ATTENUATING DAY-BOUNDARY DISCONTINUITIES IN GPS CARRIER-PHASE TIME TRANSFER

Ken Senior, Ed Powers, and Demetrios Matsakis
Time Service Department
U.S. Naval Observatory
Washington, DC 20392, USA

Abstract

Many IGS analysis centers show 1-nanosecond-level discontinuities across processing boundaries in their GPS carrier-phase time-transfer (GPSCPTT) solutions. Though these discontinuities reflect the nature of processing the GPS data, generally in 1-day batches, this paper tests the hypothesis that, with slight modifications in the standard filtering process, one might improve the degrees of freedom with respect to phase ambiguity parameters in such a way as to improve the time-transfer solutions and attenuate most of the discontinuities.

1 BACKGROUND

Analysis of dual-frequency GPS pseudorange (obtained from GPS codes) and carrier-phase data collected from 19 multi-channel geodetic receivers (15 of which are International GPS Service (IGS) stations) was performed using the GIPSY-OASIS package written at the Jet Propulsion Lab (JPL). This package pre-processes and filters (both forward and backward—generally called smoothing[1]) undifferenced GPS data with a number of modeling options for the various parameters to be estimated.

1.1. The Model. For this work, we formed ionospheric-free combinations of the observables and held fixed IGS precise orbits and earth rotation data in the filtering process. Parameters estimated include: station positions (constrained to their ITRF96 coordinates for fiducial stations), zenith troposphere (modeled stochastically as random walk), satellite and station clocks (modeled stochastically as white), and phase ambiguities (modeled as constant over each continuous data arc). An elevation cut-off angle of $15°$ was used.

Before estimation, carrier-aided smoothing of the pseudorange data is performed to the 5-minute interval and carrier-phase data are decimated to the 5-minute interval. Also, preliminary cycle-slip repair is made to the carrier-phase data. Once the

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[1] Use of the word "smoothing" in this paper refers to an optimal combination of a forward filter and a backward filter (c.f. [Bierman] or [Gelb]).

filtering/smoothing is complete, phase residuals (model applied to estimates and then subtracted from phase data) are examined for discontinuities. If discontinuities are found, new cycle slips are flagged at each such epoch, and new phase ambiguity parameters are introduced. The filter is then restarted with the new phase ambiguity parameter(s).

1.2. Filtering Alternatives. Two filtering methods have been compared in this paper:

Method 1 (M1). Standard 1-day batch processing of the data (i.e. each 1-day batch of data are filtered/smoothed separately.)

Method 2 (M2). *Continuous* forward filtering of the data with various smoothing (backward filtering) options. In other words, filtered estimates and covariances are passed continuously forward across day-boundaries; one may therefore smooth as far back into the past as desired.

M1 entails processing each 1-day batch of data separately. This approach is consistent with the way in which IGS precise orbits and earth rotation data are produced and is easier to implement and maintain than M2. The continuous filtering approach (M2) requires that each day be processed contiguously, since filtering estimates and covariance information must be passed continuously from one day to the next. The GIPSY-OASIS-II package has been written to accommodate both methods, though M2 is less well known to most users.

Using results from experiments obtained from these two approaches, the hypothesis is tested that the GPS Carrier-Phase Time-Transfer (GPSCPTT) solutions are improved as a result of using the continuous filtering approach. One might expect the time-transfer solutions obtained from continuous filtering to be improved for two reasons: M2 will involve estimating fewer parameters than M1. In particular, for each continuous arc of phase data (i.e. for each set of station-to-satellite carrier-phase data containing no cycle slips) passing through the day boundary, M1 will require that two phase ambiguity parameters be estimated, whereas M2 requires only one phase ambiguity be estimated for that arc.

Secondly, though the *precision* of estimated clock parameters depends primarily on carrier-phase data, the *absolute* value of clock estimates depends on time-averaged pseudorange data. Thus, long spans of continuous phase data without cycle slips favor better clock estimates by providing longer intervals over which the pseudorange can be averaged; M2 inherently allows the filter to average the pseudorange data over longer data arcs.

On the other hand, because IGS orbit products are independently produced in 1-day batches, a continuous filtering algorithm which fixes IGS precise orbits may incorrectly propagate orbital discontinuities at day-boundaries into estimates of other parameters (including clocks). Though IGS precise orbit repeatabilities are generally on the order of a few centimeters—much less than one L1 or L2 cycle—care must be taken to avoid propagating large orbital discontinuities.

2 RESULTS

To test whether or not the continuous filtering method (M2) of processing yields improved timing solutions over that of the standard processing approach (M1), we examine the formal errors (i.e. error covariances) of the GPSCPTT clock estimates as an internal measure of overall filter performance, as well as make external comparisons of GPSCPTT clock estimates with Two-Way Satellite Time-Transfer (TWSTT) data.

2.1.   Internal Comparisons.   As an internal measure of filter performance (with respect to clock estimates) in each method, the formal error (i.e. error covariance) of the filtered/smoothed clock estimates can be calculated. Though one expects formal errors of estimated parameters to decrease as a result of adding more data to their estimation, the formal errors should approach an overall nonzero asymptote reflecting measurement noise in the data. Of interest is both the non-zero asymptote to which the formal errors approach as well as the time constant associated with the decay.

To that end, we employed the following series of experiments: Clock estimates for a small network of 18 stations over a 15-day interval were obtained from a series of filter/smoother runs, each run varying in the length of time in which the filter is allowed to run before being reset. Figure 1 shows the results of these experiments. In particular, each datapoint in Figure 1 represents the mean (over 15 days) of the formal error of clock estimates for all 18 stations calculated from each experiment. The figure clearly indicates that the decay in formal errors has a time constant on the order of several days (i.e. longer than that used in standard 1-day filtering M1).

The results depicted in Figure 1 do not directly compare M1 and M2, but rather suggest that estimates of clock parameters may be improved (as measured by formal errors only) by allowing a longer filtering/smoothing time—though a natural consequence of the continuous filtering method M2. To further gauge the effectiveness of continuous filtering (M2), we employed an experiment in which clock estimates for the same 18-station network are calculated using both method M1 and M2 over a 4-month period. From this experiment, mean formal errors were tabulated (see Table 1) separately for each station over this period. As the table indicates, method M2 results in a 25% decrease in formal errors on average compared to method M1. Also, the mean formal error over the entire network of stations (excluding GOL2 because of extreme data outages) suggests that formal errors of clock estimates from the M2 filtering paradigm nearly reach of 0.105 nanoseconds for method M2 the asymptote suggested in Figure 1.

Having the goal of optimizing filter performance, one would necessarily wish to design a filtering paradigm in which formal errors of the parameters to be estimated are minimized. But improving formal errors may not bear direct connection to improving the true accuracies of the estimates. Thus, though it appears from the formal error analysis that M1 may be less than optimal for estimating clock parameters and that M2 reaches the minimizer predicted by Figure 1, a measure of performance involving true clock information is needed to better compare the "real" impact of M1 and M2 on clock estimates.
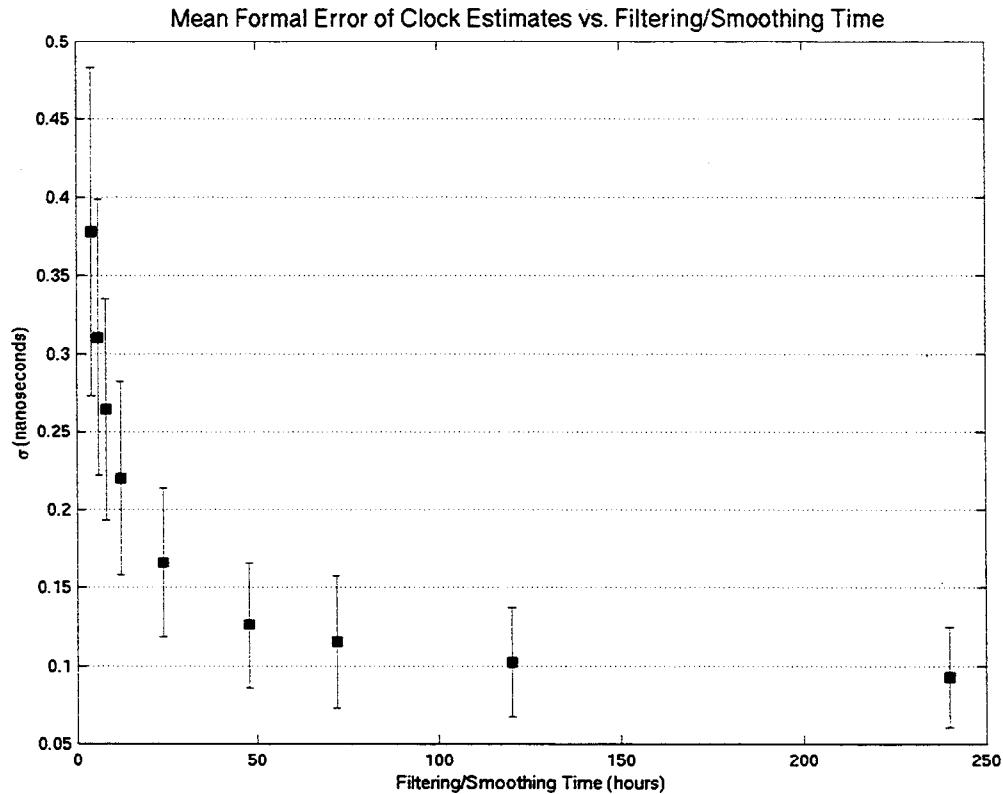
Figure 1

Mean formal error of clock estimates for 18 stations for the period April 13, 1999 through April 27, 1999. Each datapoint represents a mean formal error obtained from varying the filtering/smoothing time.

2.2.   External Comparisons.   USNO performs hourly Two-Way Satellite Time-Transfer (TWSTT) with the Alternate Master Clock (AMC) located in Boulder, CO. As an external measure for comparing M1 and M2, we consider the TTWST data between AMC and USNO as truth time-transfer data.   Because the rms of TWSTT data is typically 1 ns, we calculate a 6-hour running mean of the raw TWSTT data between USNO and AMC.   This is then compared with GPS Carrier-Phase Time-Transfer (GPSCPTT) data obtained from M1, as well as with M2 (1-day smoothing), and M2 (10-day smoothing).   Figure 2 displays the clock estimates obtained from M1 (top) and from the two M2 solutions (middle plots).   Note that only the bottom two plots have the same *y*-scale; the bottom plot shows Two-Way Satellite Time-Transfer.   Figure 3 shows each GPSCPTT solution subtracted from TWSTT data.   Also, because of receiver resets, large discontinuities (larger than 5 nanoseconds) have been removed using 1-Pulse-Per-Second (1-PPS) data.

STATION	MEAN FORMAL ERROR (picoseconds)		data coverage
	standard	M2 (1-day smoothing)	
ALGO	146	98	91%
AMC2	141	96	85%
BAHR	156	104	86%
DRAO	143	92	94%
FAIR	169	131	92%
GODE	150	90	92%
GOL2	151	155	3%
GRAZ	149	117	49%
KOKB	159	129	86%
MATE	152	138	89%
MKEA	158	127	50%
†NIM1	-	88	62%
†NIM2	-	87	86%
NLIB	151	101	94%
NRC1	148	107	92%
PIE1	148	99	93%
†PTBA	-	105	70%
†USNB	-	89	91%
average (excluding GOL2)	152	105	

Table 1

Mean formal error of clock estimates for the period January 1, 1999 through April 30, 1999. For 98% of the estimates, USNO was the reference clock.

† Indicates a non-IGS station.

As Figure 3 shows, M2 solutions are generally within ±3 nanoseconds of TWSTT data (with exceptions occurring MJD 51203-51212 and 51291-51288) compared with the 20 nanosecond for M1 solutions. The M2 (10-day smoothing) solution is generally within ±2 ns of TWSTT with exceptions at MJD 51291-51298. The exception at MJD 51203 coincidentally occurs at the same instant an RFI-like event occurred at AMC which showed itself as a marked drop in signal-to-noise on the pseudorange data for both L1 and L2 frequencies. The event caused a 1-meter level bias in the pseudorange observable corresponding to the L2 frequency, but did not cause a similar jump in the pseudorange corresponding to the L1 frequency. The drop in SNR lasted for approximately 15 minutes, while the bias in the L2-pseudorange only gradually returned to nominal value over a period of days. The anomaly for all GPSCPTT clock estimates at 51291 is clearly identifiable as coinciding with a data outage as well as spurious receiver
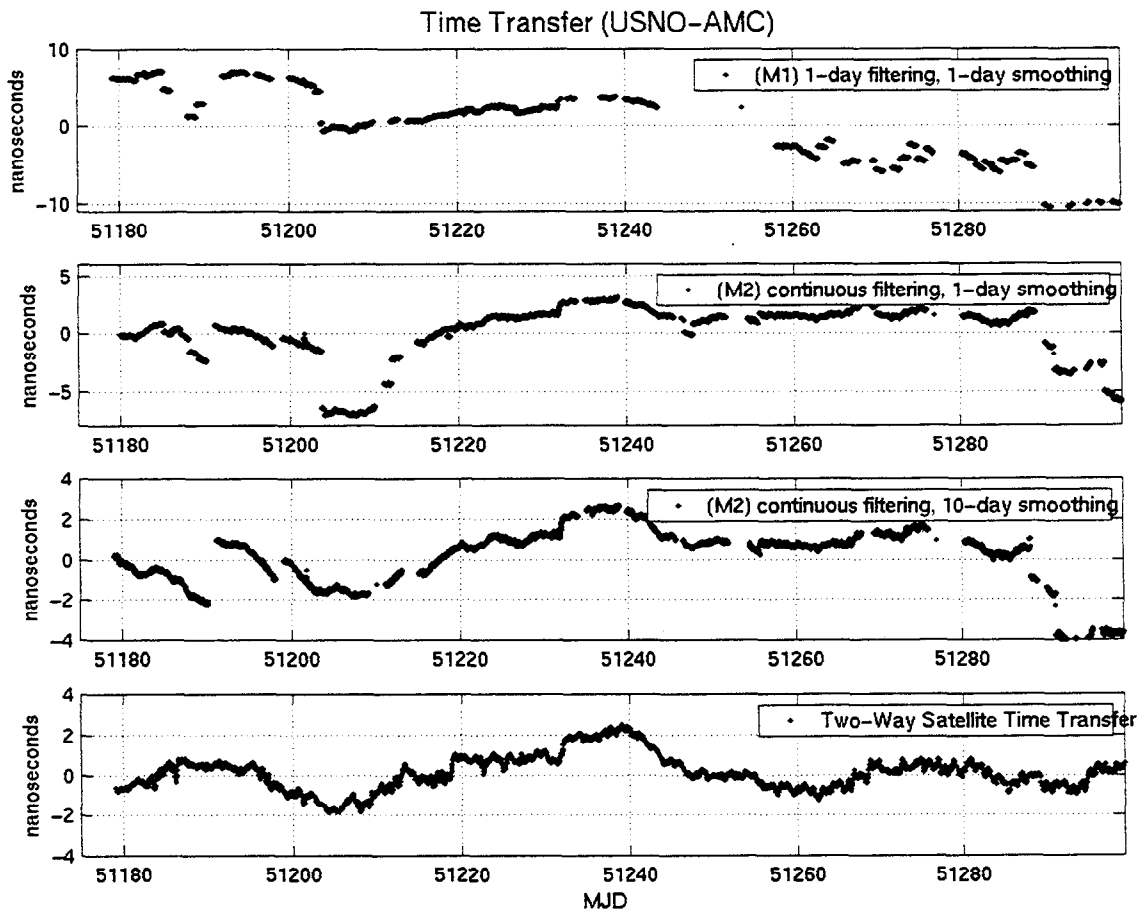
Time Transfer (USNO-AMC)

Figure 2

Time-transfer data obtained from methods M1, M2, and TWSTT data for the period January 1, 1999 through April 30, 1999. Both 1-day and 10-day backward filtering (i.e. smoothing) results are shown for M2 solutions. Discontinuities in GPSCPTT clock estimates (those obtained from both M1 and M2) larger than 5 nanoseconds (large discontinuities can occur for example when the receiver resets) have been removed as outliers using 1-PPS data. Also, TWSTTW data were obtained by forming a 6-hour running mean of the raw TWSTT data. A constant has been removed from all M1 and M2 time series.

NOTE: *y*-axis scaling is not the same for each time series.

behavior at AMC, but the resulting bias introduced into the clock estimates is unexplained.

Figure 3 suggests that M2 (10-day smoothing) performs well over this 4-month period.

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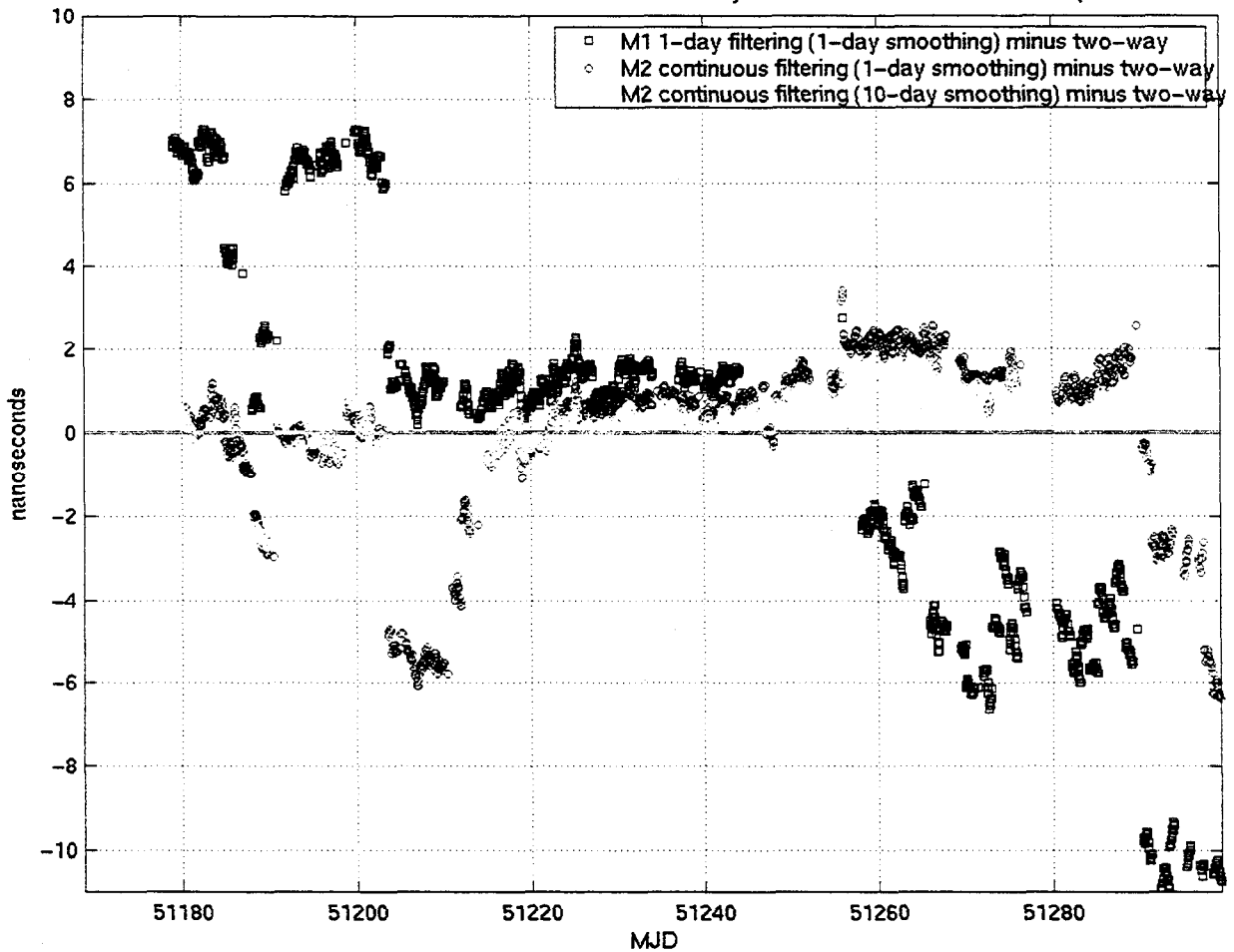GPS Carrier-Phase Clock Estimates minus Two-Way Satellite Time Transfer (USNO-AMC)

Figure 3

Comparison of GPSCPTT estimates with TWSTT data for the USNO-AMC link for the period January 1, 1999 through April 30, 1999. The GPSCPTT estimates were obtained from standard processing (M1) and from Continuous Filtering (M2) methods. Both 1-day and 10-day backward filtering (smoothing) results are shown for M2 solutions. Discontinuities in GPS Carrier-Phase clock estimates larger than 5 nanoseconds have been removed using 1-PPS data. Also, TWSTT data were obtained by forming a 6-hour running mean of the raw TWSTT data. Relative positioning of each time series is arbitrary, as the GPSCPTT system is not calibrated.

3 CONCLUSIONS

We have proposed the hypothesis that estimation of GPSCPTT clock parameters are improved by filtering the data over spans longer than the standard 1-day batch filtering and that the continuous filtering method M2 is an effective and natural method of realizing an optimal filtering interval. The formal error experiments and analysis suggested that filtering intervals larger than 1-day would be more effective and that M2 reached the optimal (as defined by the asymptote of Figure 1) level of formal errors predicted. Also, TWSTT comparisons made here suggest that the continuous filtering method M2 seems to perform well over the 4-month period analyzed. However, much remains to be proven with regard to the exact relationship between true clock estimate accuracies and filtering interval.

ACKNOWLEDGMENTS

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Questions and Answers

DAVID HOWE (NIST): A very nice presentation, Ken. But I wanted to point out that the sort of models and manipulations on data for short integration times and having systems which basically preserve covariance coefficients through what amounts to a phase step can be misleading for real long-term data between clocks. Because, as you can tell, if you're doing the splicing in short integration times, this will naturally average away even if the clocks are random walking. So I only caution that it's an objective to try to get the hardware to perform with as few discontinuities as possible. And I think that would be a better trend.

I would like to pose a question as to whether you've done any long-term integration times on these data.

KEN SENIOR (USNO): Actually, I was motivated by truth data. And so I chose the AMC to USNO link as well as the fiber link between the two buildings. It's unfortunate that, in the time period I looked at with AMC, the new receiver went in during March and there were a number of problems getting that going. And so the data were kind of choppy, and I was not able to isolate a good longer than 20 or 30-day arc in that time period. And, also, the fiber link I don't completely trust anyway. There are some problems with that.

With respect to the other comment you made about the hardware, I certainly agree with you that ultimately one would hope that you attack it from the hardware side to minimize a multi-path, like a pseudo-range multi-path, and things like that. But I think that this method is attractive because in the period on where you're just sliding the solutions together, essentially with respect to timing, you are calibrating, if you will, the carrier to the code over maybe just the very first day. Whereas this sort of method allows you to pick a longer data arc and fit the carrier to the code over a longer period of time. And I think it's attractive for that reason, also, as well as the degrees of freedom in improvement that you can realize.

And as far as waiting data too distant in the past, again, I think that that would just have to be worked out with respect to choosing the appropriate pseudo-noise model to deweight data in the past.