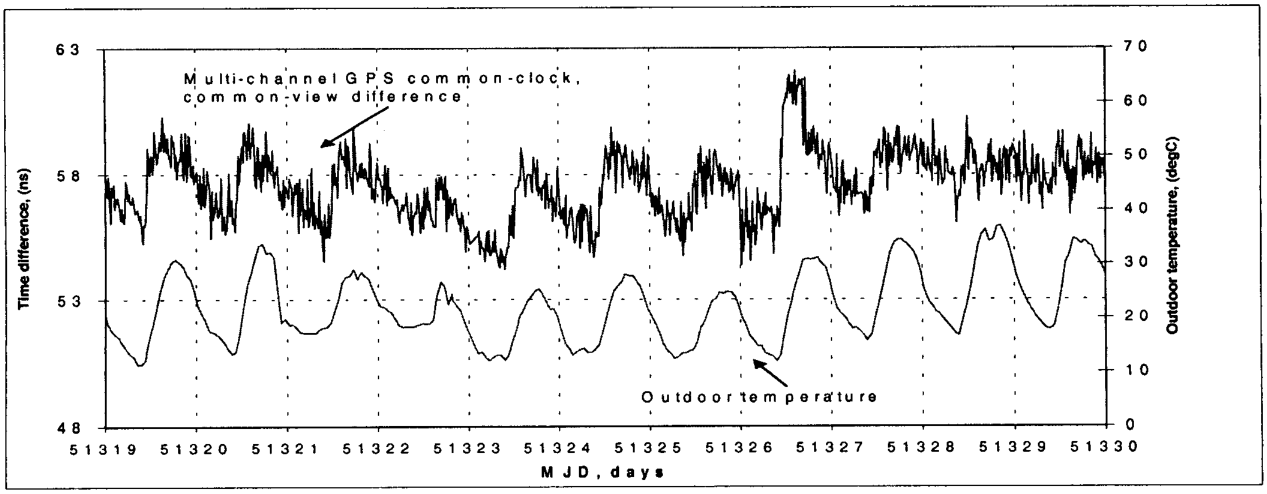

Figure 7. Correlation between Multi-channel GPS Common-view and Outdoor Temperature at USNO

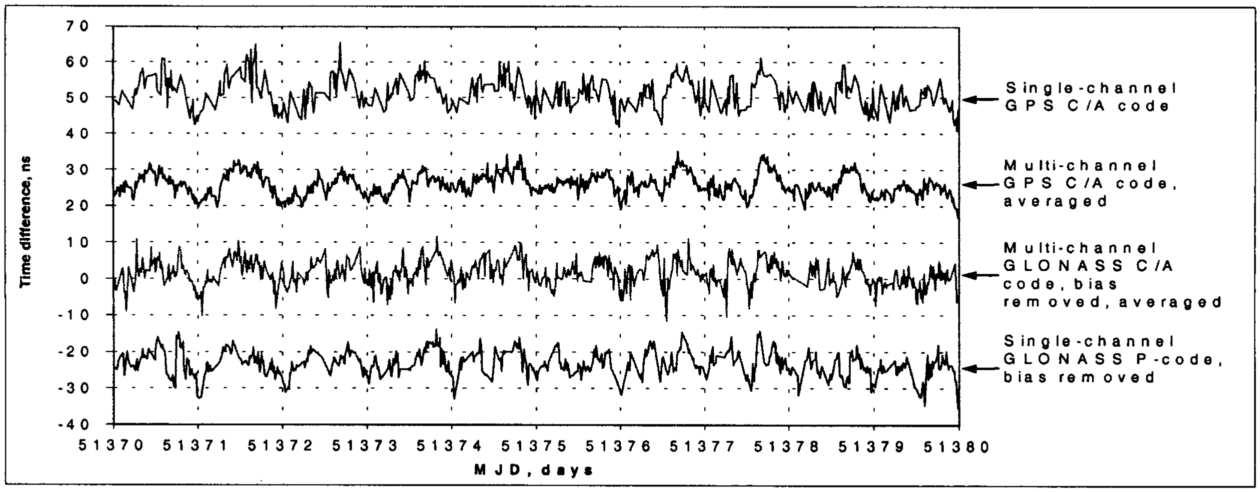

Figure 8 Sample of Common-view Differences between NIST and USNO

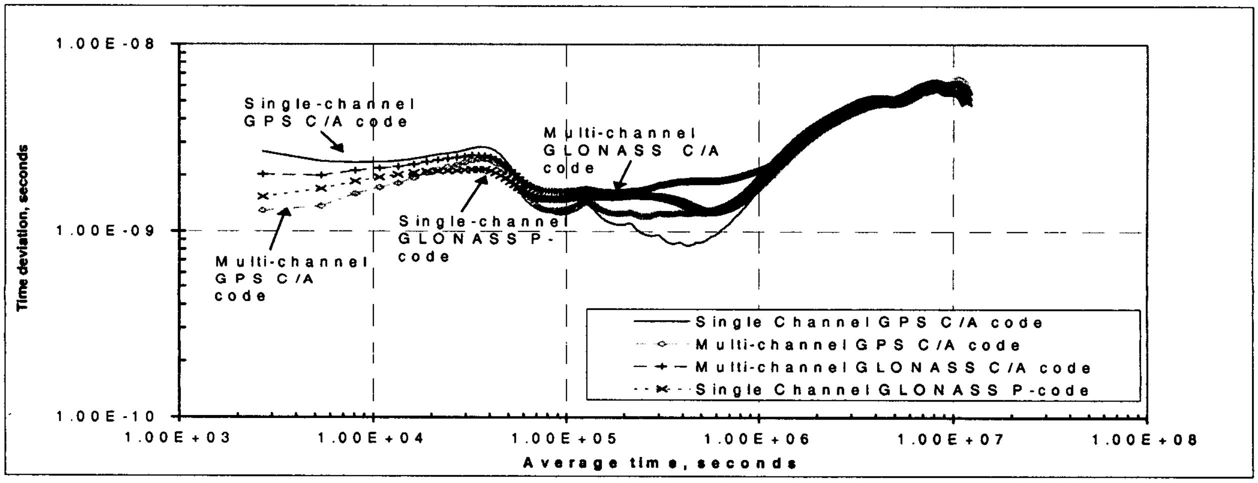

Figure 9 Time Deviation of Different Common-view Methods between NIST and USNO

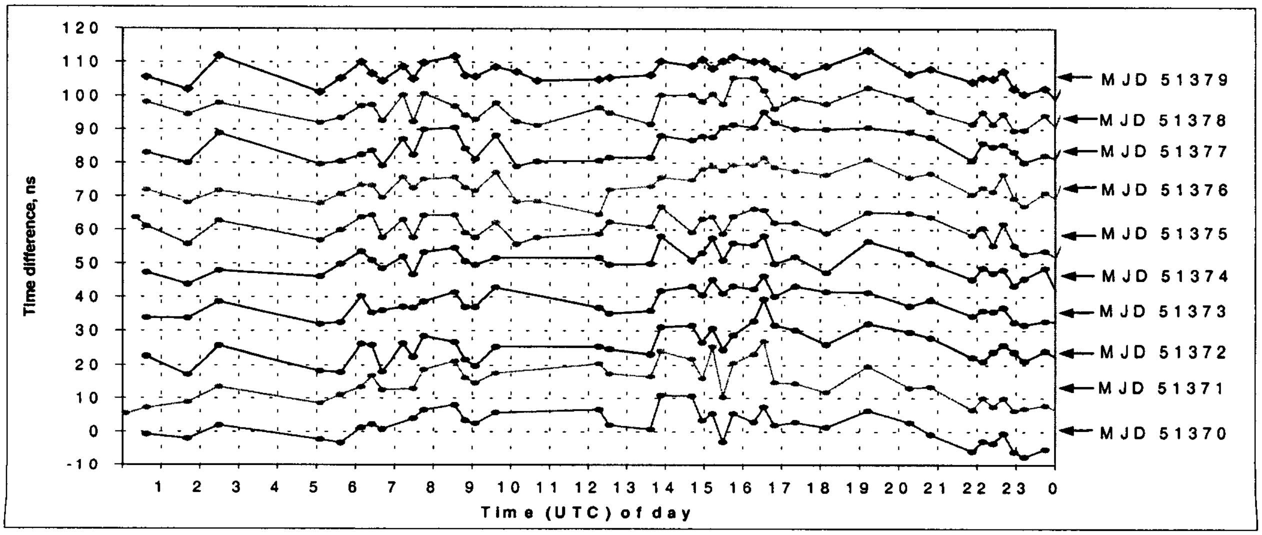

Figure 10 Diurnal Structure in Single-channel GPS Common-view between NIST and USNO

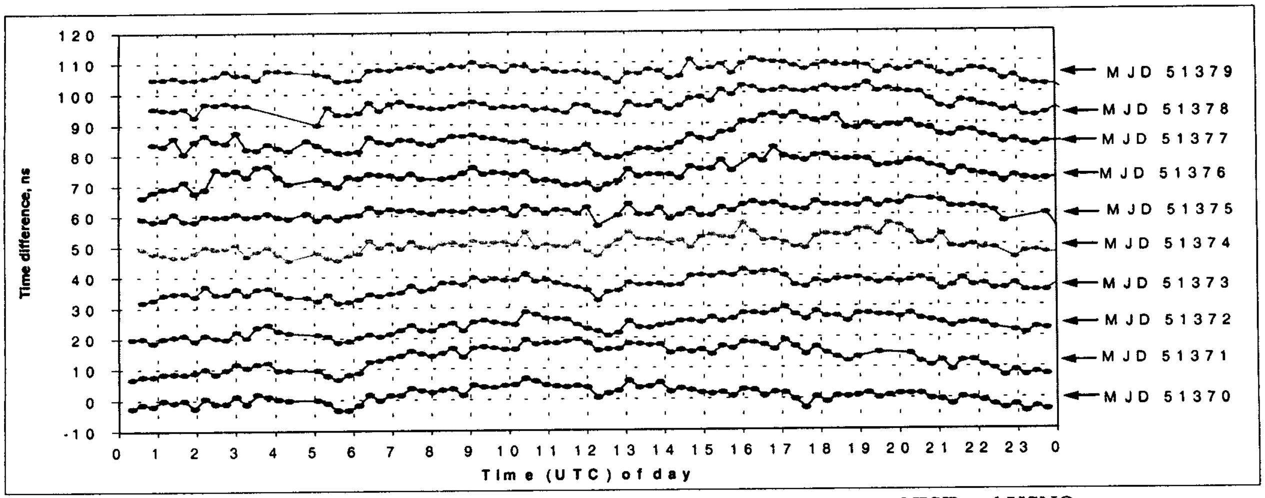

Figure 11 Diurnal Structure in Multi-channel Common-views between NIST and USNO