First Evaluation of a Rapid Time Transfer within the IGS Global Real-Time Network

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***Abstract*—This paper presents a preliminary assessment of the quality of station clock states, estimated in "near-real-time" by the process running at Natural Resources Canada (NRCan). The evaluation is mainly of the short and long-term frequency stability and the accuracy thereof with respect to the IGS Rapid and Final clock products, provided by the International GNSS Service (IGS). The aim of this work is to evaluate the feasibility of time and frequency transfer in real-time and to show the potential of such a process once access to a global IGS network of real-time GPS tracking stations becomes a reality.**

I. A Real-Time Time Transfer

A. The IGS Real-Time network

The Real-Time Working Group (RTWG) has been created in 2002 within the International GNSS Service (IGS). The role of the RTWG is to develop required infrastructure and processes for the real-time delivery of high-rate GNSS data to analysis centers and the dissemination of real-time GNSS products [1].

A subset of the IGS network of stations has been upgraded to allow real-time distribution of GPS data, forming a prototype real-time network (RTIGS). With the contribution of 10 international agencies, the number of RTIGS participating stations is now on the order of 30.

As shown in Fig. 1, several institutions involved in precise time and frequency applications contribute to the RTIGS. In particular, the Time and Frequency Department of Istituto Elettrotecnico Nazionale (IEN), Torino, Italy, has been contributing data from its "IENG" IGS station since November 2004. This station is directly referenced to the Italian realization of UTC (Universal Time Coordinated), namely UTC(IEN).

B. Real-Time estimation of receiver clock

Natural Resources Canada (NRCan) has been computing real-time wide-area differential GPS corrections for the last ten years. These corrections, known as GPS·C [2], allow real-time Canadian users of GPS to correct for errors in the broadcast satellite position and clock states for improved positioning capacity. NRCan's most recent development on GPS·C uses GPS code and carrier-phase observations to increase the precision of the corrections. Two by-products of the estimation process are station local zenith tropospheric delays and receiver clock offsets.

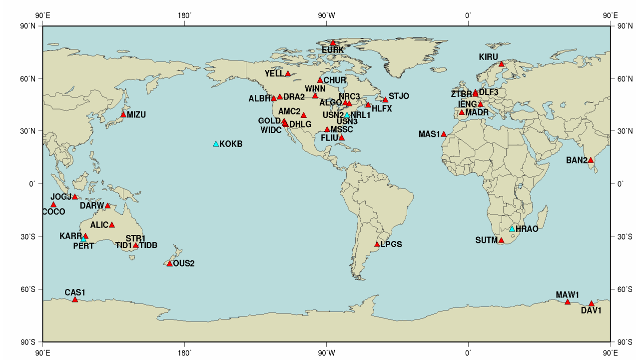

Figure 1. RTIGS network stations (red triangles) along with LEO network stations (blue triangles).

Although this code and carrier-phase based computation process is run continuously from real-time station data streams to generate corrections and station parameters at 2-second intervals (synchronized with the GPS even second) with a delay of a few seconds, NRCan is also testing the process in "near-real-time", thus taking advantage of an improved global distribution of stations. The stations include a selection of those in the RTIGS network, complemented with stations from the IGS Low Earth Orbiters (LEO) network to provide up to 30 stations. The real-time-ready estimation process is executed every 15 minutes in a continuous fashion with a current delay of 2 hours (allowing for the acquisition of the required LEO network data), yielding satellite and station parameters at 2 seconds interval.

All estimated satellite and station clock offsets are referenced to a system Virtual Reference Clock (VRC). At each solution epoch, a station is selected "on-the-fly" as time reference and its clock offset is fixed to a value predicted from a two-states model. The choice of the reference station is based on an operator-selectable priority list as well as real-time-derived quality estimates such as detected receiver clock resets and agreement statistics between two-states clock models computed over different preset intervals. The estimated epoch corrections to the *a priori* clock offsets are then used in a timescale ensembling algorithm to generate a VRC correction that is applied to all clocks. The two-states clock models (one per station) are evaluated continuously using the real-time clock estimates and its ensemble is kept aligned to GPS time by applying common corrections as required [2,3].

The station serving as time reference has its formal standard deviation set to 0. This means that the formal standard deviation of other stations results from the combination of the standard deviations of both the specific station and the reference station.

C. A "rapid time transfer" scenario

Aiming to evaluate the feasibility of time and frequency transfer in "real-time" using geodetic GPS receivers and to show the potential of such a process, a preliminary assessment of NRCan's real-time receiver clock states estimates has been performed, mainly evaluating the accuracy and frequency stability (short and long-term) with respect to the IGS Rapid and Final clock products [4].

For this purpose, a data set spanning 2.5 months (16th November 2004, MJD 53325, to 31st January 2005, MJD 53401) of clock offset estimates for selected RTIGS and LEO stations was extracted from NRCan's "near-real-time" process with a 30-seconds sampling rate. The worldwide stations included in the dataset are shown in Table I and had to satisfy the following criteria:

- GPS receiver connected to an external oscillator (H-maser preferred),
- GPS hardware hosted in national timing laboratories,
- availability of a large quantity of high-quality data (GPS observations).

The NRCan "real-time" clock solution is hereafter labeled "RT". For the time period of the dataset, the VRC ensembling correction was disabled in the process, limiting the time estimation to the selection and use of the reference station and the two-states clock models estimation.

II. CHARACTERIZATION OF REAL-TIME ESTIMATES

A. RT estimates availability

As shown in Table II, the RT clock estimates availability is quite good, typically higher than IGS Rapid and as good as IGS Final products. It is worth noticing the reduced availability of IENG station in IGS Rapid products that is due to the current "weakness" of IENG for rapid clock estimates, which data are processed by only two IGS Analysis Centers (ACs), namely CODE and NRCan. In contrast, three ACs – CODE, NRCan and MIT – use IENG data for Final clock products, thus resulting in a higher availability figure for IENG.

TABLE II. RT ESTIMATES AVAILABILITY

Station	RT (%)	IGS Rapid (%)	IGS Final (%)	Reference (%)
ALGO	98.2	97.1	99.9	0.5
USN3	97.6	99.9	94.7	65.2
IENG	96.1	63.1	99.5	0.0
AMC2	91.8	87.0	92.0	27.2
MIZU	88.5	80.1	97.7	0.0
TIDB	85.7	83.6	86.5	0.04
PERT	80.7	91.6	93.3	0.0
HRAO	79.5	84.2	86.9	0.0
KOKB	77.7	72.5	73.2	0.0

TABLE I. SELECTED STATIONS AND ASSOCIATED EQUIPMENT

Station	City	Country	Receiver Type	Frequency standard
ALGO	Algonquin Park	Canada	AOA BENCHMARK ACT	H-Maser
AMC2	Colorado Springs	U.S.A.	ASHTECH Z-XII3T	H-Maser
HRAO	Krugersdorp*	South Africa	ASHTECH Z-XII3T	H-Maser
IENG	Torino	Italy	ASHTECH Z-XII3T	Cesium
KOKB	Kokee Park*	U.S.A.	ASHTECH UZ-12	H-Maser
MIZU	Mizuzawa	Japan	AOA BENCHMARK ACT	Cesium
PERT	Perth*	Australia	ASHTECH UZ-12	Cesium
TIDB	Tidbimbilla	Australia	ASHTECH Z-XII3T	H-Maser
USN3	Washington D.C*	U.S.A.	ASHTECH Z-XII3T	H-Maser

* Contributing to IGS LEO network.

B. *RT estimates standard deviation*

As mentioned above, in the RT process any station can be chosen "on-the-fly" as reference station and it is indicated by an associated formal standard deviation set to 0 (see statistics in Table II). The formal standard deviation of non-reference stations is normally at the level of 30 ps. However some real-time estimates are associated with larger standard deviations (Fig. 2), indicative of anomalies. These usually result from tracking difficulties, such as loss of lock on all satellites or pseudorange-phase inconsistencies. In order to remove potentially anomalous data, a preliminary "standard deviation filtering" should be applied, preferably able to adapt to specific station data noise levels. Many kinds of filter can be used, such as a simple "mean+3sigma" filter or a more robust MAD (Median of the Absolute Deviation) based filter [5,6], with an appropriate tuning process.

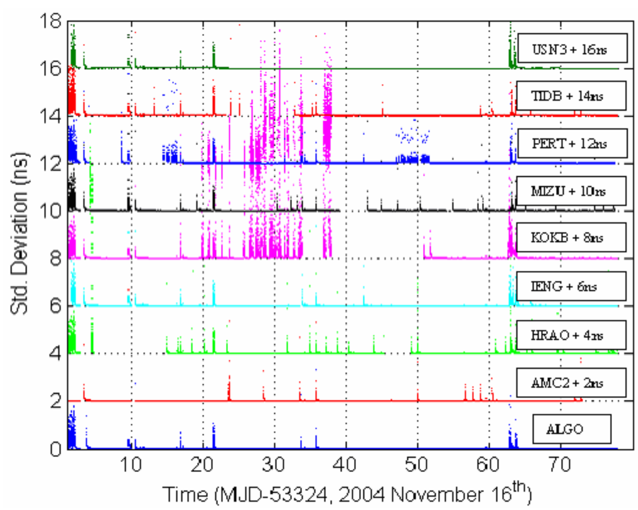

Figure 2. Standard deviations associated to RT estimates for a single station. For purpose of plotting an offset has been added to each series.

Also, from the analysis of the single station clock estimates, it is very easy to infer that some real-time estimates present anomalous trends, although their associated standard deviation is not anomalous. An example of such anomalous trend is shown in Fig. 3 for AMC2 station, especially from 60th to 70th day. These kinds of problem are normally the result of problems with the VRC management and thus disappear when differencing clock estimates between stations.

C. *Comparison with IGS clock products*

In order to evaluate the RT capabilities in time transfer applications, a number of baselines have been selected (summarized in Table III) and comparisons with IGS Rapid/Final clock products have been performed.

As shown in Fig. 4 for the ALGO-AMC2 baseline, the NRCan's RT process provides continuous estimates, whereas significant day-boundary jumps affect IGS clock products, due to the daily batch estimation performed by IGS. Both estimation methods, however, follow the same general trend.

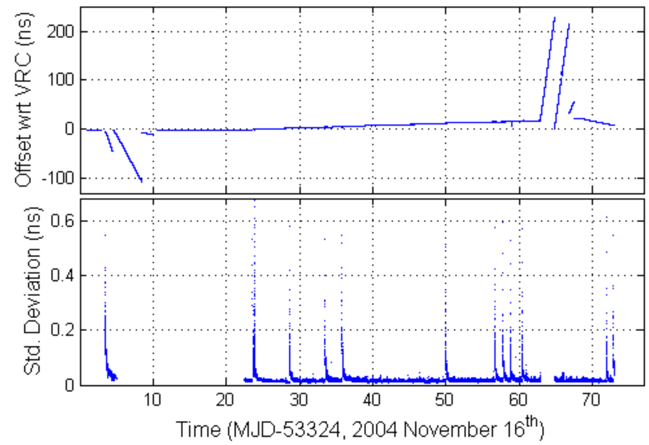

Figure 3. RT estimates anomalous trend (upper plot) for AMC2 station and associated standard deviation (lower plot).

TABLE III. SELECTED BASELINES FOR RT ESTIMATES EVALUATION

Baseline	Length (km)
USN3-ALGO	785
ALGO-AMC2	2293
USN3-AMC2	2360
PERT-TIDB	3053
KOKB-AMC2	5349
IENG-ALGO	6093
IENG-USN3	6418
MIZU-AMC2	8346
IENG-MIZU	8759
TIDB-AMC2	9245
IENG-AMC2	9439
HRAO-AMC2	11903
IENG-TIDB	12282

Besides, some daily fluctuations can be noticed in RT estimates, as clearly shown by the double differences (DDs) with IGS Final clock products (Fig. 6). This situation is an open issue but it may be related with hardware temperature dependency (mainly outdoor units, such as the antenna) particularly exhibited by RT estimates. It follows that RT estimates seem then to be a more responsive estimation method than IGS, seemingly able to track the actual behavior of the station hardware (antenna, cable, receiver, frequency standard).

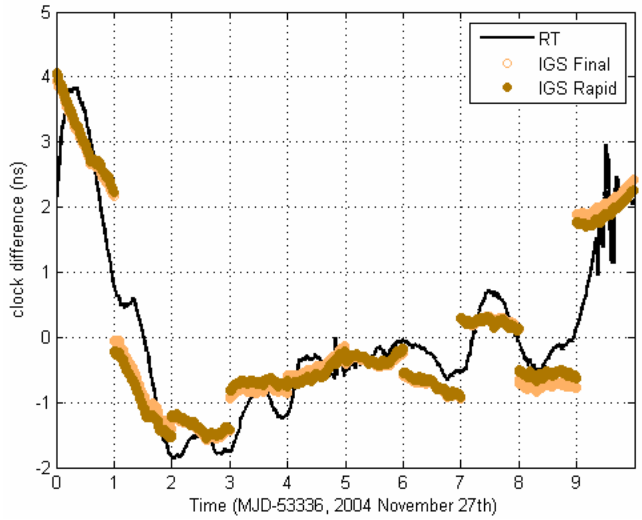

Figure 4. Comparison between RT estimates and IGS clock products for the ALGO-AMC2 baseline. A common linear fit has been removed for purpose of plotting.

Fig. 6 gives the DDs between RT estimates and IGS Final clock products for six of the selected baselines in Table III. It can be observed that they fall within ±1ns, except for baselines involving ALGO station that exhibit larger fluctuations (3ns), maybe due to temperature-related pseudorange bias.

A significant bias (about -0.9 ns) in IENG-MIZU baseline and, in general, in all baselines involving MIZU, is also noticed. This fact is under investigation, but seems to come out from ambiguities management in RT process resulting in code residuals divergence.

More statistical information regarding the residuals between RT and IGS are summarized in Table IV. Very good results are achieved, especially considering that RT estimates are generated with a very short latency time (2 hours, potentially real-time), with respect to IGS products, that are available after a few days (e.g., the Final combination is available at 12 days latency).

TABLE IV. STATISTICAL INFORMATIONS FOR SELECTED BASELINES

Baseline	DD RT vs IGS Rapid		DD RT vs IGS Final	
	Average (ns)	**RMS (ns)**	**Average (ns)**	**RMS (ns)**
IENG-USN3	0.287	0.410	0.226	0.412
USN3-AMC2	0.019	0.350	-0.048	0.363
TIDB-AMC2	-0.009	0.349	-0.065	0.351
IENG-MIZU	-0.880	0.950	-0.833	0.900
IENG-ALGO	0.109	1.179	0.197	1.058
ALGO-AMC2	0.036	1.042	-0.017	1.045

D. *Frequency stability*

Other important information about RT estimates can be obtained by a frequency stability analysis (in terms of Allan deviation), for a set of selected baselines. Comparison results versus IGS clock products are given in Fig. 5.

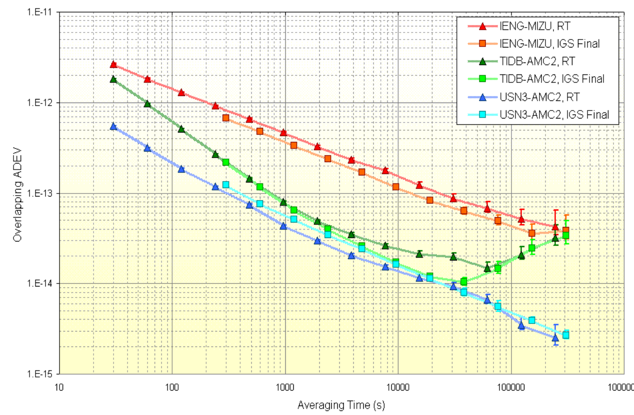

Figure 5. Frequency stability comparison between RT estimates (triangles) and IGS Final clock products (squares) for three selected baselines over the period from December 20th, 2004 (MJD 53359) to January 8th, 2005 (MJD 53378).

It follows that the different frequency standards connected to the receivers can be clearly distinguished from RT estimates. As expected, the Cesium (Cs) based baseline (i.e., IENG-MIZU) show a white frequency noise according to industrial Cs specifications. In contrast, H-maser based baselines (e.g., USN3-AMC2) reveal a short-term instability higher than nominal (typically below 10^{-14} for observation times up to 10^{5} seconds), possibly due to intrinsic noise affecting the GPS permanent stations (e.g., signals distribution chain, receiver's hardware, antenna), that is a few parts in 10^{-14} at 300 seconds.

However, it is worth noticing that no significant difference between RT estimates and IGS Final clock products are observed in terms of stability.

Also, concerning the TIDB-AMC2 baseline, a strange trend of the Allan deviation can be observed in the short-term, that diverges from the typical figure of a H-maser oscillator which is indeed the reference for both stations. This fact (exhibited by both RT and IGS) is probably due to the inherent high short-term noise of the TIDB station's infrastructure.

At last, in Fig. 7 the dynamic Allan deviation (DADev) [7] for the USN3-AMC2 baseline is given. The DADev provides a quantity that characterizes the variation of the stability of an atomic clock over time (e.g. non-stationary conditions of noise).

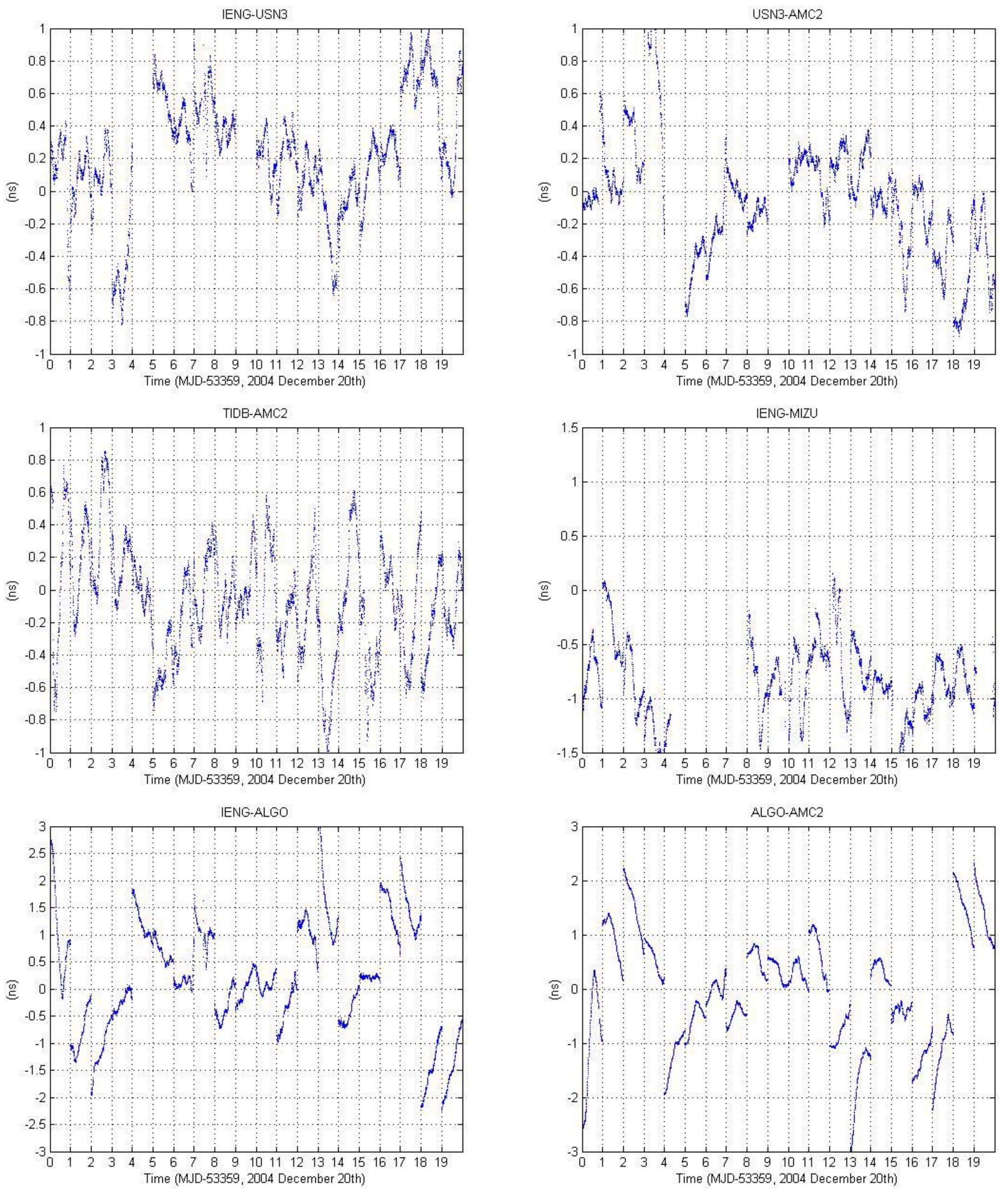

Figure 6. Double differences between RT estimates and IGS Final clock products for six selected baselines, for the period from December 20th, 2004 (MJD 53359) to January 8th, 2005 (MJD 53378).

Watching the cross-sections of DADev at different averaging times (Fig. 7, lower plot), it is easy to infer that on the second-half of MJD 53362 (December 23rd, 2004) some problem occurred, because the smoothed "bump" of the stability for long averaging times. This assumption is confirmed in Fig. 8, where an anomalous "saw-tooth" behavior can be observed on both RT estimates and IGS clock products (representing then the actual performance of one of the two stations and not an artifact of the processing method).

For this reason the DADev can also be used to monitor in real-time the performance of station hardware or RT processing. Moreover, DADev could assist in VRC ensembling to improve its stability.

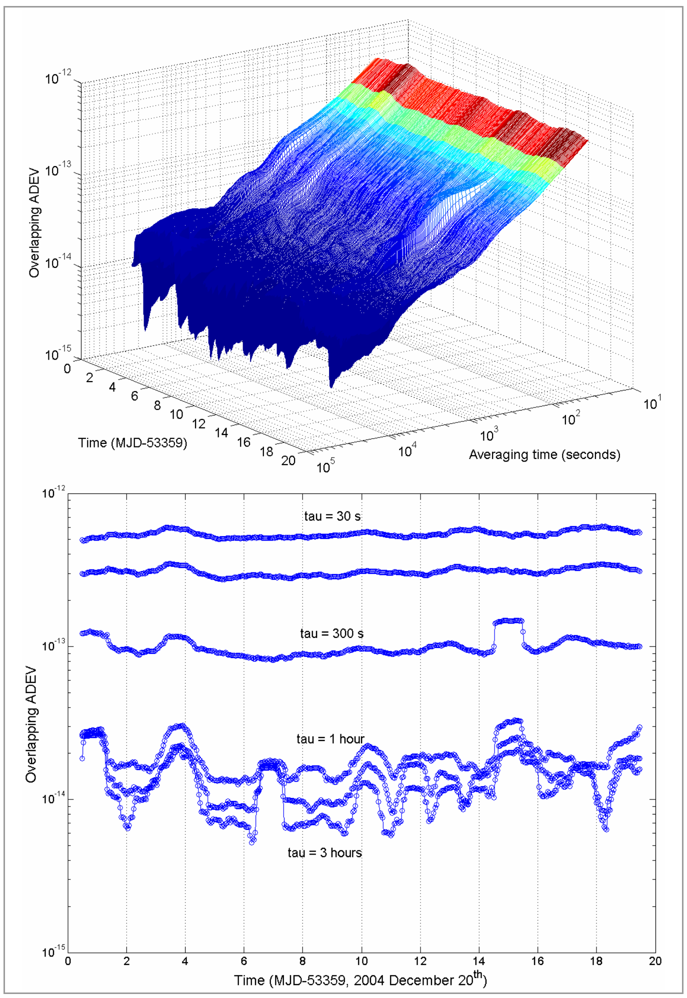

Figure 7. Dynamic Allan deviation for USN3-AMC2 baseline (upper plot) and its cross-sections (lower plot) at different averaging times.

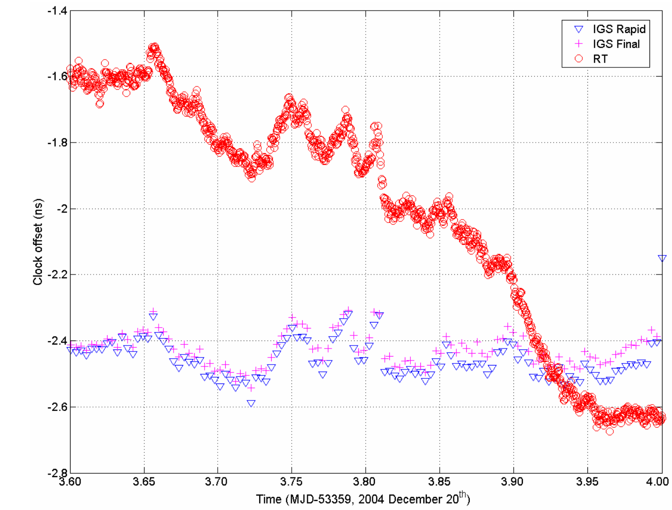

Figure 8. Comparison between RT estimates and IGS clock products for the USN3-AMC2 baseline in the second-half of MJD 53362.

III. Putting RT in Perspective

Two of the RT stations considered in this analysis (USN3 and IENG) are operated at timing laboratories, namely USNO in Washington D.C., USA, and IEN in Turin, Italy, and are thus collocated with other time-transfer means. They are directly referenced to local realization of UTC, i.e. UTC(k), thus allowing RT to provide an estimation of the UTC(USNO) to UTC(IEN) offset time, plus a calibration constant (i.e., electrical delays of hardware).

This allows to directly compare the RT estimates with the UTC(USNO) to UTC(IEN) offset provided by BIPM Time Section in monthly Circular T [8]. For the period 16th November, 2004 (MJD 53325) to January 1st 2005 (MJD 53371), the estimates (300 seconds spaced) for USN3-IENG baseline are also available from ongoing experimental activity to assess the time transfer capability of the Precise Point Positioning (PPP) technique [9]. Since RT estimates are computed using the data streaming from the same geodetic GPS receivers providing RINEX data files for PPP processing, the RT and PPP method are not completely independent and are also affected by the same uncompensated calibration delay.

As a consequence, a direct comparison of RT, PPP and BIPM data can be performed on the time link between USNO and IEN laboratories. Moreover, a TWSTFT link is regularly operated between these timing laboratories, so a fourth source of data is available for purpose of comparisons. Fig. 9 reports the four resulting time series (RT at 30 seconds, PPP at 300 seconds, TWSTFT at 1 day and BIPM at 5 days), where an offset has been added to the un-calibrated TWSTFT series for purpose of plotting.

It can be observed that, apart from calibration delays, the RT estimates for USN3-IENG baseline are consistent at ns-level with both BIPM Circular T and TWSTFT data, and at sub-ns level with PPP computed using IGS Final products, but providing a strongly reduced latency (2 hours or even less).

Besides, the resulting bias between geodetic techniques (RT and PPP) and BIPM data represents the differential delay of geodetic equipment hosted at both USNO and IEN laboratories (e.g., antenna, cable, receiver…).

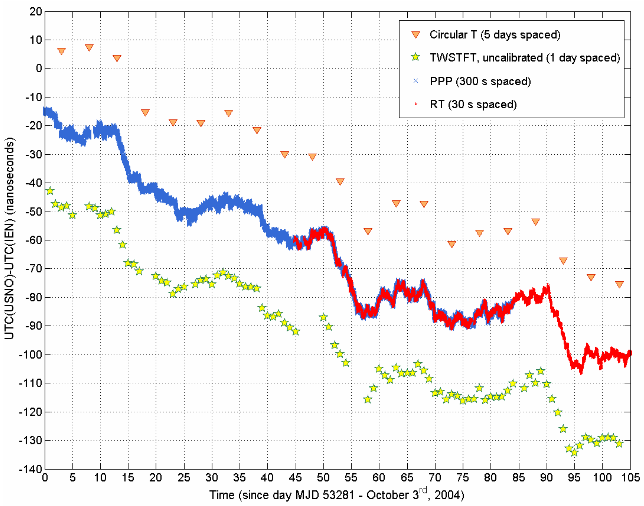

Figure 9. Time offset between UTC(USNO and UTC(IEN) as estimated using RT, PPP, TWSTFT and BIPM data for the 105-days period from October 3rd, 2004 (MJD 53281) to January 16th, 2005 (MJD 53386).

IV. CONCLUSIONS

In this work, an evaluation of the feasibility of time and frequency transfer in "real-time" using geodetic GPS receivers has been addressed, dealing with the real-time (RT) receiver clock states estimates computed by the NRCan's "near-real-time" process using 30 globally distributed stations.

The results reported in this paper show that RT estimates are consistent with IGS Final clock products in terms of availability, accuracy (at ns-level) and frequency stability, but with much reduced latency, currently few hours and potentially a few minutes.

In addition, a qualitative survey of the time link between USNO and IEN timing laboratories reveals that RT estimates are potentially consistent at ns-level with both BIPM Circular T and TWSTFT data, but providing again a reduced latency.

Nevertheless, preliminary filtering of the RT clock estimates, based on computed formal standard deviations, is required to remove potentially anomalous data. Useful information can be also obtained using the DADev, which could be applied as real-time dynamic detector of degraded performance of station hardware or RT processing. Moreover, DADev could assist in VRC ensembling to improve its inherent stability.

ACKNOWLEDGMENT

International agencies contributing data to the RTIGS network and their staff are acknowledged for provision and support of real-time data access.

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