COMMON-VIEW TIME TRANSFER USING MULTI-CHANNEL GPS RECEIVERS

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Abstract

Common-View GPS has proven to be an accurate and reliable time transfer method capable of producing estimates of clock differences with a precision of 2-3 nanoseconds with averaging[1]. The advent of multi-channel timing receivers promises enhanced coverage and increased precision due to the large number of common-view passes available between any two sites. This paper discusses the processing techniques used to reap the benefits of the multi-channel receivers, and compares common-view results with those achieved using standard single-channel receivers. The precision of multi-channel common-view is shown to be less than a nanosecond with averaging over one day for a 2400-km baseline.

INTRODUCTION

Multi-channel GPS timing receivers offer the opportunity to greatly increase the number of common-view passes between any two sites. The extent to which these additional passes enhance the precision of the common-view results can be deduced from the underlying statistical theory. For a random sample from a Gaussian distribution, the variation of the sample mean is inversely related to the sample size. Thus we might expect that the variance of the "average" common-view differences between two sites to decrease dramatically with increases in the sample size, i.e., the number of common-view passes. In order to validate this scenario, the USNO conducted a three-month experiment comparing common-view results obtained via single-channel receivers with those obtained using multi-channel receivers.

HARDWARE AND SOFTWARE

TIME TRANSFER RECEIVERS

AOA TTR4P multi-channel receivers were used in the experiment. All receivers were upgraded to the 050 processor and were operating with version 3.0.34.3 software. This software version has two new features which are necessary for successful common-view time transfer, a new mode of operation called *Clock*, and the ability to apply ionospheric model corrections. When operating in *Clock* mode, the receiver will not try to automatically determine its position when it is reset, undergoes a power cycle, or loses lock on all satellites. Instead, the receiver maintains the position entered by the user. The ability to select the ionospheric model eliminates the problem of noisy ionospheric measurements for satellites below 30 degrees elevation, a characteristic of the TTR4P receiver. Furthermore, applying modeled ionospheric corrections maintains continuity with most common-view time transfer receivers in operation today.

MULTI-CHANNEL COMMON-VIEW SCHEDULES

In the traditional common-view (CV) algorithm, satellites are tracked according to a schedule issued by the BIPM twice annually. This schedule spaces the CV passes at least 15 minutes apart to allow for a two-minute acquisition period needed by many single-channel receivers. When using a multi-channel receiver in "all-in-view" mode, several satellites are tracked at once, potentially from horizon to horizon. Thus, the standard CV schedule is ineffective, both in terms of number and concentration of passes. To maximize the number of CV passes between the USNO and the USNO AMC, several different multi-channel common-view (MCV) schedules were tested.

The first schedule building technique identifies the time intervals when each satellite is in common-view between the two sites, and divides these time intervals into 13-minute MCV passes. In such a schedule, there are approximately 20 passes per satellite, as opposed to two or three passes in a traditional CV schedule. Like the traditional schedule, however, the MCV passes are slewed four minutes per day. Drawbacks to this schedule building technique include the following. (1) If common-view is to be done with a new site, a similar schedule must be constructed listing all passes in common between the USNO and the new site. This is undesirable if short-term MCV experiments occur with numerous sites. (2) The schedule must be "maintained," since satellite positions change over time. (3) There is no guarantee that there will be *any* CV passes between receivers operating on this schedule and other time transfer receivers using the standard BIPM schedule.

The second schedule building technique reduces the time spent maintaining the schedules by disregarding the time intervals when each satellite is in common-view. Instead, MCV passes for every satellite are constructed by dividing the day into 110 thirteen-minute intervals. Thus, each 13-minute interval is a *potential* MCV pass for *all* satellites. In reality, of course, only approximately 20 of these will be tracked per satellite at both sites. While this does eliminate the need for constantly maintaining the schedule, it increases processing time since the raw data are searched for 110 passes per satellite, as opposed to 20 passes as in the first method. This technique is, however, flexible enough to be adapted to any new site, as it does not depend on location specific satellite view times.

A third technique was adopted after discussions with C. Thomas of the BIPM which allows all of the traditional CV passes to be included as a subset of the MCV passes. This is accomplished by dividing the day into 16-minute time intervals and setting the effective date of the MCV schedule to be the effective date of the most recent BIPM International CV Schedule. This technique not only allows CV comparisons with single-channel receivers, it is a convenient format that can be mutually agreed upon in order to exchange 13-minute data with any other lab. Data for exchange with other timing labs are formatted in accordance with the GGTTS guidelines.[2]

MULTI-CHANNEL COMMON-VIEW PROCESSING

Using one of the above techniques to establish start and stop times of 13-minute passes for each satellite, the raw 10-second data are processed using a linear fit routine to produce 13-minute values which are referenced to the midpoint of the pass. Common-view differences are then identified in the standard way using a 20-degree elevation mask.[3] The MCV differences are then filtered. Traditionally, a two-standard-deviation filter is used to remove outliers, but 5% upper- and lower-tail trimming were found to be more effective at removing systematic error sources from the common-view difference data between the USNO and the USNO AMC. The rationale for the trimming procedure will be discussed below. Next, linear fits are calculated using the filtered 13-minute differences from 1200 UT of one day to 1200 UT of the next day, and referenced to 0000 UT of the second day.[4]

RESULTS

USNO - USNO AMC

Multi-channel common-view has been underway between the USNO in Washington, DC and the USNO AMC in Colorado Springs, Colorado since January 1997. Over this 2400-kilometer baseline, approximately 360 MCV passes are observed daily. The receivers at each site are referenced to steered hydrogen masers which are generally kept within a few nanoseconds of each other via Two-Way Satellite Time Transfer (TWSTT).[5] The results presented are for the time period 01 June 1997 through 05 September 1997, and include common-view passes for all healthy satellites except PRN02/SVN13.

During the experiment, the distribution of daily Reference-GPS measurements made by receivers at both sites was found to be approximately Gaussian when treating the Reference-GPS data as a random sample, not as a time series. The MCV difference data were thus expected to be Gaussian. In practice, however, it was found that the distribution of the MCV differences was heavy-tailed, indicating a systematic error source. Although this error source was not eliminated, the distribution was normalized by a 5% trimming of the upper and lower tails. Trimming the data as opposed to filtering based upon a two-standard-deviation limit was shown to reduce the scatter of the 13-minute differences by up to 0.5 nanoseconds with minimal loss of data.

Based upon one-day linear fits of the filtered 13-minute data, the average MCV difference between the two clocks was reported as -0.22 nanoseconds with an average one day RMS of 2.33 nanoseconds. The USNO also maintains STel 5401C single-channel, dual-frequency, P/Y code receivers which complete the same common-view link. During the same time period, the STel receivers reported an average RMS at one day of 4.38 nanoseconds using approximately 55 CV passes per day. It should be noted that the STel receivers apply a measured ionospheric correction which is quantized to nine nanoseconds, and undoubtedly contributes to the higher scatter of the 13-minute differences.

Receiver Type	Filtering Method	Precision at 13 Minutes	Number of CV Passes per Day	Precision at 1 Day
AOA TTR4P	$\bar{x} \pm 2s$	2.71 ns	377	0.72 ns
	5% trim	2.33 ns	358	0.71 ns
STel 5401C	$\bar{x} \pm 2s$	4.38 ns	55	1.05 ns

Estimates of the precision of the 1-day common-view differences were computed via the residuals of smoothed 13-minute MCV values. Figure 1 displays the smoothing performed. A five-day moving average was utilized to remove longer-term effects such as clock rates and temperature effects. The variability of the residuals of the moving average was then used to estimate the precision of the MCV differences at one day. Due to the large number of MCV passes produced by the TTR4P receivers, the precision of the daily common-view estimates is smaller than that of the single-channel STel receivers. The estimated precision of the daily MCV values is 720 picoseconds, as shown in the table above.

By using a higher elevation mask when computing MCV differences, variation can be reduced at the price of fewer MCV passes. For example, using an elevation mask of 60 degrees lowers the RMS at one day to 2.15 ns, but the average number of MCV passes is reduced to 60 per day, which in turn reduces the precision over longer averaging times (see Figure 2).

USNO - BIPM

A short-lived MCV experiment between the USNO and the BIPM took place during 13 August 1997 to 18 August 1997 over a baseline of approximately 6000 kilometers. The BIPM TTR4P receiver was also running version 3.0.34.3 software, had a sample rate of one second, and was referenced to a HP5071A cesium clock.[6] The scatter of the 13-minute differences was generally less than five nanoseconds, and the precision of the daily MCV estimates was approximately 630 picoseconds.

The link between the USNO and the BIPM is also made using AOA TTR6 single-channel receivers. Over the same time period, an average daily RMS of 3.2 nanoseconds was calculated for traditional CV between TTR6 receivers using approximately 16 passes daily, yielding an estimated precision of 1.30 nanoseconds.

Receiver Type	Filtering Method	Precision at 13 Minutes	Number of CV Passes Daily	Precision at 1 Day
AOA TTR4P	$\bar{x} \pm 2s$	4.68 ns	138	0.74 ns
	5% trim	4.50 ns	132	0.63 ns
AOA TTR6	$\bar{x} \pm 2s$	3.20 ns	16	1.30 ns

Once again, the use of multi-channel receivers increases the precision of the daily MCV estimates. In this case, the eight-channel receivers yield estimates of USNO-

BIPM that are approximately twice as precise as estimates obtained from the single-channel receiver.

RECEIVER CALIBRATION PROBLEM

During the experiment, a major problem with the time measurement hardware and software was discovered. A 24-nanosecond uncertainty in the absolute calibration of the TTR4P manifests itself each time the unit undergoes a power cycle or is reset. Therefore, once the unit has been powered on and the receiver bias has been set, the power must not be recycled. This was not a serious problem at either USNO site since all equipment is provided with an uninterrupted power supply. Additionally, to ensure the stability of the calibration of the receivers in Washington, common-view time transfer with a co-located AOA TTR6 receiver is continually performed to monitor the integrity of the receivers. AOA has acknowledged the 24-nanosecond uncertainty and has committed to resolving the problem. Figure 3 shows the results of several power cycles performed during testing at the USNO.

SUMMARY AND CONCLUSIONS

Aside from the standard common-view procedures utilized in this study, alternative data processing techniques should be investigated. Such techniques may include consolidating Reference - GPS measurements across several channels to produce 13-minute values which are averages of data from several satellites tracked concurrently at both sites. Estimates of clock differences formed in this fashion may prove to be more stable in the short term. However, using the standard common-view technique, it was shown that the increased number of common-view passes contributes to the increased precision of the estimates of clock differences. For the CV link between the USNO and the USNO AMC, the multi-channel receivers produced six times the number of CV passes as single-channel receivers, and enhanced the precision by a factor of 1.5 while showing little difference in the magnitude or variability of the raw measurements.

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ACKNOWLEDGEMENTS

The authors would like to thank Claudine Thomas and Philippe Moussay of the BIPM for sharing GPS data, Jim DeYoung and Steven Hutsell of the USNO for contributing to the data analysis, and Francine Vannicola, Wendy King, and Ed Powers for contributing to hardware and software efforts.

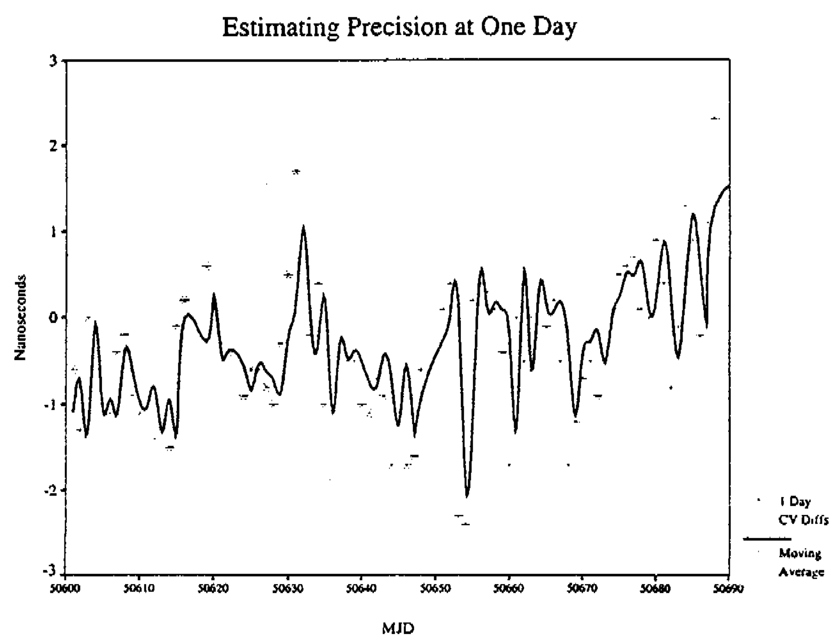

Figure 1.

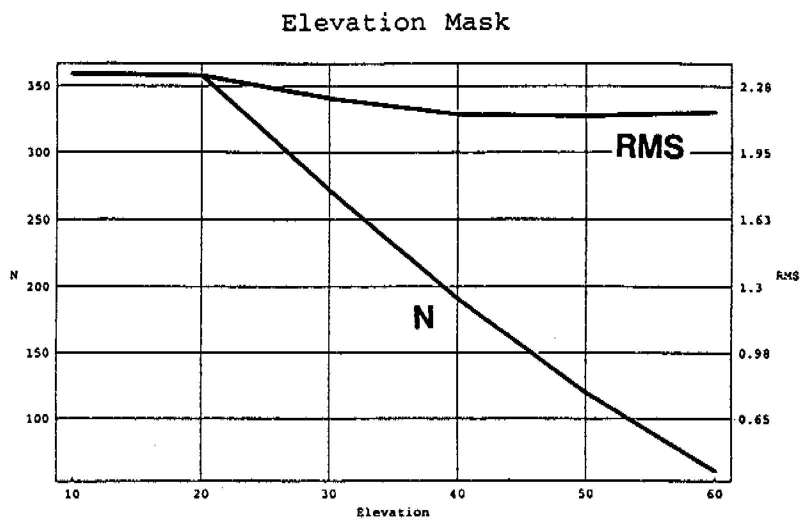

Figure 2.

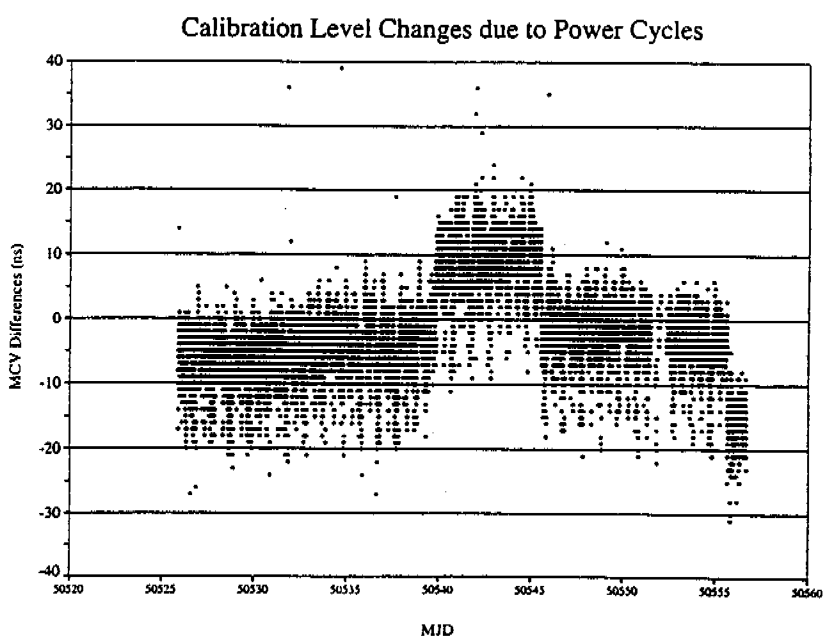

Figure 3.