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Estimating Empirical Station Timing Biases using IGS Clock Products

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Abstract

We demonstrate a method to determine empirical station timing biases for geodetic receivers located at timing laboratories. Mutual observations of GPS time, as reported by the Bureau International des Poids et Mesures (BIPM) in its Circular T and as observed by the International GPS Service (IGS), are used together with the Circular T offsets of the lab timescales (UTC − UTC_i). This method effectively extends the previously determined calibration bias of a lab's main time transfer system differentially to a colocated geodetic receiver system, without need of any additional local measurements. The empirical biases include both the internal delays within the geodetic GPS receiver/antenna hardware as well as the intra-laboratory offset to the source of UTC_i. When applied to the subset of IGS stations located at timing labs, we find that useful results can be obtained provided that the geodetic system uses a frequency standard closely related to the local UTC_i realization and that the GPS receiver does not reset its internal clock too frequently. We find daily RMS repeatabilities in some cases of about 1 to 2 ns over periods up to about a year. Given sufficient available data, the mean station bias can be estimated from a single monthly Circular T update to the 1 ns level, which is smaller than the uncertainty in current absolute calibrations. This method can be used to validate laboratory calibration measurements for the geodetic systems and to continuously monitor intra-laboratory calibration stability without disrupting normal operations. It can also be exploited to improve the near real-time steering of the IGS timescale to track UTC more closely.

Keywords

GPS, IGS, Calibration, Time Transfer, Carrier-Phase Time Transfer

I. Background

Any process which relies on comparisons among independently running clocks or the dissemination of time from a central source to remote users requires that the enabling time transfer equipment be adequately calibrated for internal delays and other biases. The time transfer process itself is generally not self-calibrating. Instead, calibration usually consists of a procedure or set of procedures that interrupt normal time transfer operations and is consequently performed infrequently. This can lead to subtle calibration errors due to effects such as impedance mismatches at couplings that are changed. Any errors in the assumed values for timing biases enter directly into the results of time transfer users. However, frequency comparisons and syntonization are sensitive only to changes in the physical characteristics of the time delay mechanisms and to variations in the accuracy of successive bias measurements, but not to uncertainty in the mean bias.

Given the very prominent role GPS has assumed for high-accuracy time and frequency comparisons and dissemination, considerable attention has been devoted to characterizing and calibrating GPS timing hardware. This is obviously a critical part of the work coordinated by the BIPM to form UTC/TAI. For historical reasons, most such calibration efforts have been for common-view, single-frequency timing receivers. Only recently have dual-frequency geodetic receivers drawn careful study, and so far, for only one model [1]. Many of the newer time transfer systems in use, including two-way satellite methods, have been calibrated differentially to the older common-view systems. Generally, the relatively few absolute delay calibrations have estimated uncertainties of approximately 3 ns whereas differential techniques are usually able to transfer calibrations among nearby systems with a smaller error.

Here we investigate the use of the station and satellite clock products of the IGS, together with published results from the BIPM, to infer empirical calibration biases for a subset of the IGS stations colocated at timing laboratories (see Figure 1). No additional direct hardware measurements are needed. Instead, we rely on the calibration of prior operational time transfer hardware already in use at the labs, effectively extending existing calibrations to the new geodetic receiver systems.

Possible uses for this method include validation of independent measurements of hardware biases. Indeed, such checks are necessary in order to avoid potential discontinuities in UTC/TAI when time transfer operations are switched between techniques. The method can also be exploited to continuously monitor intra-laboratory timing stability in a completely non-disruptive way without requiring any additional measurements. Our main interest, however, is to improve the steering of the IGS internal timescale [2] to UTC over intervals of about 1 d and longer, which is currently limited by the use of broadcast GPS time. To do so will also require predictions of the evolution of laboratory UTC offsets since the latest issue of Circular T [3]. These applications will be considered in future studies. Our interest here is to examine the stability of the empirical station bias results and to determine whether a large enough set of IGS stations can be usefully calibrated as these are preconditions to any practical applications.

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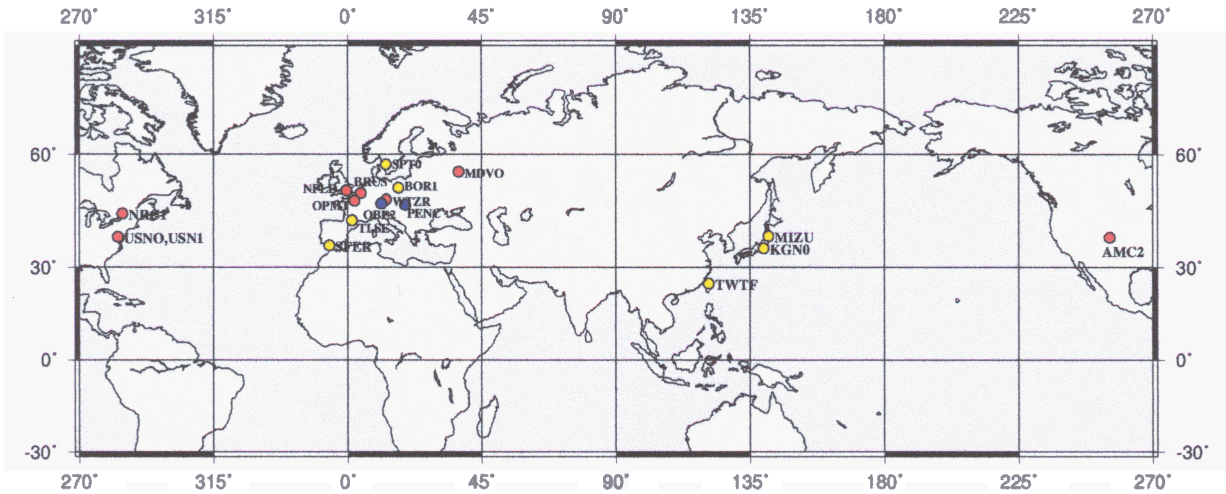

Fig. 1. Geographical distribution of IGS stations currently (May 2003) colocated at timing laboratories. Red denotes stations using hydrogen masers, yellow denotes cesiums, and blue denotes rubidiums.

II. Approach

Consider a geodetic GPS receiver located at a timing lab that contributes regular results to the BIPM and maintains a local realization of UTC, denoted UTC_i. Time transfers to the BIPM currently rely on the common-view GPS method (using single-frequency data and coordinated observing schedules to permit common-mode cancellation of many geodetic effects) or two-way satellite time transfers (TWSTT). Dual-frequency geodetic receivers also operate at numerous timing labs and contribute data to the IGS, but are not yet used for time transfer operations, in part because accurate calibrations are generally lacking. If the geodetic receiver is driven with an external frequency standard closely related to UTC_i, then we can consider the timing bias B_i defined by

$$B_i = \mathrm{CLK}_i - \mathrm{UTC}_i \tag{1}$$

where CLK_i is the time series of clock readings as observed using the geodetic GPS system. Clock results are obtained through a complete geodetic solution consistent with the standards and conventions used by the IGS. The accuracy of such geodetic clock determinations ranges widely, from the formal error level of about 0.12 ns for 24-hour analysis arcs up to nearly 1 ns, depending on the particular station configuration ([4]). Pseudorange multipath is usually the leading source of geodetic clock error although other effects, including temperature-sensitive components, can also be significant.

The biases B_i include both the internal delays within the GPS receiver/antenna hardware producing CLK_i as well as the intra-laboratory offset between the receiver clock circuit and the source of UTC_i. Direct absolute measurements of B_i are non-trivial and have typical uncertainties of several ns [1]. Alternatively, we can empirically estimate a closely related bias, B_i', for those IGS stations with all the following information available:

$$B_i' = (\mathrm{CLK}_i - \mathrm{GPST})_{\mathrm{IGS}} - (\mathrm{UTC} - \mathrm{GPST})_T + (\mathrm{UTC} - \mathrm{UTC}_i)_T \tag{2}$$

where

$(\mathrm{CLK}_i - \mathrm{GPST})_{\mathrm{IGS}}$	=	observed values from the IGS clock products, aligned and referenced nominally to GPS time
$(\mathrm{UTC} - \mathrm{GPST})_T$	=	daily monitor values for GPS time published in the BIPM Circular T
$(\mathrm{UTC} - \mathrm{UTC}_i)_T$	=	5-day values for the offset of the lab i time UTC_i from UTC as published in the BIPM Circular T

By selecting the IGS clock values at or near the midnite epochs used in Circular T and by interpolating (with a cubic spline) the $(\mathrm{UTC} - \mathrm{UTC}_i)$ time series, we can compute B_i' values at nominally daily intervals. Eqn (2) reduces to

$$B_i'(t) = (\mathrm{CLK}_i - \mathrm{UTC}_i) + (\mathrm{GPST}_T - \mathrm{GPST}_{\mathrm{IGS}}) \tag{3}$$

$$= B_i(t) + \Delta\mathrm{GPST}(t) \tag{4}$$

which is equivalent to B_i in eqn (1) if the GPS times observed and reported by Circular T and the IGS are identical. Of course, the empirical estimates of B_i' will only be meaningful if B_i is indeed approximately constant. If, for instance, the timing relationship between the geodetic receiver, CLK_i, and UTC_i is not fixed or if the TAI calibration of UTC_i is unstable, then estimates of B_i' will vary and not be useful.

Considering then only those installations with stable internal configurations, it is necessary to evaluate whether the magnitude of the differences in observed GPS time, ΔGPST(t), are significant. In fact, small differences exist in the IGS and BIPM methods. The BIPM follows the GPS Interface Control Document (used for the broadcast navigation message) and refers its observations of the satellite clocks to the system values for the transmitter antenna to spacecraft center-of-mass offsets, whereas the IGS uses its own set of satellite offsets. The differences are small for the older, more numerous Block II/IIA spacecraft (7.11 cm), but are 1.51 to 1.61 m for the newer Block IIR satellites. The average value of ΔGPST over the full constellation of N satellites is given by

$$\langle \Delta\mathrm{GPST} \rangle \;=\; \frac{1}{N}\sum_{j=1}^{N}(dZ_j(\mathrm{IGS}) - dZ_j(\mathrm{GPS}))/c$$

where c is the speed of light (299,792,458 m/s) and dZ_j are the respective center-of-mass to antenna phase center offsets (in the Earth direction) for each satellite j as used by the IGS and GPS. For the currently active constellation, the long-term average value of $\langle\Delta$GPST$\rangle$ is therefore about −1 ns (varying from −0.92 to −1.3 ns over the past few years), which must be subtracted from B_i' to obtain an unbiased estimate of B_i.

Other differences in the two methods of measuring GPS time do not contribute significantly to the long-term average $\langle\Delta$GPST$\rangle$ but may cause quasi-random variability. Principally, the IGS and BIPM monitor GPS time from different fields of views and may use different subsets of the full constellation. The BIPM observes the satellites only while they are visible above Paris whereas the global IGS tracking network allows the full constellation to be continuously in view. This causes small day-to-day differences. On infrequent occasions, the IGS linear alignment of its clocks to GPS time has malfunctioned in its Rapid products (those issued about 17 hours after each observed day). This effect will compound the random differences.

Another difference is the use of the L1 C/A pseudorange by the BIPM while the IGS uses P1 and P2 codeless pseudoranges. Due to delays in the signal processing hardware in the transmit systems, small satellite-specific biases occur between the P1 and C/A observables. However, this has no net effect on $\langle\Delta$GPST$\rangle$ because the (P1 - C/A) bias convention adopted by the IGS has zero mean over the full constellation.

The quasi-random variations about the $\langle\Delta$GPST$\rangle$ average can be compensated if $B_i'(t)$ time series are simultaneously available for more than one station because the same ($\mathrm{GPST}_T - \mathrm{GPST}_{\mathrm{IGS}}$) deviations from the mean will affect each station bias estimate by the same amount. That is, equation (4) can be rewritten

$$B_i(t) = B_i'(t) - (\langle\Delta\mathrm{GPST}\rangle + \delta(t)) \tag{5}$$

where we separate the effect of GPS time differences into a static part that can be well estimated as described above and a variable part, $\delta(t)$, that is common to $B_i'(t)$ determinations from all labs at time t. Both contributions are small, of the order of 1 ns. When time series of empirical station timing biases, $B_i'(t)$, are available for several independent stations, the $\delta(t)$ variations can be determined by an iterative process that seeks to minimize the variance of $B_i(t)$ for all the stations simultaneously. We have implemented such a procedure here to refine our raw $B_i'(t)$ measurements to give improved estimates of $B_i(t)$.

III. Results and Discussion

Table I summarizes our basic findings, including means and RMS values for both the raw empirical B_i' estimates and the corrected B_i biases. Time ranges for individual stations are discontinuous because of changes in station configuration or because of resets of the internal receiver clocks. No results are given for MDVO, MIZU, NRC1, OBE2, OPMT, PENC, PTBB, SFER, SPT0, TLSE, or WTZR either because of insufficient data or because the geodetic receiver is not locked to the local UTC_i standard. The AMC2, BRUS, NPLD, USN1, and USNO receivers are all equipped with external hydrogen maser frequency standards, while BOR1, KGN0, and TWTF use cesium standards. Generally, the stability of the B_i bias results is poorer for the latter stations, probably because of inherently larger scatter in the ($\mathrm{UTC} - \mathrm{UTC}_i$) offsets for those labs.

Figures 2 and 3 show examples of the time variations of $B_i'(t)$ and $B_i(t)$ estimates for six stations during the period 14 August 2002 to 31 March 2003. We have used the IGS Rapid and Final clock products independently as a confidence check. However, more robust estimates could be made by combining the two observational series into a single calibration bias estimate for each station, something that should be done in any operational use of this method. Table II shows excellent agreement between the bias estimates from the Rapid and Final clocks. In only one case, USN1, does the bias difference exceed the RMS scatter of the two estimates, probably because of a drift in the local UTC_i calibration (see more below) combined with sparse Final series data. The average overall Rapid-Final agreement, weighted by the individual RMS scatters, is −0.11 ns with an RMS scatter about that of 0.89 ns.

Visual inspection of Figures 2 and 3 illustrates the effectiveness of accounting for small temporal variations in the observed GPS time differences ($GPST_T - GPST_{IGS}$) about its long-term mean. Even after this correction procedure, some residual drifts and scatter are sometimes apparent. For instance, the three stations linked to UTC(USNO), namely AMC2, USNO, and USN1, all show a common increase in bias, albeit small, over the August 2002 - March 2003 period. We interpret this as a calibration drift in the time transfer of UTC(USNO) to BIPM since each of these three receivers is at a different physical location.

In two cases we have the opportunity to compare our empirical bias estimates with independent, absolute calibration values. For AMC2 and USN1 calibration offsets have been applied to the raw pseudorange data so that the nominal GPS clock offsets should be zero with respect to UTC(USNO). (For further information, refer to the IGS station log files at http://igscb.jpl.nasa.gov/igscb/station/log/.) Our empirical biases for AMC2 (after modifications in July 2002 to apply the absolute calibrations to the data) are 4.2 and 5.1 ns with scatters of 1.4 ns each, while the biases for USN1 are 1.4 and 3.0 ns with scatters of 0.8 and 1.0 ns, respectively (see Table I). These results are within the calibration error budget for USN1 ([1]) but are marginal for AMC2. At least part of the discrepancy for AMC2 could possibly be due to a bias in the AMC2 master clock calibration relative to UTC(USNO), since AMC2 is physically remote from USNO (Colorado Springs, CO, versus Washington, DC). A more controlled and detailed study would be needed to determine whether the empirical and absolute bias differences are significant for AMC2. It would also be worthwhile to compare our empirical calibrations against side-by-side relative instrumental calibrations being coordinated by the BIPM for some of the same receivers using a roving standard receiver.

IV. Conclusions

We have demonstrated a method to determine empirical station timing biases for geodetic receivers located at timing laboratories and found that it can be effective at a level better than absolute calibration accuracies. That is, the repeatabilities of daily bias estimates can be 1 to 2 ns provided that the geodetic receiver is closely linked to the local UTC_i realization and the configuration is otherwise stable. This approach effectively extends the existing calibration of a timing lab's TAI system differentially to a colocated geodetic receiver system without need of any additional local measurements and without interrupting the operations in any way. Using this method, we plan to explore possible improvements in the near real-time steering of the IGS timescale to track UTC more closely.

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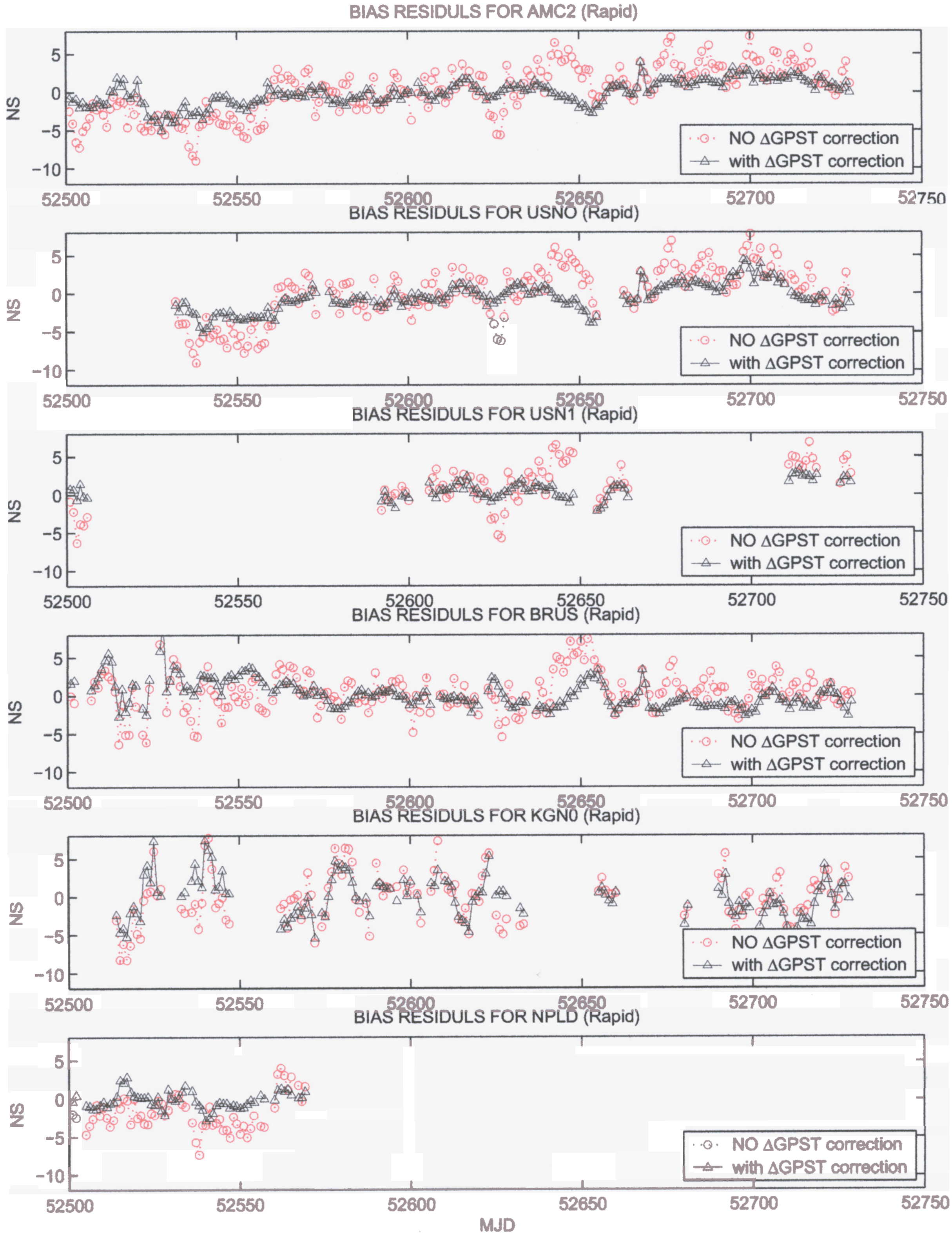

Fig. 2. Station bias residuals (ns) derived using the IGS Rapid clock products for six stations, AMC2 (Colorado Springs, USA), BRUS (Brussels, Belgium), KGN0 (Koganei, Japan), NPLD (Teddington, UK), and USN1 and USNO (both in Washington, DC, USA) during the period 14 August 2002 (MJD 52500) through 31 March 2003 (MJD 52729). Each plot shows the bias residuals before and after the ΔGPST correction.

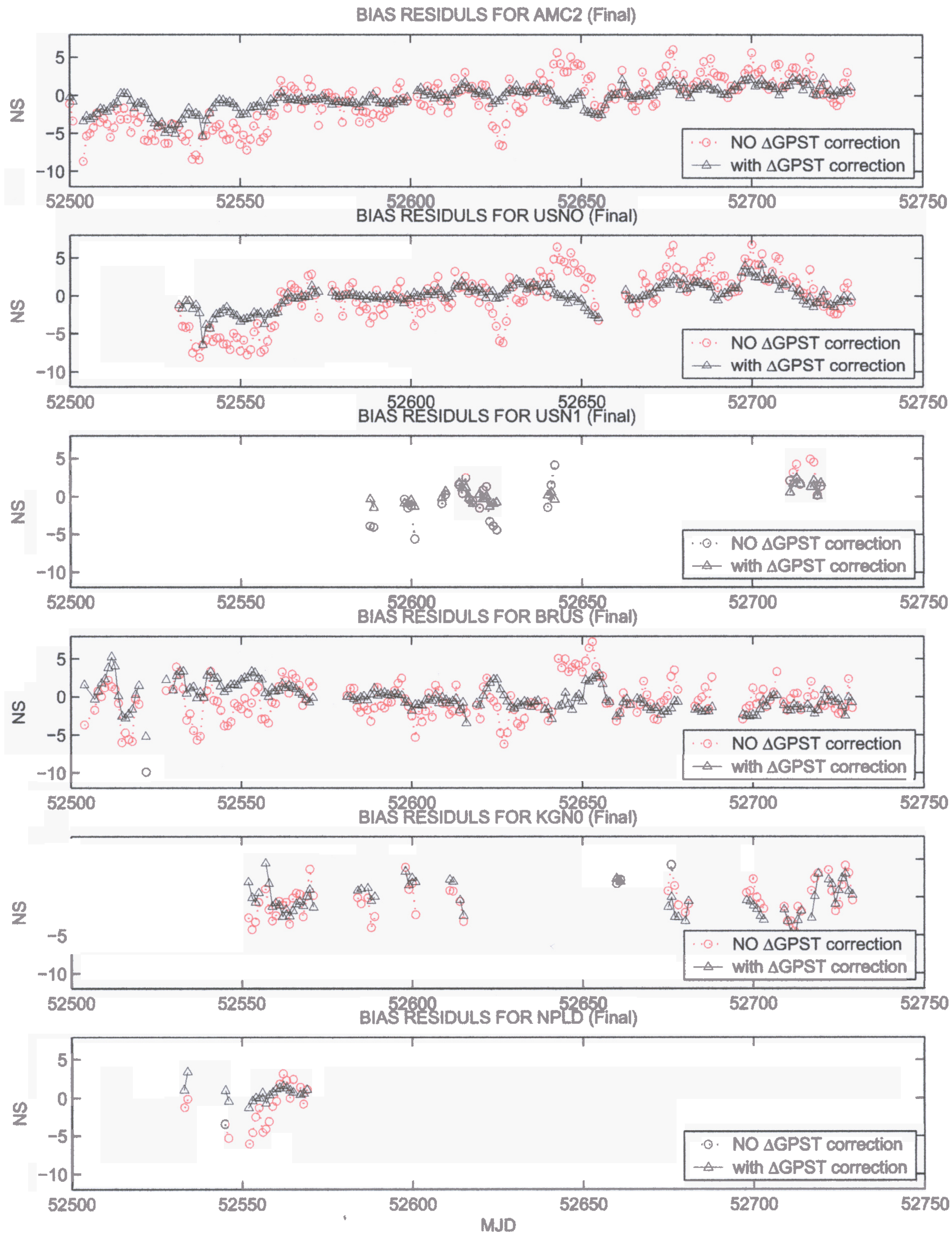

Fig. 3. Same as Figure 2 except using the IGS Final clock products.

Empirical Station Biases (units = ns)
(November 2000 - April 2003)

IGS	MJD	# Values		Mean B_i'		RMS B_i'		Mean B_i		RMS B_i	
site	Range	Rapid	Final	Rapid	Final	Rapid	Final	Rapid	Final	Rapid	Final
H-maser frequency standards:											
AMC2	52117-52437	299	42	-451.40	-452.38	2.87	1.47	-450.72	-452.02	1.93	0.75
AMC2	52480-52729	247	230	2.71	4.26	2.69	2.60	4.19	5.10	1.39	1.41
BRUS	52213-52374	136	4	454.83	452.77	3.46	0.30	454.42	453.68	1.31	0.06
BRUS	52420-52729	292	238	585.83	586.15	2.59	2.42	585.81	586.89	1.24	1.43
NPLD	52133-52569	376	112	-8075.90	-8075.78	2.82	3.33	-8074.74	-8074.25	1.35	2.33
USN1	52467-52729	95	30	0.76	1.65	2.24	1.89	1.40	3.04	0.76	1.03
USNO	51922-51986	60	65	-69.71	-69.69	2.43	2.52	-68.78	-68.85	2.15	2.39
USNO	52069-52129	61	61	619.04	619.53	3.25	3.97	620.04	620.53	3.25	3.97
USNO	52131-52158	26	28	-157.25	-157.72	2.27	2.36	-155.08	-156.46	0.30	2.24
USNO	52180-52256	72	73	-69.07	-68.83	2.24	1.93	-68.30	-67.80	0.91	1.62
USNO	52260-52339	74	80	5.91	5.89	1.55	1.38	7.24	6.75	0.45	1.01
USNO	52360-52529	159	164	85287.15	85287.19	1.62	1.56	85288.65	85288.68	0.83	1.39
USNO	52532-52729	185	187	639.92	639.59	3.33	2.69	641.59	641.72	2.01	1.21
Cesium frequency standards:											
BOR1	51854-52020	60	54	-2955.91	-2955.26	11.94	12.68	-2955.00	-2954.49	11.77	12.59
BOR1	52251-52296	34	45	-353.05	-352.91	2.75	2.02	-353.19	-353.19	1.49	0.98
BOR1	52504-52531	26	28	31.72	31.15	3.31	2.62	34.40	33.77	2.88	2.32
BOR1	52611-52678	56	60	120.79	121.23	3.98	3.51	120.32	121.26	1.92	1.72
BOR1	52693-52724	32	31	-25.63	-25.60	2.63	2.18	-25.69	-25.73	1.54	1.77
KGN0	52421-52729	168	103	-28.95	-29.26	3.43	2.68	-27.92	-28.31	2.64	2.44
TWTF	52400-52453	41	34	298.87	298.93	4.91	6.13	301.34	301.33	4.91	5.35
TWTF	52483-52562	68	79	381242.55	381243.81	4.64	3.66	381245.16	381246.47	4.15	3.47
TWTF	52563-52729	160	166	288.45	289.84	7.69	9.05	288.27	290.12	7.42	8.60

No results are given for MDVO, MIZU, NRC1, OBE2, OPMT, PENC, PTBB, SFER, SPT0, TLSE, or WTZR because of insufficient data or because the geodetic receiver is not locked to the local UTC_i standard.

TABLE I

Empirical Station Bias Rapid - Final Differences (units = ns) (November 2000 - April 2003)			
IGS site	MJD Range	B_i Differences (Rapid - Final)	RSS(RMS)
AMC2	52117-52437	1.30	2.12
AMC2	52480-52729	-0.91	1.83
BOR1	51854-52020	-0.51	12.29
BOR1	52251-52296	0.00	1.78
BOR1	52504-52531	0.63	3.70
BOR1	52611-52678	-0.94	2.58
BOR1	52693-52724	0.04	2.35
BRUS	52213-52374	0.74	1.31
BRUS	52420-52729	-1.08	1.89
KGN0	52421-52729	0.39	3.59
NPLD	52133-52569	-0.49	2.69
TWTF	52400-52453	0.01	7.26
TWTF	52483-52562	-1.31	5.41
TWTF	52563-52729	-1.85	11.36
USN1	52467-52729	-1.64	1.28
USNO	51922-51986	0.07	3.21
USNO	52069-52129	-0.49	5.13
USNO	52131-52158	1.38	2.26
USNO	52180-52256	-0.50	1.86
USNO	52260-52339	0.49	1.11
USNO	52360-52529	-0.03	1.62
USNO	52532-52729	-0.13	2.35

TABLE II