LONG BASELINE COMPARISONS OF THE BRAZILIAN NATIONAL TIME SCALE TO UTC(NIST) USING NEAR REAL-TIME AND POST-PROCESSED SOLUTIONS

Michael A. Lombardi and Victor S. Zhang
Time and Frequency Division
National Institute of Standards and Technology
Boulder, CO 80305
email: *lombardi@nist.gov*

Ricardo J. de Carvalho
Time Service Division
National Observatory
Rio de Janeiro, Brazil
email: *carvalho@on.br*

ABSTRACT

We present the results of C/A code common-view Global Positioning System (GPS) comparisons between the UTC(NIST) time scale, located at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, and the Brazilian national time scale, UTC(ONRJ), located at the National Observatory (ONRJ) in Rio de Janeiro, Brazil. The two time scales are separated by a long baseline of ~8600 km. The comparisons were made with measurement systems developed for the Sistema Interamericano de Metrologia (SIM) comparison network, a network designed to intercompare the national standards of time and frequency in North, Central, and South America. Data from four different types of measurements are presented, two of which involve near real-time processing and two that involve post processing. The near real-time comparisons apply the ionospheric corrections broadcast by the GPS satellites to the measurements recorded at both sites. The data are then reduced both as "classic" common-view, where only the satellites simultaneously in view at both sites are used in the solution, and as all-in-view, where all of the satellites received at both sites are used in the solution. The post-processed comparisons apply measured ionospheric delay corrections to the measurements recorded at both sites before proceeding with the common-view and all-in-view data reduction. The results obtained from each of the measurements are compared and summarized.

I. INTRODUCTION

The *Sistema Interamericano de Metrologia* (SIM) is a regional metrology organization that extends throughout North, Central, and South America, and the Caribbean region. The national metrology institutes (NMIs) of 34 nations belong to SIM, and roughly half maintain (or are in the process of starting) a national time and frequency laboratory. The SIM common-view GPS comparison network was designed to make it easy for SIM laboratories to compare their time standards. It utilizes eight-channel

L1-band GPS receivers, time interval counters with less than 0.1 ns resolution, and Internet file transfer to collect and process common-view measurements in near real-time. Currently (November 2007), nine NMIs are members of the SIM network, and each has a measurement system (Figure 1) installed in their time and frequency laboratory. These laboratories can view the results of comparisons between their time standard and all of the other standards in the network with any Java-enabled web browser. The measurement results are updated every 10 minutes. **[1]**

Figure 1. The SIM measurement system and antenna.

The SIM network began operation in June 2005, continuously comparing the national time scales of the Centro Nacional de Metrologia (CNM) in Queretaro, Mexico; the National Research Council (NRC) in Ottawa, Canada; and NIST in Boulder, Colorado, in the United States. **[1]** The Brazilian national time scale, located at the National Observatory (ONRJ) in Rio de Janeiro, Brazil, began contributing data to the SIM network in May 2006. The ONRJ time scale was constructed more recently than the CNM, NRC, and NIST time scales, and is described in the next section.

II. DESCRIPTION OF BRAZILIAN NATIONAL TIME SCALE

The Brazilian national time scale is located at the Time Service Division of the National Observatory in Rio de Janeiro (ONRJ), and includes an ensemble of five commercial cesium clocks. The first published report of UTC(ONRJ) based on an ensemble time scale appeared in the November 2006 *Circular-T*. Since then, the difference between URC and UTC(ONRJ) has not exceeded 30 ns. Prior to November 2006, the output of a single free-running cesium clock from the ensemble was selected to serve as UTC(ONRJ). This configuration made it impossible to maintain close synchronization with UTC, and the difference between UTC and UTC(ONRJ) was typically several microseconds or more.

The current ONRJ time scale consists of three parts (Figure 2). The first part is the clock ensemble that serves as the reference for the generation of the time scale. The second part is an automated data acquisition system that measures the time differences between the clocks. The third part is a time scale algorithm that computes a paper time scale and generates a real-time time scale using a micro-phase stepper as the output device. Reference **[2]** provides a complete description of each of these parts, but a short description is provided here.

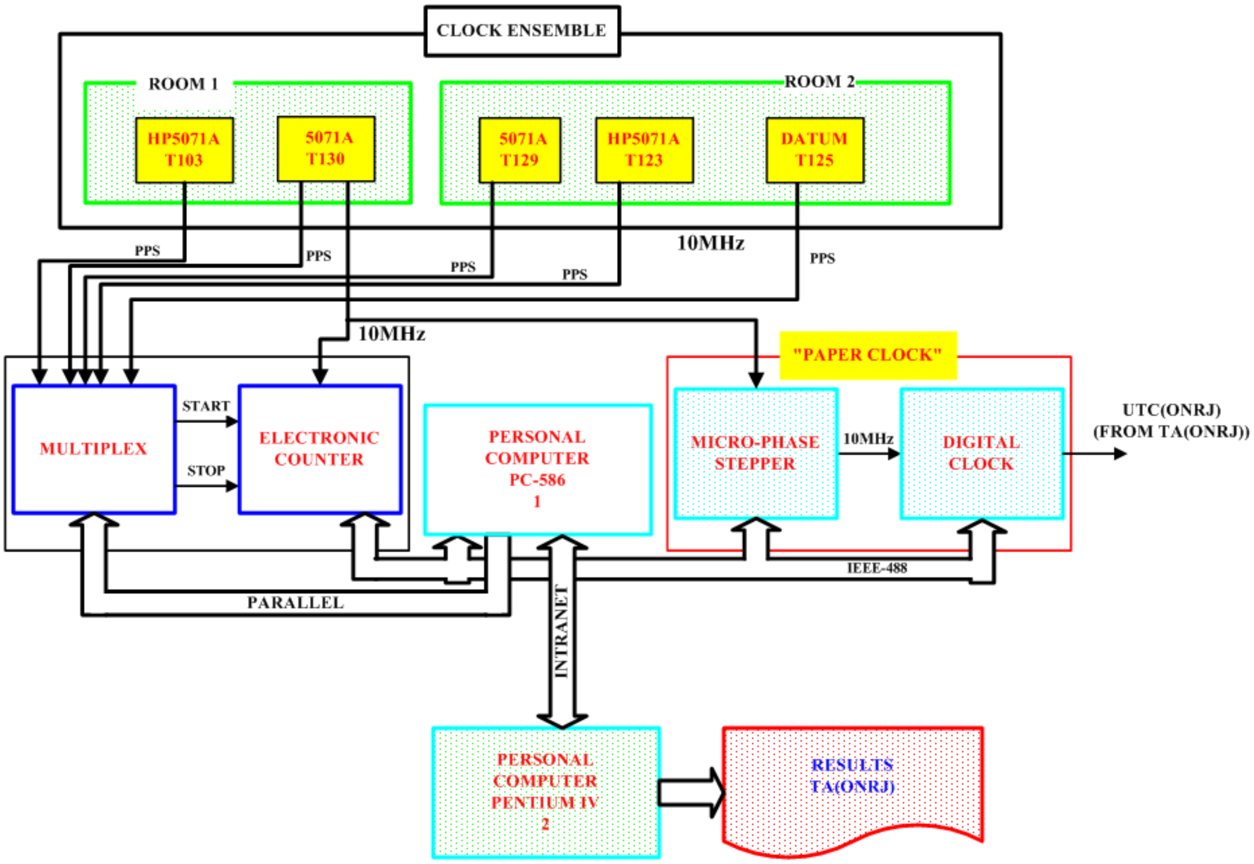

Figure 2. Block diagram of ONRJ time scale.

The clock ensemble consists of five commercial cesium standards. Four of the standards were manufactured by Hewlett-Packard (model 5071A with high performance beam tubes), and one was manufactured by Datum (model 4310). * The five standards are kept in two separate rooms as shown in Figure 2. The rooms are temperature controlled, with a nominal ambient temperature of about 25 °C ± 0.5 °C, and nominal humidity of about 60 % ± 10 %.

The data acquisition system measures time differences using a commercial electronic counter. The pair of clock signals to be measured are selected using a multiplexer, which is controlled by a computer through a parallel interface. The multiplexer routes the selected signals to the counter, a 1 pulse per second (pps) signal from the reference clock starts the counter, and a 1 pps signal from another clock stops the counter. The same computer that controls the multiplexer reads the counter through an IEEE-488 interface and stores the data on a hard disk. The time differences between one specific clock and all the others are measured in sequence. This sequence lasts for just a few seconds and is repeated every minute.

The time scale algorithm takes the time difference measurements between clocks and combines them mathematically to produce an average time scale. The algorithm [2] follows the same steps of an ensemble algorithm previously published at NIST [3], and generates a time scale with better stability than any of its contributing clocks. Both a paper time scale, TA(ONRJ), and a real-time time scale, UTC(ONRJ), are generated. UTC(ONRJ) is output from TA(ONRJ) through the use of a micro-phase stepper and a digital clock. At present, the steering parameters are manually entered into the micro-phase stepper. Signals from the UTC(ONRJ) time scale are connected to both the SIM measurement system, and to the reference receiver that submits data to the BIPM as a contribution to TAI.

The SIM measurement system was used to compare UTC(ONRJ) to UTC(NIST) for two separate 60-day periods by use of four different measurement techniques. Two of these techniques produce measurement results in near real-time, and two require post processing. The measurement techniques are defined in Section III, the real-time measurement results are presented in Section IV, and the post processed measurement results are presented in Section V.

III. DESCRIPTION OF MEASUREMENT TECHNIQUES

In its default configuration, the SIM network uses the “classic” common-view technique to reduce data. This technique aligns and differences data from the individual satellite tracks, and discards data collected from satellites that are not in common view at both sites. The basic equation for the “classic” common-view method is

$$TD = \frac{\sum_{i=1}^{N} (REFGPS_i(A) - REFGPS_i(B))}{CV}, \qquad (1)$$

where TD is the average time difference between the clocks at sites A and B during the measurement interval, N is the number of satellites tracked by the multi-channel GPS receivers (for the SIM receivers, N has a maximum value of 8), $REFGPS_i(A)$ is the series of individual satellite tracks recorded at site A, $REFGPS_i(B)$ is the series of tracks recorded at site B, and CV is the number of satellite tracks common to both sites.

The SIM measurement systems apply the modeled ionospheric (MDIO) corrections broadcast from the satellites to the measurements in real-time, and do not apply measured ionospheric (MSIO) corrections. The use of broadcast corrections make the measurement results nearly instantly available, with the delays limited only by the averaging time, and a tiny amount of computer processing and Internet transfer time. For the SIM network, the averaging time has been arbitrarily chosen as 10 minutes. Since no post processing is required by the SIM implementation of common-view, we refer to this method as real-time common-view (RTCV).

The ONRJ – NIST baseline is currently the longest in the SIM network. The two laboratories are separated by 8623.5 km (the “surface” distance between them exceeds 9500 km) and are on opposite sides of the equator. This long baseline presents problems for the RTCV technique, because there are intervals when no satellites are in common view at both sites. This is illustrated in Figure 3, which shows the number of satellites in common view as a percentage of the day. Note that there were no satellites in common view about 9.8 % of the time, and that there were never more than three satellites in common view. The Figure 3 data were collected from actual measurements made over a 60-day interval, when the elevation mask angle was set to 10° at both sites. During this 60-day interval, the eight-channel receivers at ONRJ and NIST tracked an average of 7.4 and 7.3 satellites, respectively, but an average of just 1.4 satellites were simultaneously visible at both sites.

To allow for situations when few if any satellites are in common view, the SIM network software can also present results using the "all-in-view" method (Eq. 2), where the satellite tracks are not aligned and no tracks are discarded. **[3]** Instead, the average of the $REFGPS_i(A)$ and $REFGPS_i(B)$ data series recorded at both sites is calculated, and the time difference TD equals the difference between the two averages:

$$TD = \overline{REFGPS_i(A)} - \overline{REFGPS_i(B)} \quad . \qquad (2)$$

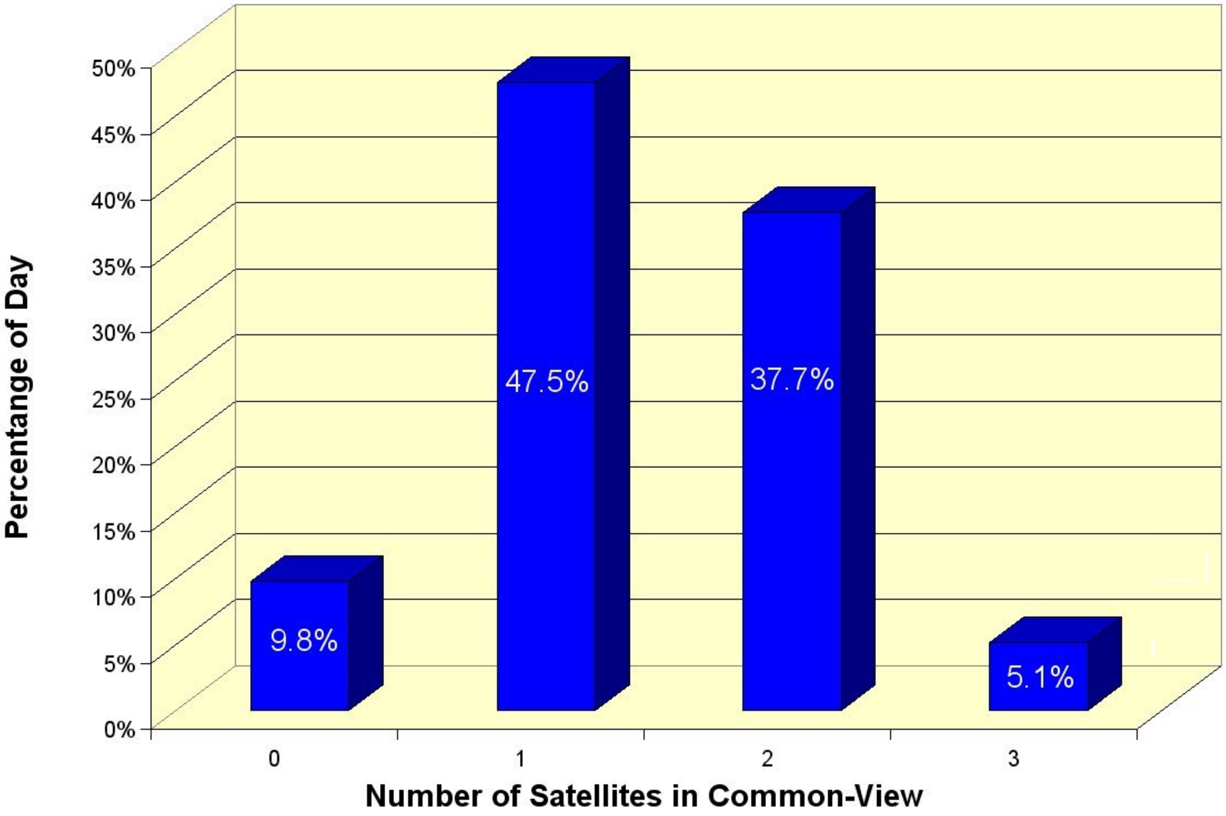

Figure 3. GPS Satellites in Common View for the ONRJ – NIST Baseline.

Since September 1, 2006, the all-in-view method has been used by the Bureau International des Poids et Mesures (BIPM) to process the GPS data used in the calculation of International Atomic Time (TAI), replacing the "classic" common-view method. The TAI computations now utilize the Physikalisch-Technischen Bundesanstalt (PTB) in Germany as the pivot laboratory for all GPS links. **[4]** The all-in-view method allows comparisons to be made between two laboratories located anywhere on Earth regardless of the length of the baseline, because none of the GPS satellites used in the comparison are required to be in common-view at both sites. **[5, 6, 7]** As is the case with the RTCV method, the SIM network implements the all-in-view method by simply applying the broadcast MDIO corrections to the measurements in real-time. Since no post processing is required by the SIM implementation of all-in-view, we refer to this method as real-time all-in-view (RTAV).

The SIM measurement system (Fig. 1) stores data as 10-minute and 1-minute tracks and does not use the 13-minute track format defined by the Consultative GPS and GLONASS Time Transfer Subcommittee (CGGTTS). **[8]** However, we developed software that converts the SIM data to a CGGTTS compatible format with either 10-minute or standard 13-minute tracks. We could then apply MSIO delay corrections from the International GNSS Service (IGS) **[9, 10]** to the SIM data with software tools that were previously developed to work with CGGTTS files. Another software tool was then developed to convert the corrected files back to the SIM format.

We refer to the method where MSIO corrections are applied to data reduced with the common-view technique (Eq. 1) as post-processed common-view (PPCV). The method where MSIO corrections are applied to data reduced with the all-in-view technique (Eq. 2) is referred to as post processed all-in-view (PPAV). Before applying the MSIO corrections, we also processed the real-time data with no ionospheric corrections (neither MDIO nor MSIO) applied. This technique, of course, would never be utilized in normal operation, but was done here for the sake of comparison. We refer to the real-time common-view no ionospheric correction data as RTCVNI, and to the real-time all-in-view no ionospheric correction data as RTAVNI. Section IV compares measurement results obtained with the RTCV and RTAV methods. Section V compares results obtained with the PPCV, PPAV, RTCVNI, and RTAVNI methods.

IV. NEAR REAL-TIME MEASUREMENT RESULTS

Comparisons between UTC(ONRJ) and UTC(NIST) were made for a 60-day period from 05/27/2007 to 07/25/2007 (MJD 54247 to 54306). During this interval, data were collected with the SIM receivers in their default configuration, with the broadcast ionospheric corrections turned on. The measurements were processed on the fly in near real-time by the SIM network, using both the RTCV and RTAV methods. Figure 4 shows the phase graph of the 10-minute averages from the first day of this comparison. The RTCV data are missing about 10 % of the 10-minute segments due to periods when no satellite was in common view. The RTAV data have no missing segments, and are less noisy. However, the difference between the average time offset of the RTCV and RTAV data for this particular day was just 0.3 ns.

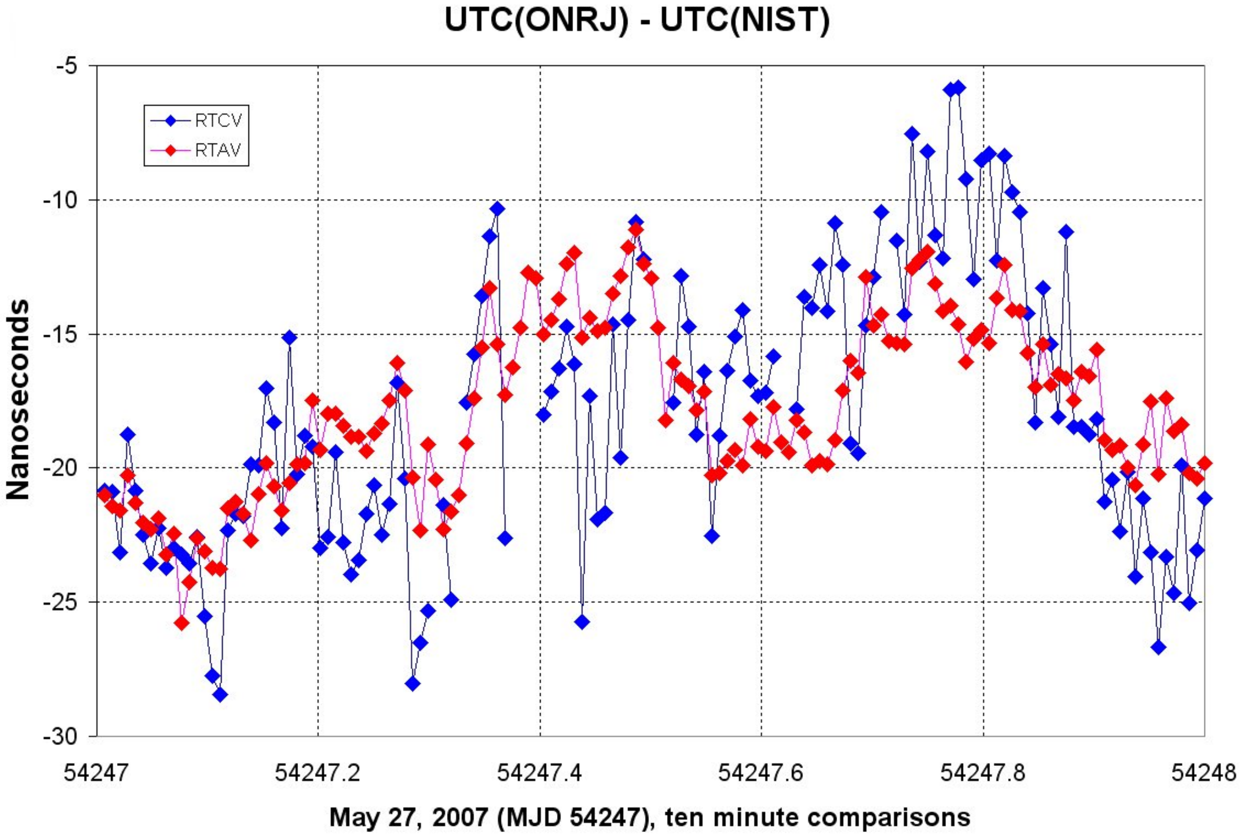

Figure 4. Phase graph showing RTCV and RTAV data over a 1 day interval.

Figure 5 shows a time deviation (TDEV), $\sigma_x(\tau)$, graph for the entire 60-day measurement interval, using the "all-tau" method. The RTAV method produces lower TDEV values for all intervals from τ = ~10 min to τ = ~5 d (note that due to the missing tracks, τ_0 = 665 s for the RTCV method), and it improves upon the stability of the RTCV method by more than a factor of 2 at averaging times of less than 30 minutes. Both methods produce a distinct diurnal at τ = ~0.5 d due to the error in the MDIO correction, which is more accurate during the nighttime hours than during the daytime. It is interesting to note that the difference in stability between the RTAV and RTCV methods at intervals longer than τ = 1 d is relatively small, because clock noise begins to dominate the transfer process over longer intervals.

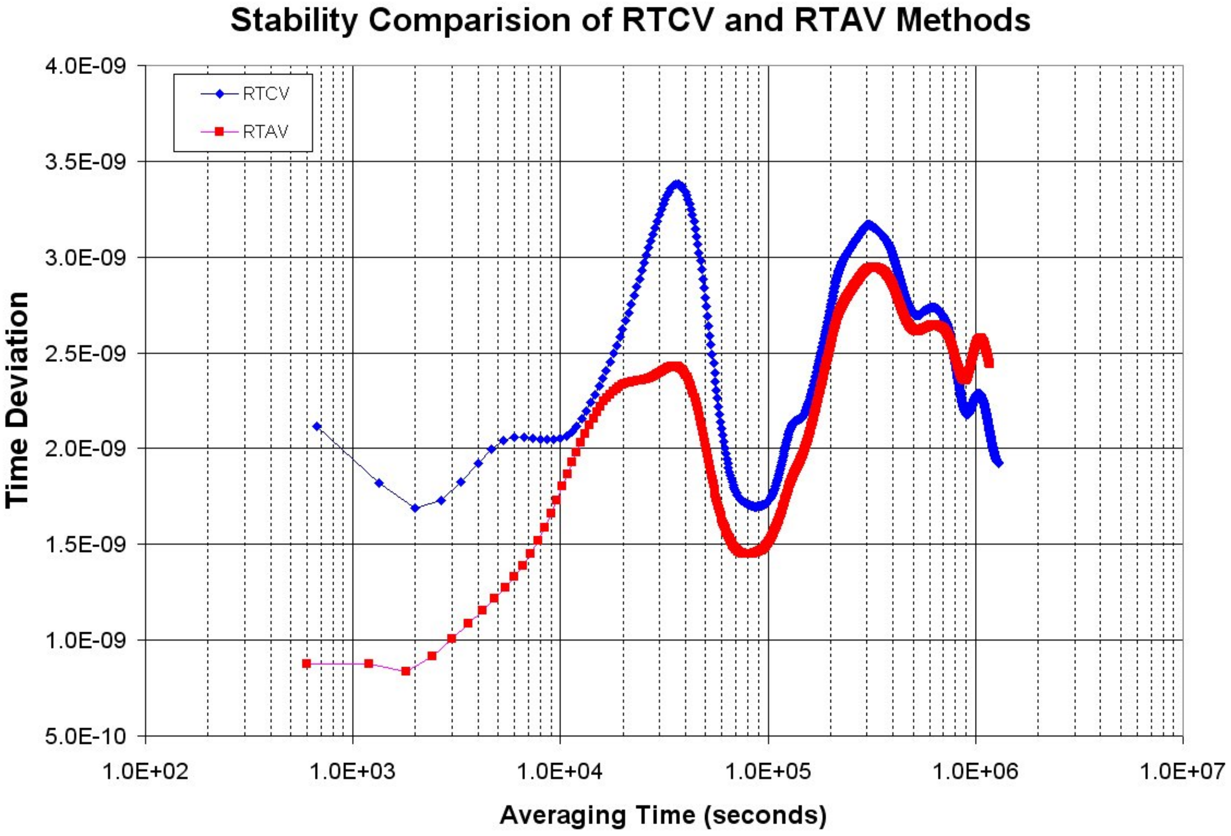

Figure 5. TDEV graph comparing the RTCV and RTAV methods.

Table 1 summarizes the results of comparisons of the RTCV and RTAV methods over SIM network baselines of varying length during the same 60-day interval. In addition to the time scales at ONRJ and NIST, these comparisons included the time scales of CNM, NRC, the Centro Nacional de Metrologia de Panama (CNMP) in Panama City, Panama, and NIST radio station WWV, where SIM compatible equipment has been installed. The baseline lengths ranged from 78.2 km (WWV – NIST) to 8623.5 km (ONRJ – NIST).

As Table 1 indicates, the RTCV and RTAV methods provide slightly different estimates of the average time offset between time scales, but this difference never exceeded 3 ns for any of the baselines tested. When used over short baselines, the RTCV and RTAV methods produce nearly identical TDEV results for both short term and long term measurements. This is because the same (or nearly the same) set of satellites is in view at both sites, and any errors cancelled by the common-view method will also be cancelled by all-in-view. Over medium length baselines (~2000 to 5000 km) when four or five satellites are typically in common-view, the RTCV method often does a slightly better job (at least over north/south baselines) of cancelling common errors, and can produce marginally better results than the RTAV method. Over long baselines (> 5000 km) when the number of satellites in common view drops to three or less, the RTAV method produces quieter data than the RTCV method. In this instance, the few satellites that are in common view are at low elevation angles, and thus more susceptible to ionospheric delay correction errors. However, even in situations where just one or two satellites are in common-view, as is the case with the ONRJ – NIST baseline, the advantage of the RTAV method is most evident at short averaging times. The RTCV method can produce nearly equivalent results when the averaging time is extended to one day or longer (Figure 5). Of course, the greatest advantage of the RTAV method is simply that it works in situations where no satellites are in common view, when the RTCV method is not usable at all.

Table 1. Near real-time measurement results using broadcast ionospheric (MDIO) corrections.

Baseline	Length (km)	Average CV satellites	Period (05/27/07 to 07/25/07) MJD 54247 to 54306, 60 d					
			Time Offset (ns)		Time Deviation (ns)			
			60 d average		τ = ~10 min		τ = 1 d	
			RTCV	RTAV	RTCV	RTAV	RTCV	RTAV
WWV – NIST	78.2	7.2	2.3	2.3	0.78	0.76	0.72	0.72
CNM – NIST	2198.9	5.1	-8.8	-7.6	0.97	1.11	1.27	1.29
NRC – NIST	2471.3	5.3	21.8	21.4	1.03	0.99	0.90	0.93
CNM – CNMP	2544.0	5.3	87.3	88.7	1.30	1.30	1.88	1.94
CNM – NRC	3520.7	4.5	-30.2	-28.6	1.20	1.18	1.44	1.49
CNMP – NRC	3989.0	4.7	-117.4	-118.3	1.06	1.19	1.54	1.59
CNMP – NIST	4194.9	4.4	-95.5	-97.1	1.03	1.10	1.49	1.53
CNMP – ONRJ	5153.1	3.5	-75.6	-72.8	1.50	1.09	1.96	1.90
CNM – ONRJ	7351.1	2.2	17.9	16.8	2.03	1.11	1.71	1.69
NRC – ONRJ	7681.2	2.1	45.5	44.7	2.33	1.00	1.49	1.51
ONRJ – NIST	8623.5	1.4	24.8	24.2	2.12	0.88	1.62	1.46

V. POST PROCESSED MEASUREMENT RESULTS

To compare post-processed measurement results, a second 60-day comparison between UTC(ONRJ) and UTC(NIST) was conducted from 08/11/2007 to 10/09/2007 (MJD 54323 to 54382). This second comparison was necessary, because the SIM systems do not have the ability to record the value of the MDIO correction, but it can be turned on or off using a software switch. During normal operation, the MDIO switch is always on, but during this second comparison the MDIO was turned off at both ONRJ and NIST. These "raw" data collected by the SIM system were processed in real-time using the RTCVNI and RTAVNI methods. After the MSIO corrections were applied, the data were processed again using both the common-view (PPCV) and all-in-view (PPAV) methods.

Figure 6 shows a phase comparison of the four methods, with the data series separated by 100 ns for clarity. Note that the all-in-view methods produce less noise than the common-view methods, and the PPAV method removes much of the diurnal phase shift that is visible in the RTAVNI data series.

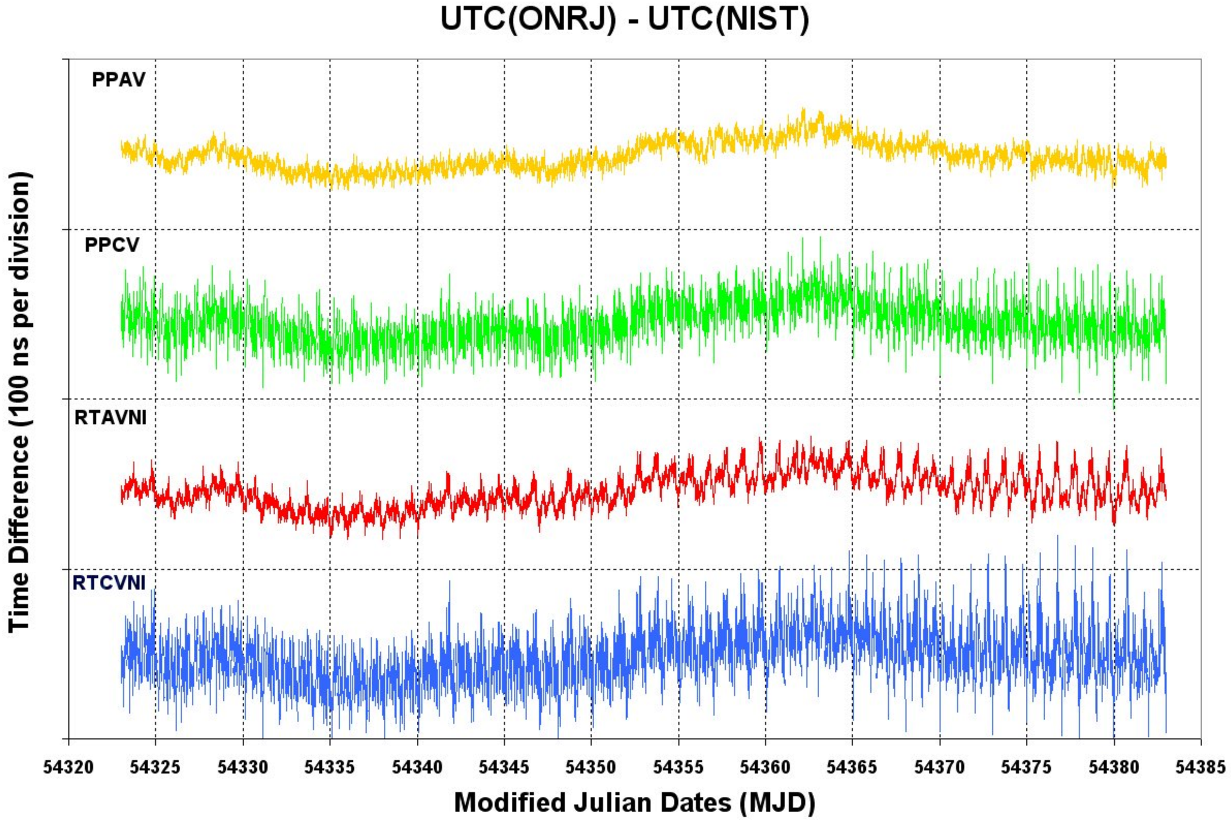

Figure 6. UTC(ONRJ) – UTC(NIST) using the PPAV, PPCV, RTAVNI, and RTCVNI methods.

Figure 7 shows a TDEV graph of the four methods, computed from the phase data shown in Figure 6. As was the case in Figure 5, τ_0 = 665 s for the two common-view methods due to the missing tracks. At short averaging times, the two all-in-view methods are much quieter than the two common-view methods. However, the RTAVNI method has a large diurnal variation where TDEV is near 5 ns at τ = ~0.5 d. This diurnal is removed by the PPAV method, which maintains a TDEV of less than 2 ns for nearly all averaging times out to about 2 days. The time deviations of the four methods converge at about 1 day, when clock noise begins to dominate the transfer process. The results clearly show that processing the data in all-in-view mode is beneficial over the long ONRJ – NIST baseline, and that applying the MSIO corrections (PPAV method) provides further improvement. Even so, the stability of the PPAV method is very similar to the RTAV method previously shown in Figure 5.

As mentioned earlier, the SIM systems do not record the values of the MDIO corrections that they automatically apply. This shortcoming makes it impossible to remove the MDIO correction before applying the MSIO correction, and therefore MDIO and MSIO data collected during the same interval cannot be compared. However, a comparison of the RTCV and PPCV methods was made possible by using the reference GPS receivers at ONRJ and NIST that collect and submit data to the BIPM for the calculation of TAI. Figure 8 plots all of the 13-minute common-view tracks collected from the reference receivers (~100 tracks per day) for the same 60-day interval (MJD 54323 to 54382) previously shown in Figure 6. The results show that the stability of the two methods is similar, but the difference in the average time offset between the MDIO and MSIO data sets is ~3 ns. Because the real-time SIM network applies only the broadcast MDIO corrections to its measurements, and because the post-processed MSIO correction is known to be more accurate **[11]**, this ~3 ns difference has previously been identified as a systematic (Type B) uncertainty in SIM network comparisons made over long baselines. [**1**]

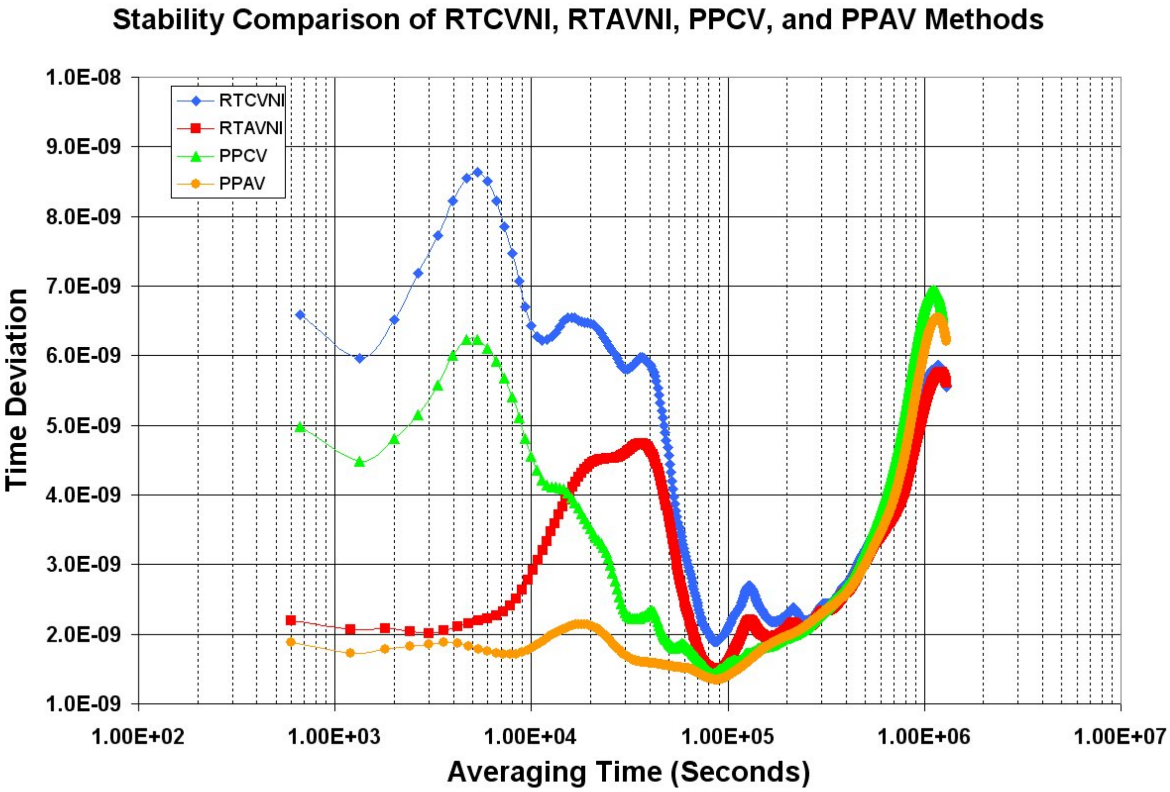

Figure 7. TDEV graph comparing the RTCVNI, RTAVNI, PPCV, and PPAV methods.

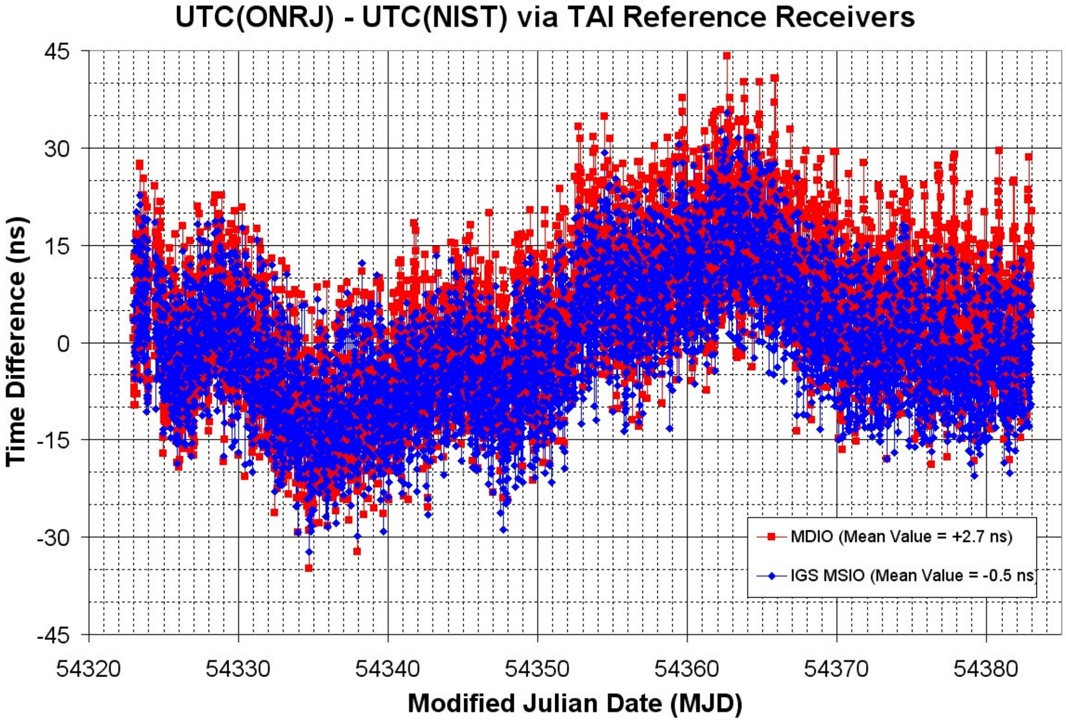

Figure 8. UTC(NIST) – UTC(ONRJ) with MDIO and MSIO corrections applied.

VI. SUMMARY AND CONCLUSIONS

The relatively new time scale at ONRJ in Brazil is exhibiting excellent accuracy and stability with respect to UTC and to UTC(NIST). In spite of the very long baseline between them, the ONRJ and NIST time scales can be easily compared, with the measurement results processed in near real-time by the SIM network. The real-time comparisons do not apply MSIO corrections, relying instead on the MDIO corrections broadcast by the satellites. This introduces a Type B uncertainty of about 3 ns to the mean time offset. However, the stability of the real time comparisons (particularly when using the RTAV method) is nearly equivalent to comparisons made using post-processed methods.

** The identification of commercial products is done for technical completeness only, and implies no endorsement by NIST or ONRJ.*

VII. ACKNOWLEDGMENTS

The authors thank CNM, CNMP, and NRC for the use of the data shown in Table 1. We also thank Judah Levine, John Lowe, and Tom Parker for their technical review of this manuscript.

VIII. REFERENCES

[1] M. A. Lombardi, A. N. Novick, J. M. Lopez, J-S. Boulanger, R. Pelletier, and C. Donado, 2006, *"Time Coordination Throughout the Americas via the SIM Common-View GPS Network,"* in Proceedings of the 38th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 5-7 December 2006, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 427-437.

[2] R. J. de Carvalho, 2005, *"The establishment of a Brazilian atomic time scale,"* in Proceedings of the Joint 2005 IEEE Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, Canada (IEEE 05CH37664C), pp. 254-260.

[3] M. A. Weiss, D. W. Allan, and T. K. Peppler, 1989, "A Study of the NBS Time Scale Algorithm," **IEEE Transactions on Instrumentation and Measurement**, **IM-38**, pp. 631-635.

[4] Bureau International des Poids et Mesures (BIPM), "*BIPM Annual Report on Time Activities*", Vol. 1, 2006.

[5] Z. Jiang and G. Petit, 2004, *"Time transfer with GPS satellites all in view,"* in Proceedings of the Asia-Pacific Workshop on Time and Frequency, 18-19 October 2004, Beijing, China, pp. 236-243.

[6] T. Gotoh, 2005, *"Improvement GPS Time Link in Asia with All in View,"* in Proceedings of the Joint 2005 IEEE Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, Canada, pp. 707-711.

[7] M. A. Weiss, G. Petit, and Z. Jiang, 2005, *"A Comparison of GPS Common-View Time Transfer to All-in-View,"* in Proceedings of the Joint 2005 IEEE Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, Canada, pp. 324-328.

[8] D. W. Allan and C. Thomas, 1994, *"Technical Directives for Standardization of GPS Time Receiver Software,"* **Metrologia, 31,** pp. 69-79.

[9] S. Schaer, G. Beutler, and M. Rothacher, 1998, "*Mapping and Predicting the Ionosphere*," in Proceeedings of the IGS AC Workshop, 9-11 February 1998, Darmstadt, Germany, pp. 1-12.

[10] S. Schaer, W. Gurtner, and J. Feltens, 1998, "*IONEX: The IONosphere Map EXchange Format Version 1*," in Proceeedings of the IGS AC Workshop, 9-11 February 1998, Darmstadt, Germany, pp. 1-15.

[11] M. Weiss, V. Zhang, M. Jensen, E. Powers, W. Klepczynski, and W. Lewandowski, 2002, *"Ionospheric Models and Measurements for Common-View Time Transfer,"* in Proceedings of the 2002 IEEE Frequency Control Symposium, 29-31 May 2002, pp. 517-521.