Using the Canadian Active Control System (CACS) for Real-Time Monitoring of GPS Receiver External Frequency Standards

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ABSTRACT

The Canadian Active Control System is a national network of twelve continuously operating geodetic quality GPS receivers equipped with external atomic frequency standards. Each GPS tracking station provides dual-frequency pseudorange and carrier phase measurements in real-time at 1 Hz to a central computer where wide area GPS corrections are generated using filtered ionosphere-free combined pseudoranges and predicted ultra-rapid GPS orbits. In contrast to the technique of fixing one of the station clocks, the central process estimates satellite and station clock phase offsets with respect to a Virtual Reference Clock (VRC) that is maintained as a weighted mean of all estimated receiver clocks. The VRC is related to the smoothed mean GPS system time as provided by the broadcast clock parameters of tracked satellites, and its alignment is maintained by regular steering operations. This approach mitigates the effects of instabilities of individual station frequency standards and provides continuity of the time reference.

This paper discusses the use of this system to monitor GPS satellite and receiver clocks. First, the central computing system provides continuous synchronisation of the network of GPS receiver clocks and GPS satellite clocks at the ns level. Second, using the wide area satellite orbit and clock corrections, users can synchronise dual-frequency GPS receivers in real time at a precision consistent with the satellite clock estimates.

INTRODUCTION

The Geodetic Survey Division (GSD) operates, in conjunction with the Geological Survey of Canada, the Canadian Active Control System (CACS). It comprises of a Master Active Control Station (MACS) and a network of continuously operating GPS data acquisition stations, called Active Control Points (ACPs), which are distributed across the Canadian landmass and track all GPS satellites in view. The GPS data from several ACPs are contributed to the International GPS Service (IGS). The NRCan Analysis Centre (EMR), also located at GSD, processes the Canadian and a portion of the global IGS data to generate daily precise GPS satellite ephemerides and clocks, earth orientation parameters (EOP), ionospheric, tropospheric and terrestrial reference frame information, as well as rapid GPS orbit predictions [Tétreault *et al*, 1998].

Twelve of the CACS tracking stations (**Figure 1**) facilitated by real-time data communication form the Canada-wide network of Real-Time ACPs (RTACPs). Another RTACP (USN2) is located at the U.S. Naval Observatory, in Washington, DC, and an additional one (RAYM) is located at the Ottawa GSD offices and serves for development purposes. Data from these RTACPs are communicated to the Real-Time Master Active Control Station (RTMACS) in less than two seconds for processing and storage. The RTMACS combines the tracking data and forms ionosphere-free, carrier-phase filtered pseudoranges to compute in real-time, clock phase offsets for all available satellites and receivers, using the predicted IGS ultra-rapid GPS satellite ephemerides and fixed RTACP coordinates. Corrections to the broadcast satellite orbits and a grid of vertical ionospheric delays for a single layer model of the ionosphere are also generated. The corrections to the broadcast satellite clocks and orbits along with the ionosphere model make up the GPS corrections service (GPS•C), which facilitates real-time GPS positioning of about half a meter horizontally and a

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meter vertically (1σ), when using geodetic quality receivers. The system architecture, data communication infrastructure and the real-time application software are described in *Caissy et al* [1996]. The RTMACS configuration, processes and the GPS•C positioning performance are described in *Skone et al* [1996] and *Lahaye et al* [1997].

Solving for all available clocks at each epoch requires a time reference and usually, as most IGS Analysis Centres do, this reference is achieved by removing a selected (reference) clock from the system of equations. All clock phase offsets are thus estimated with respect to the selected clock. In the context of a real-time system, with potential communication interruptions and variable delays, this technique proved inadequate, especially in the light of two requirements of the GPS•C service: maintaining continuity of the reference clock and maintaining its alignment to GPS time within reasonable bounds. To meet these requirements, we have implemented a so-called Virtual Reference Clock (VRC) that is maintained as a weighted mean of selected clocks in the system. Since the clock weights need to be controlled automatically, performance measures based on clock models were developed. Specifics of the VRC implementation and clock models were described in *Lahaye et al* [1998] and are summarised in a section below.

This paper focuses on the use of this system for monitoring frequency standards in support of the Geodetic Survey's VLBI and GPS operations, specifically for the maintenance of its ensemble of reference frequency standards, including passive and active Hydrogen Masers (HM), Cesium (Cs) and Rubidium (Rb) standards (**Table 1**). The first section assesses the quality of the real-time estimates of satellite and receiver clock phase offsets, using results extracted from the real-time processing for the month of July 2001. Then, the clock models and performance measures are described and supplemented with specific monitoring cases of RTCACS frequency standards. Finally, a post-processing demonstration of the potential for remote frequency standard monitoring using the GPS•C wide-area corrections is given.

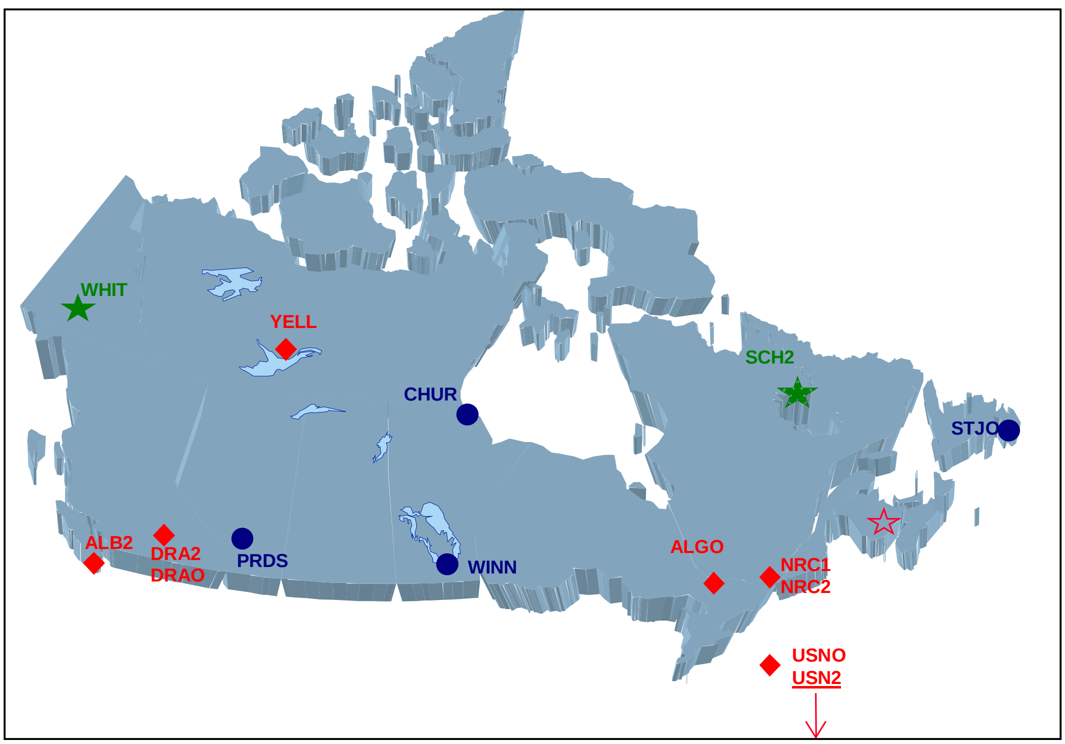


Figure 1 CACS network of real-time automated tracking stations (solid symbols), potential new sites (open star). Red diamonds are Hydrogen Masers, blue disks are Cesium and green stars Rubidium standards.

Table 1 Status of RTACP/ACP atomic frequency standards for the month of July 2001.

Station(s)	Freq. Std.
ALB2	Passive HM
ALGO	Active HM
CHUR	Cs
DRA2(DRAO)‡	Passive HM
NRC1†	Active HM/AOG
NRC2†	Passive HM
PRDS	Cs
RAYM	Off-line
SCH2	Rb
STJO	Cs
USN2	Steered HM
WHIT	Rb
WINN	Cs
YELL	Active HM

†common antenna reference.
‡common clock reference and antenna.
AOG: auxiliary output generator.

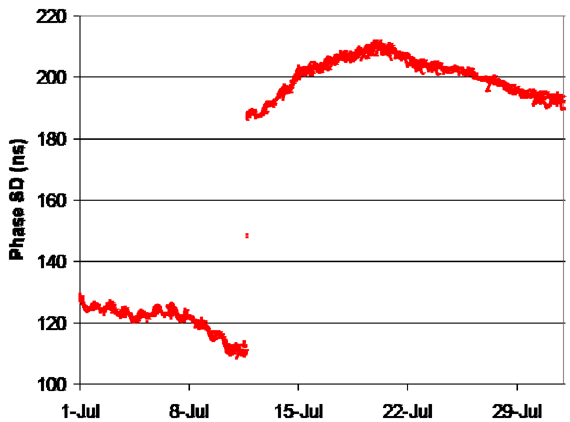


Figure 2 Clock phase single differences for 5 RTCAP/IGS receivers.

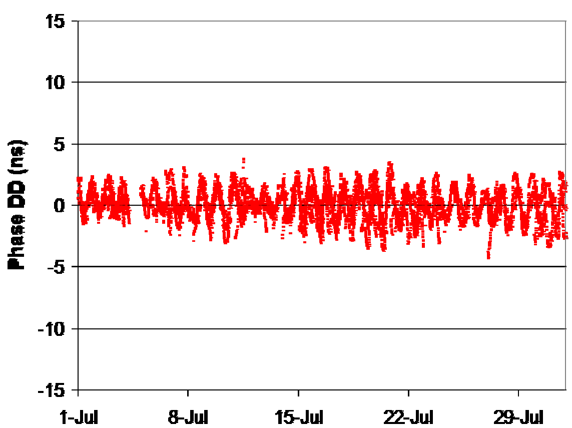


Figure 3 Clock phase double differences for 4 RTCAP/IGS receivers with respect to station ALGO.

REAL-TIME CLOCK PHASE ESTIMATES

Results from the real-time operations were extracted for the month of July 2001 at 1-minute intervals i.e., while the system computes clock phase offsets every 2 seconds, the states of the system were sampled and saved at one-minute intervals. During the month of July the system operated automatically almost without interventions except for a correction of the VRC GPS time alignment on July 11th, 2001.

The extracted real-time estimates of station and satellite clock phases are compared with the new realigned combined clocks product of IGS (IGST) [*Senior et al*, 2001]. This clock product, currently under development, is the original IGS clock combinations realigned to a continuous integrated time scale that is derived from frequencies obtained from a subset of the IGS clock combinations. This pilot project is aiming at removing small clock phase breaks at day boundaries partly caused by independent daily alignment of the combined clocks to the GPS time through the satellite broadcast clock parameters. These clock phase breaks are also present in

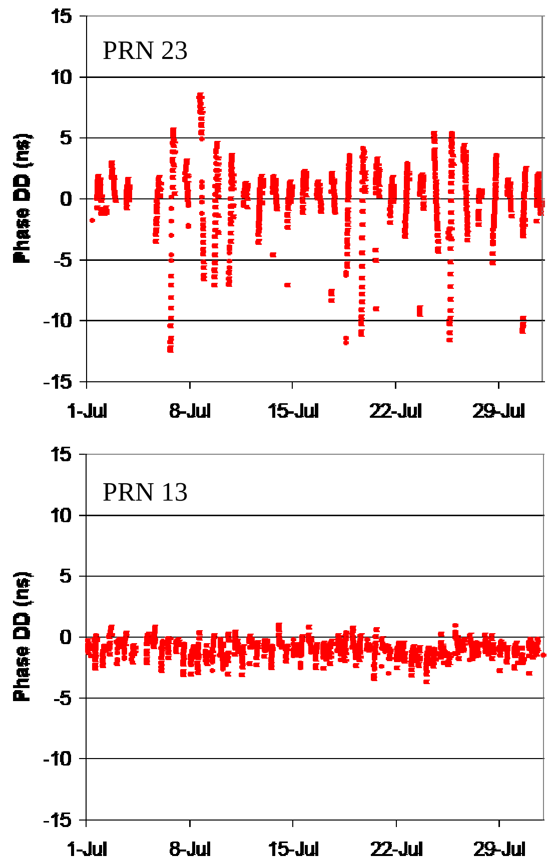


Figure 4 Clock phase double differences for 2 satellites (with marginal and good orbit prediction) with respect to ALGO.

the original Analysis Centres solutions. The internal consistency of the IGS combined clock product, excluding the day boundary phase discontinuities, is at the 100 ps level. The single differences between real-time and IGST clock phase solutions for common receivers are affected by the different reference clocks underlying each solution. This is apparent in **Figure 2** which shows the clock phase single differences for 5 receivers and where the July 11th VRC correction is clearly visible. To better assess the quality of the real-time clock phase estimates, double differences are formed with respect to the ALGO receiver clock phases, as these remove the respective reference clock differences. **Figure 3** and **Figure 4** show such clock phase double differences for 4 receivers and two satellites, respectively.

From **Figure 3** it is clear that the real-time clock phase offsets are affected by a daily signal with amplitude of 2-3ns. The source of this signal is currently under investigation. We have however observed similar signals for code residuals from the carrier-phase based, precise orbit determination at the NRCan Analysis Centre [*Tétreault*, 2001]. To confirm this, the ALGO and DRAO tracking data for the month of July 2001 were processed in a carrier-phase Precise Point Positioning (PPP) and a smoothed pseudorange PPP with the IGS Rapid satellite orbits and clocks products. Note that this IGS orbit/clock product is based on carrier-phase global processing. Both pseudorange and phase were processed with GSD's PPP software [*Héroux and Kouba*, 2001], thus using the same models. The recovered phase-based and pseudorange-based clock phases were differenced at 15-minutes intervals and plotted in **Figure 5**, where a daily signal of similar amplitude can be seen.

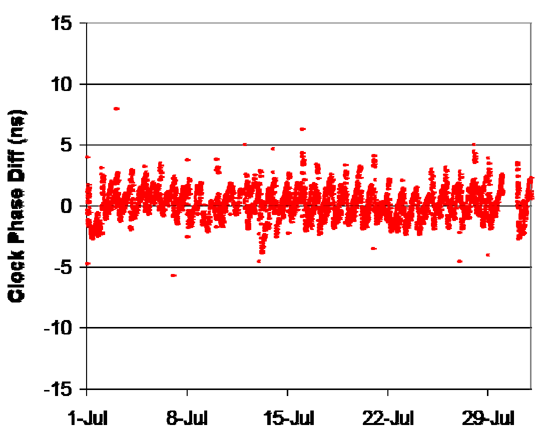


Figure 5 Clock phase difference between smoothed-pseudorange-based and carrier-phase-based PPP using the IGS Rapid orbits/clocks products.

The quality of the predicted orbits affects the real-time satellites clock phase estimates. Low accuracy predictions can result in lower quality clocks depending on how the orbit error maps into the lines-of-sight to the tracking receivers. Even with better quality orbits the GPS•C satellite clock phase estimates are subject to other effects. For example, satellites are not tracked continuously due to the regional character of the RTCACS network and consequently, the *a priori* satellite clock phase offsets are not constrained at the beginning of satellite passes. This, combined with the poor quality of low-elevation pseudorange observations and limited number of observations to rising satellites, adds other undesirable effects to the real-time estimates of the satellite clock phase offsets.

The RTMACS uses the receivers and satellites epoch clock phase estimates in real-time to model each clock in order to derive performance measures. The satellite estimates are also used to estimate the VRC alignment to the GPS time. These models and processes are described and illustrated in the next section.

RTMACS CLOCK MODELS

Linear models of clock phase with respect to time are used to model both the RTACP receivers and the GPS satellites clock phase variations in time with respect to the VRC. Real-time clock model parameters are updated using a sequential filter scheme in which epoch clock phase estimates are weighted according to a first order Markov process with a selectable correlation time, and according to their age. Two such models, short- and long-term, are maintained for each receiver clock with typical correlation times of a few minutes and 1 to 2 days, respectively. Since May 7, 2000 when the SA was switched off, similar models and correlation times are used to model the GPS satellite clocks. The zero- and first-degree terms of each polynomial yield estimates of clock phase and frequency offsets while the short- and long-term correlation times provide different levels of filtering.

The VRC alignment to the GPS time is monitored in real time by differencing the real-time GPS satellite clock phase estimates with those computed from the broadcast navigation messages. Denoting δC_{GPS}^{sat} as the broadcast satellite clock phase referenced to the GPS time and δC_{VRC}^{sat} as the value estimated in real-time with respect to the VRC, then differencing yields an estimate of the phase offset of the VRC with respect to GPS time as realised from the satellite broadcast parameters:

$$\delta C_{GPS}^{sat} - \delta C_{VRC}^{sat} = (t^{sat} - t_{GPS}) - (t^{sat} - t_{VRC}) = (t_{VRC} - t_{GPS}) = \delta VRC^{sat}$$

At each epoch, the system produces as many of these estimates as the number of satellites tracked by the network. All these estimates are fit into a linear model, similar to those developed for the satellite and receiver clocks, with typical correlation time of 1 to 2 days. **Figure 6** shows the resulting estimated phase and frequency offsets of the VRC with respect to GPS time for the period of July 2001. Looking at the period following the July 11th correction, the VRC alignment with respect to the GPS Time is maintained within ±15ns in phase and within $\pm 5\text{x}10^{-14}$ in frequency. This is consistent with the 6ns RMS of the model fit to the δVRC^{sat} estimates. Prior to the above correction, the VRC frequency had been diverging, away from the GPS time rate, due to a frequency event at one of the HM included in the VRC formation. In the current system, the clock weights used in the VRC formation are slow to respond to sudden frequency changes, therefore they can pull the VRC away from the GPS time. Thus occasionally the automatic VRC operation may require intervention.

Performance measures are derived from the above clock models. The short-term models are used to provide *a priori* estimates of the receiver and satellite clock phase offsets for the corresponding epoch solution. Filtered-pseudorange misclosures are examined to trap clock phase jumps. These jumps usually result from the loss of lock of GPS receivers and are not indicative of the external frequency standard behaviour. When phase jumps are detected, their magnitude is estimated and a corresponding discontinuity is introduced into both short- and long-term models. The long-term models attempt to remove some of the undesirable signals, described earlier. Its first-degree term corrected for the estimated VRC frequency misalignment to the GPS time serves as an estimate of the frequency offset of the external frequency standard. Since the long-term model loses memory of past values beyond the correlation time through the first order Markov process, it is, in a sense, adaptive, therefore it can also provide indications of frequency drift.

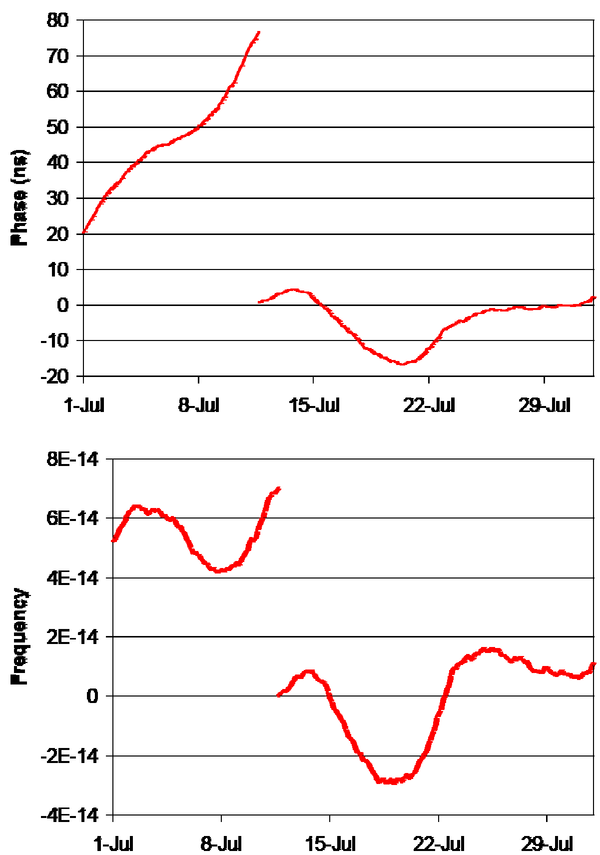


Figure 6 VRC long-term estimate of phase and frequency offsets with respect to the GPS time.

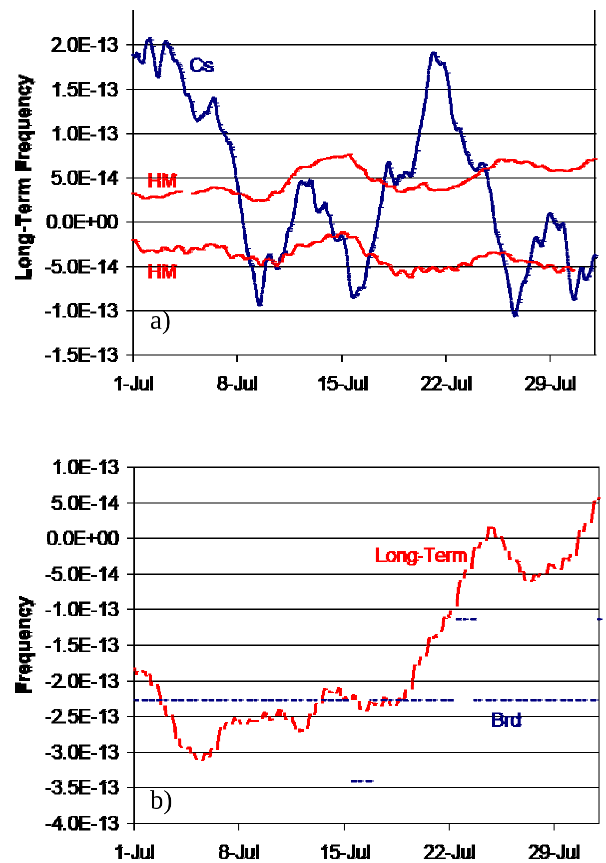


Figure 7 Typical: a) receiver HM and Cs long-term frequency offsets; b) satellite real-time long-term and broadcast models frequency offset.

Examples of these long-term model frequency offsets, corrected for the VRC frequency alignment estimates shown in **Figure 6**, are given in **Figure 7** for typical frequency standards and for typical satellites. Judging from the results for HM's which have short-term frequency stability well below $1x10^{-14}$/day, the real-time alignment corrected long-term frequency offset allows for monitoring frequency standards at $5x10^{-14}$ resolution.

Single differences between the modelled long-term clock phase offsets (corrected for the VRC misalignment) and the IGST clock phase estimates were formed for 4 receivers (3 HM and 1 Cs) and two satellites and plotted in **Figure 8**. Also, the satellite clock phase single differences between the broadcast clock models and IGST are included in the graph. These graphs show, especially for the HM's, the consistency of the implied real-time reference, the VRC, and its alignment to the GPS time as provided by the broadcast clock parameters. The large (10ns) variations of the Cs results are likely due to over smoothing by the long-term clock models adopted for these clock types in the real-time processing.

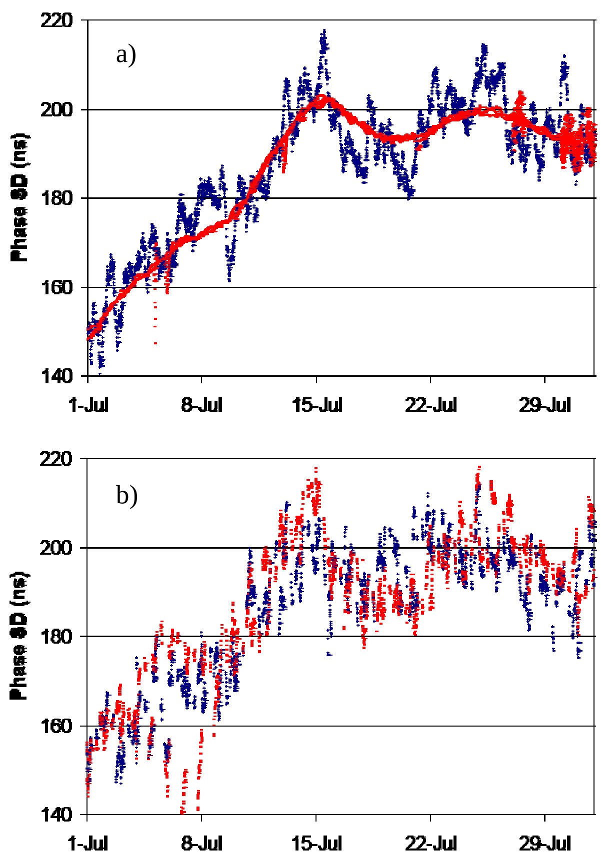


Figure 8 Single differences of long-term clock phase estimates for a) 3 HM's (red) and 1 Cs (blue) and b) 2 satellites real-time (red) and broadcast (blue) clock phase estimates.

Other performance measures are derived from the short- and long-term models to automatically modify clock weights, allowing the system to adapt to the frequency standards' behaviour and detect potential malfunctions. At each epoch and for each of the modelled clocks, the difference between the modelled short- and long-term phase offsets is monitored and processed through two moving average RMSs, over short and long correlation times respectively. These are called short- and long-term model difference RMS and the maximum of these two measures is used as a performance measure. The other clock performance measure is the RMS fit of the short-term clock model. **Figure 9** shows these measures for typical HM, Rb and Cs clocks types.

Three examples of frequency standard monitoring using the GPS•C central processing are now presented: 1) a scheduled frequency correction to a HM, 2) an unscheduled HM frequency change, and 3) a receiver switching from an external HM to a steered, internal crystal clock.

1) Scheduled HM frequency correction (Figure 10)

On August 30th, 2001, the YELL HM was corrected for frequency offset and drift of $4.2x10^{-13}$ and $1.4x10^{-15}$ respectively. The frequency drift estimate was obtained from the analysis of more than 3 months of real-time long-term frequency offset. Simultaneous to the HM correction, the GPS receiver was manually reset to adjust its clock phase lock to the HM frequency, causing a clock phase jump. This phase jump was automatically detected and caused the long-term model to go into "learning mode", where the correlation time is reduced, allowing the long-term model to reposition its frequency. After some time, based on convergence measures, the model automatically returns to its nominal correlation time.

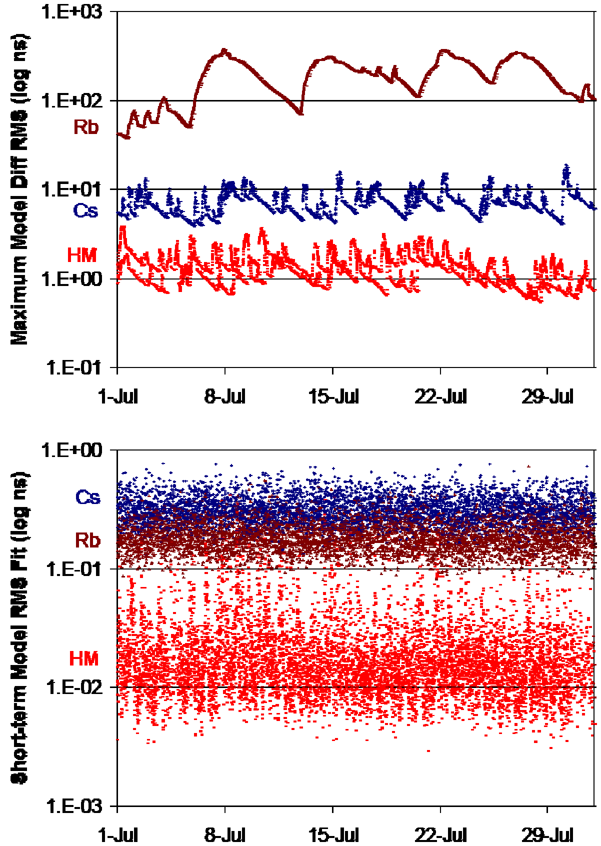
2) Unscheduled HM frequency change (Figure 11)

On July 5th, 2001, a power interruption combined with HM battery failure caused a sudden frequency drift [IGSMAIL-3405; http://igscb.jpl.nasa.gov/mail/igsmail/] at the YELL site. The short-term frequency responded within minutes to the change of frequency, as did both performance measures.

3) Receiver lost the external frequency (Figure 12)

After power interruptions at the ALBH site during the period of July 24 to 27 [IGSMAIL-3447], the GPS receiver resumed tracking using its steered internal crystal clock instead of the passive HM. The short-term model RMS of fit exhibited an increase of two orders of magnitude when satellite tracking resumed.

These examples of real-time monitoring show a system response time within minutes to frequency standards behaviour.



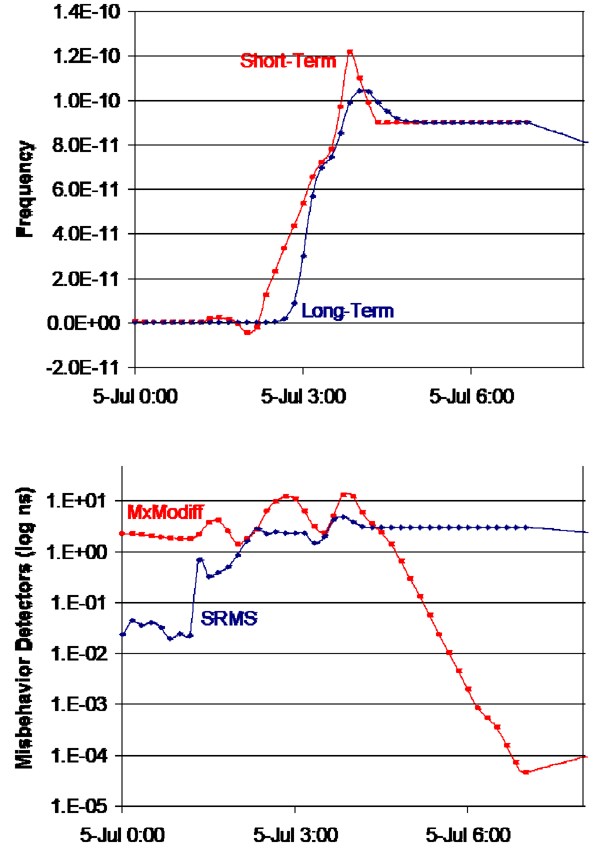
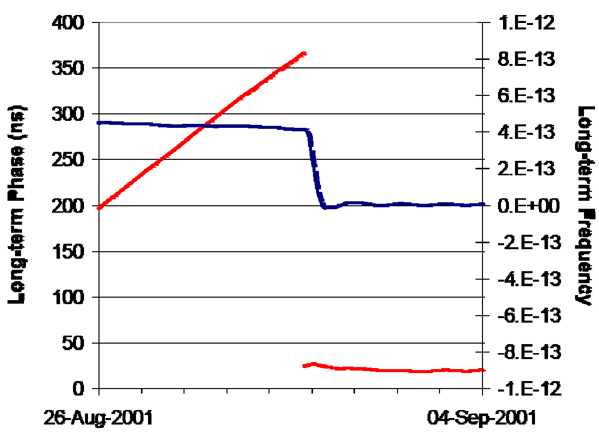


Figure 9 Quality-monitoring parameters for typical HM, Cs and Rb standards.

Figure 11 July 5, 2001, YELL HM unscheduled frequency change.



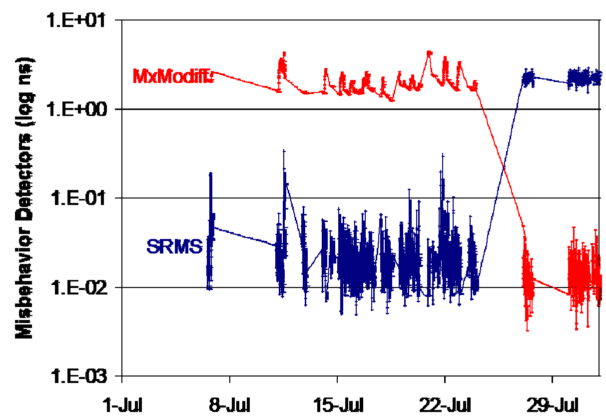


Figure 10 August 30, 2001 YELL HM scheduled frequency correction.

Figure 12 ALB2 loss of an external frequency standard on July 27, 2001, resumed tracking with a steered internal crystal clock.

REMOTE RECEIVER CLOCK MONITORING

In this section, we demonstrate the potential of the GPS•C system for monitoring a remote receiver/external frequency standard assembly through the GPS•C wide-area clock and orbit corrections. To do this, we have used the real-time satellite corrections in a smoothed pseudorange PPP algorithm to recover clock phases of the following three IGS receivers, all driven by an external HM's: FAIR, DRAO and USNO. Prior to PPP processing, the satellite clock corrections were corrected for the VRC misalignment to GPS time, so that the recovered clock phases are referenced to the GPS time as realised by the central processing. All the three stations were processed independently with 30 seconds interval for the month of July 2001, using the GPS•C corrections at the same rate and with the antenna positions held fixed at known positions. This procedure was not carried out in real-time and the GPS•C correction format was not used. Also the VRC alignment corrections are not applied to the real-time satellite clock corrections in the current GPS•C production system.

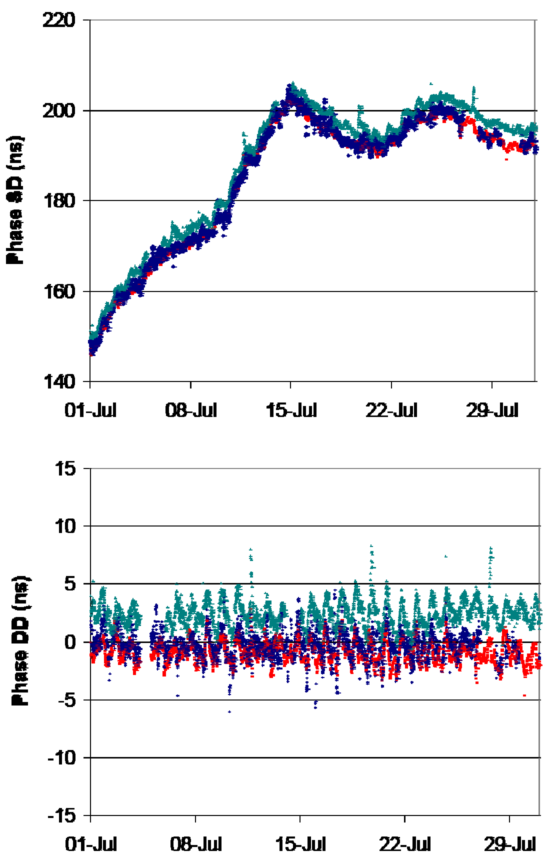


Figure 13 Single and double differences between IGST and recovered GPS•C/PPP clock phases for remote frequency standards at DRAO, FAIR and USNO IGS sites.

The recovered clock phases and the IGST estimates for the 3 receivers were single and double differenced (with respect to ALGO) (**Figure 13**). The single differences when compared to those obtained with the centrally processed HM show how well the reference is transferred. The double differences show a quality of recovered clock phases similar to that obtained centrally. However, unexplained clock phase biases of –1.0, -0.3 and 2.3 ns remain for DRAO, FAIR and USNO respectively. Although these biases require further investigations, they do not impede on the capacity for frequency and quality monitoring as implemented in the central processing.

CONCLUSION

The central processes of the GPS•C real-time pseudorange-based wide-area correction service of the Canadian Active Control System were presented. The quality of the real-time clock phase estimates was assessed against the IGS combined clocks product realigned to the new integrated IGS timescale. The receiver clocks show a daily signal with 2-3ns amplitude, similar to that seen in pseudorange residuals from precise carrier-phase-based GPS satellite orbit determinations and PPP using IGS precise orbit/clock products. The quality of satellite clock phase estimates is affected by precision of the predicted satellite orbits used and by the discontinuous tracking of the satellites due to the regional character of the RTCACS network. For the cases with the best orbits, the quality of clock phase estimates approaches that of receivers.

The clock models obtained from the real-time clock phase estimates, combined with the estimate of the alignment of the Virtual Reference Clock to the GPS time as realised by the broadcast satellite clock parameters, allow for monitoring of the frequency of external frequency standards with a resolution of about $5x10^{-14}$. Several other measures allow for system adaptation to the behaviour and detection of potential malfunctions of frequency standards and have a response time of several minutes, consistent with the short-term correlation time adopted for clock models.

Finally, the potential for remote frequency standard monitoring similar to that obtained from the central processing through the use of the GPS•C clock and orbit corrections was demonstrated, although clock phase biases require a further investigation.

Future improvements are needed to: 1) address the phase biases that affect the results, 2) improve the quality of the real-time phase estimates and 3) improve the stability and robustness of the VRC. Specific work towards these objectives has already begun at GSD, namely the implementation of real-time carrier phase processing [*Collins et al*, 2001] and real-time orbit quality checks/improvements. Frequency jump detection and clock weight adaptability improvements are also in the planning phase.

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