Integer satellite clock combination for Precise Point Positioning with ambiguity resolution

Garrett Seepersad[1,2], Simon Banville[2], Paul Collins[2], Sunil Bisnath[1], François Lahaye[2]
[1] Department of Earth and Space Science and Engineering, York University, Toronto, Canada
[2] Canadian Geodetic Survey, Natural Resources Canada, Ottawa, Canada

BIOGRAPHIES

Garrett Seepersad is a Ph.D. candidate at York University, Toronto, Canada, in the Department of Earth and Space Science and Engineering. He has completed his B.Sc. in Geomatics at the University of West Indies and his M.Sc. in Geomatics Engineering at York University. Currently he is a research affiliate at the Canadian Geodetic Survey (CGS) of Natural Resources Canada (NRCan).

Simon Banville is a senior geodetic engineer for the CGS of NRCan, working on precise point positioning (PPP) using global navigation satellite systems (GNSS). He obtained his PhD degree in 2014 from the Department of Geodesy and Geomatics Engineering at the University of New Brunswick (UNB), Canada, under the supervision of Dr. Richard B. Langley. He is the recipient of the Institute of Navigation (ION) 2014 Parkinson Award.

Paul Collins works for the CGS of NRCan, investigating the use of satellite navigation systems for geodesy, geodynamics, and positioning. His main focus is on the generation of real-time corrections and their application in precise point positioning.

Sunil Bisnath is an Associate Professor in the Department of Earth and Space Science and Engineering at York University in Toronto, Canada. His research interests include GNSS processing algorithm development for positioning and navigation applications.

François Lahaye leads the Geodetic Space-Based Technology team at the CGS of NRCan and is involved in the development of satellite geodesy applications, principally for real-time and near-real-time precise GPS products generation, and user applications thereof.

ABSTRACT

While satellite clock combinations are routinely utilized within the IGS, they currently disregard the fact that some ACs provide integer clocks. Users have been expected to choose either a robust combined solution or select individual AC solutions that provide integer clocks allowing the user to compute a PPP-AR solution. The goal of our investigation was to develop and test a robust satellite clock combination preserving the integer nature of the clocks and therefore the carrier-phase ambiguities at the user end.

Two sets of combined clock products were generated: 1) combined integer satellite clock products, and 2) IGS clocks aligned to integer clocks. The combined products were evaluated in the position domain by processing GPS data from 29 IGS stations, observed during DOY 178 to 184 of 2016. mm-level differences were noted, which was expected as the strength lies mainly in its reliability and stable median performance and the combined product is better than or equivalent to any single AC's product in the combination process. IGS clock products aligned to an AC integer clocks yielded the best PPP-AR results, for both static and kinematic solutions.

INTRODUCTION

Precise Point Positioning (PPP) uses precise satellite orbit and clock corrections from global navigation satellite systems (GNSS) to provide users with accurate positioning capabilities with respect to a global reference frame. In recent years, the Centre National d'Études Spatiales (CNES), an analysis center (AC) of the International GNSS Service (IGS), began providing satellite clock corrections preserving the integer nature of carrier-phase ambiguities. These "integer clocks" allow for PPP with ambiguity resolution (PPP-AR) and therefore a more rapid convergence and improved stability of the position estimates. Other ACs, such as Natural Resources Canada (NRCan), also generate such products for internal use.

Even though all IGS ACs follow a set of guidelines and standards to assure a certain level of consistency, flexibility is allowed to improve and innovate through the development of new processing strategies. Hence, many ACs utilize their own software packages and methodologies, and all have their solutions based on an independent selection of ground stations. Theoretically, a combination of the AC products is not rigorous since solutions are correlated. On a practical level, given AC-specific characteristics, a combined solution is more robust against outliers and failures within individual AC solutions. The strength of a combination product is always its reliability and stable median performance which is better than or equivalent to any single AC product (Kouba and Springer 2001).

Satellite clock combinations were first proposed by the IGS in 1993 (Springer and Beutler 1993) and became an official product of the IGS starting in January 1994 (Beutler et al. 1995; Beutler et al. 1999) as a post-processed product. Real-time or near-real-time products are even more prone to robustness issues due to unpredictable factors such as communication outages. The real-time combined product was proposed at the 2002 IGS workshop: "Towards real-time Network" and the pilot project was launched in 2011 (Caissy et al. 2012).

Satellite clock combinations produced by the IGS currently disregard the integer-preserving characteristics of the clock products. Users can then either opt for the robustness of the combined solution or select individual AC solutions that provide integer clocks, allowing users to compute a PPP-AR solution. The motivation of the work presented was to develop and test a PPP-AR clock combination product, improving on the reliability and robustness of the original products.

REVIEW OF PPP-AR AND PRODUCTS

PPP-AR requires the hardware delays within the GPS measurements to be properly handled, which allows for the resolution of the integer nature of the carrier-phase measurements (Laurichesse and Mercier 2007; Collins 2008; Mervart et al. 2008; Ge et al. 2008; Teunissen et al. 2010; Bertiger et al. 2010; Geng et al. 2012; Lannes and Prieur 2013). Integer ambiguity resolution of carrier-phase measurements from a single receiver can be implemented by applying additional satellite products, where the fractional component of the satellite hardware delay has been separated from the integer ambiguities in a network solution. There are two common methods for deriving such products: 1) provide users with the fractional component of the satellite hardware delays, known as the Fractional Cycle Bias (FCB) method (Ge et al. 2008), or 2) include pseudorange and carrier-phase satellite hardware delays directly into the clock products to obtain "integer clocks." Two implementations of this model are the decoupled-clock model (DCM) (Collins 2008) and the integer recovery clock (IRC) model (Laurichesse et al. 2009). Teunissen and Khodabandeh (2015) demonstrated the mathematical equivalency of these and other PPP-AR methods.

Currently, there are three main public providers of products enabling PPP-AR. These include Scripps Institution of Oceanography (Geng and Bock 2013; Scripps 2016) which provides regional real-time FCB products, Natural Resources Canada (Collins 2008; NRCan 2015) which provides post-processed and real-time DCM products, and the Centre National d'Études Spatiales (Laurichesse et al. 2009; CNES 2015) which also provides post-processed and real-time IRC products. As no products were available from Scripps (2016), from January to September 2016, they were excluded from this study.

Therefore, this paper focuses mainly on the integer clock approaches, such as the DCM and IRC models. Both approaches use the ionosphere-free pseudorange and carrier-phase observables for GPS, combined with the widelane phase and narrowlane pseudorange (i.e., the Melbourne-Wübbena) observable. This parameterization allows for uncombined ambiguities to be estimated without the need to explicitly estimate slant ionospheric delay parameters. The main difference between the two approaches is that the IRC model uses daily averages of the widelane biases and aligns the pseudorange clock to the carrier-phase clock, while the DCM approach makes no assumption on the temporal variability of the biases.

For dissemination to users, both the DCM and IRC products can be cast into the RTCM SSR representations (Laurichesse 2015). However, in this paper, we first combined directly the widelane satellite biases originating from the Melbourne-Wübbena combination, and then combined the DCM phase clock with the IRC clock product.

SATELLITE CLOCK COMBINATION OF COMMON CLOCKS

In this paper, we refer to satellite clock products that do not preserve the integer nature of the ambiguities as common clocks. It is well-known that combining common clock products is an effective method to address the vulnerabilities an individual AC is susceptible to. The combined clock products have performed marginally better than the uncombined products (Beutler et al. 1995; Kouba and Springer 2001), which is expected, as the strength of satellite combination is in improving reliability and availability of the products and not necessarily accuracy. Clocks can be combined epoch-by-epoch through weighted least squares (Weber et al. 2007; Weber et al. 2011) or combined sequentially using a Kalman or sequential least-squares filter (Mervart and Weber 2011; Chen et al. 2016).

In the sequential filter approach, clocks estimated by individual ACs are used as observations (dt_a^s) within the adjustment process, where $s = \{1 \ldots m\}$ represents a set of m number of satellites. Each observation is modeled as a linear function of three parameters: 1) the combined satellite clock ($\overline{dt}^s$); 2) an AC-specific offset (B_a); and 3) an AC-specific satellite-dependent offset (A_a^s), where, $a = \{1 \ldots n\}$ is a set of n analysis centers and s is the number of satellites. The observation equation can be represented as:

$$dt_a^s - \psi_a^s = \overline{dt}^s + B_a + A_a^s \quad (1)$$

where ψ_a^s is a consistency correction which is time varying and AC specific. ψ_a^s aligns the individual AC solutions to the selected reference frame which, in our case, was defined by the IGS combined orbit solution. The consistency correction is computed as follows:

$$\psi_a^s = \frac{(\vec{X}_a^s - \vec{X}_{IGS}^s - \vec{D}_a) \cdot \vec{X}_a^s}{\left|\vec{X}_{IGS}^s\right|} \quad (2)$$

where $\vec{X}_a^s$ is the AC satellite position vector, $\vec{X}_{IGS}^s$ represents the IGS combined satellite position vector, and $\vec{D}_a$ is the geocenter offset vector provided by the respective AC. Finally, $\left| \; \right|$ represents the computation of the radius vector with respect to the center of the Earth (Ferland et al. 2000; Kouba and Springer 2001).

The term B_a in equation (1) varies with each AC because of the different timing constraints imposed on the network. Timing constraints are defined by fixing the clock parameter of a reference station. Since it is not possible to estimate one such parameter for each AC, one AC needs to be selected as a timing reference. A_a^s varies based on the different solution-specific ambiguity datum ambiguities and the AC adjustment constraints. A_a^s is unique to each AC and satellite and is considered constant in time. It is used to model different time references for each satellite within each AC solution. In practice, A_a^s is routinely included as shown in Mervart and Weber (2011) and Chen et al. (2016) in their real-time implementation of satellite combinations of common clocks. A_a^s is included because it absorbs any differently modeled satellite-specific errors. Also, including A_a^s facilitates expanding the satellite clock combination from common clocks to integer clocks. In the sequential filter, $\overline{dt}^s$ and B_a were assigned an infinite process noise variance where as A_a^s were modeled as constant parameter. Table 1 summarizes the different estimated parameters in the satellite clock combination and associated constraints.

Table 1: Estimated parameters in satellite clock combination and associated constraints.

Parameter	Description	Process noise
$\overline{dt}^s$	Combined satellite clock	∞
B_a	Time reference offset (AC-specific)	∞
A_a^s	Satellite-dependent offset (AC-specific)	0

In the adjustment, there is a total of $n + m + m \cdot n$ unknowns and $m \cdot n$ measurements and, as such, there is a rank deficiency of $n + m$ at the first epoch. To remove this singularity, different terms were held fixed within the system. As mentioned previously, the timing reference (B_a) of one AC must be held fixed. Furthermore, it is required to fix one A_a^s parameter for each satellite and AC. Presented in Table 2 are the fixed terms in the adjustment to remove the system's rank deficiency.

Table 2: Fixed terms in the adjustment to remove rank deficiency.

Parameter	Fixed terms	Number of estimated terms
$\overline{dt}^s$	0	m
B_a	1	$n-1$
A_a^s	$n+m-1$	$(m-1)\cdot(n-1)$

COMBINATION OF INTEGER SATELLITE CLOCK PRODUCTS

The previous section discussed the combination process of the common clocks. This section focuses on the steps required to combine integer satellite clocks products, which are highlighted in Figure 1. The first step requires accounting AC specific modeling such as different axis conventions and yaw manoeuvers during a satellite eclipse. Accounting for AC specific modeling is critical to ensure the integer nature of the carrier-phase ambiguity is not compromised. The next step combines the widelane products which is followed by the combination of the integer satellite clocks.

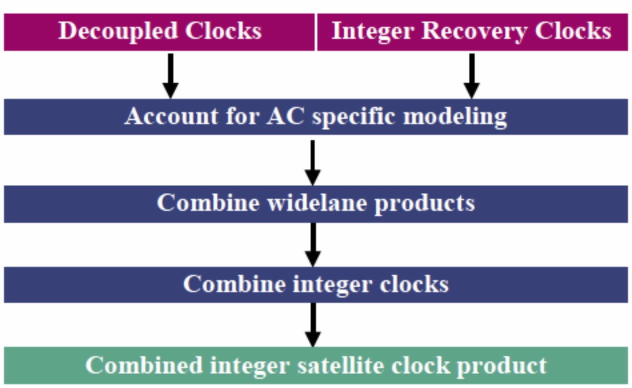
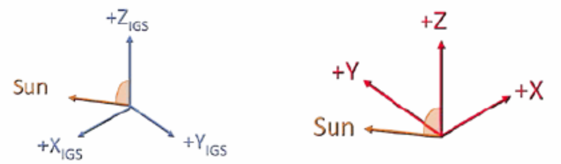


Figure 1: Overview of the steps required to combine integer satellite clocks products

Axis convention

As mentioned before, ACs are allowed a certain level of flexibility to improve and innovate through the development of new processing strategies. In the combination process, it is important that the different strategies utilized by the ACs are taken into consideration in the adjustment process. For example, IRC adopted the IGS axis convention whereas the internal DCM products followed the manufacturer specification. Presented in Figure 2 is the orientation of the spacecraft body frame for GPS Block IIR/IIR-M satellites adopted within the IGS axis convention, subplot (a), and provided in the manufacturer specifications, subplot (b). The difference between the manufacturer specifications and IGS axis convention is the orientation of the X and Y axes.



(a) IGS axis convention **(b) Manufacturer specifications**

Figure 2: Orientation of the spacecraft body frame for GPS Block IIR/IIR-M satellites. Sub-plot (a) refers to the manufacturer specification system while sub-plot (b) refers to the IGS axis conventions (Montenbruck et al. 2015).

Yaw manoeuvers during satellite eclipse

Another critical component to be accounted for is the difference in the modeling of yaw manoeuvers. Yaw manoeuvers occur when the actual yaw angle differs from the nominal yaw angle. The nominal yaw angle is the orientation angle by which a satellite would maintain optimal solar visibility throughout its orbit, provided it could spin arbitrarily fast. The actual yaw angle is the orientation that the satellite is able to maintain due to its limited rate of yaw.

All satellites fail to maintain their nominal orientation when their orbits pass close to the Earth-Sun axis. These are the eclipsing orbits with turns at both orbit noon and orbit midnight. During a satellite eclipse, Block II GPS satellites behaved unpredictably because of hardware sensitivity, spinning beyond the nominal amount upon entering the sun's shadow. The Block IIR and Block IIF generations of satellites were designed to be able to maintain their nominal attitude even during orbit noon and orbit midnight (Bar-Sever 1996; Dilssner et al. 2011). For Block IIR, the yaw manoeuver is constrained by a maximum yaw rate of 0.2 deg/sec (Kouba 2009) and Block IIF is constrained by a maximum yaw rate of 0.11 deg/sec (Dilssner 2010). The attitude model of the GPS satellites affects the computation of measurement geometry through variations of the transmitter phase center location and carrier phase measurement wind-up. It also affects the modeling of the solar radiation pressure force acting on the GPS satellites due to the changes in illumination geometry (Kuang et al. 2016).

The uncertainty of the yaw manoeuver is higher during midnight orbit as the satellite crosses the Earth's shadow. During the shadow crossing, the satellite's view of the Sun is obstructed partially from the region known as the penumbra or fully by the Earth from the region known as the umbra. A GPS satellite goes through eclipse season approximately every 6 months and the length of the eclipse season varies from 4 to 8 weeks. A typical orbit geometry during eclipse season is depicted in Figure 3. Eclipse season typically begins for a GPS satellite when β goes below 13.5°, where β is elevation of the Sun above the orbital plane. The time the satellite spends in the Earth's shadow increases as β approaches 0°, for a time period of up to a maximum of approximately 55 minutes (Bar-Sever 1996; Kouba 2009; Dilssner et al. 2011). Typically, the nominal attitude model fits actual GPS measurements well. During eclipsing season when β typically goes below 4°, the physical GPS satellite yaw attitude rate cannot keep up with what is expected from the nominal model. Dilssner et al. (2011) observed that the orbit noon turn of the Block IIF satellites manifests in the wrong direction for a small negative β angle as much as -0.9°.

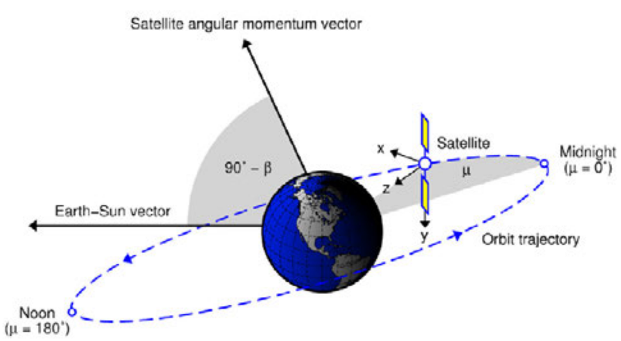


Figure 3: Geometry of an eclipsing satellite, where β is elevation of the Sun above the orbital plane and μ is the spacecraft's geocentric orbit angle. "Midnight" denotes the farthest point of the orbit from the Sun whereas "noon" denotes the closest point. From author Dilssner et al. (2011).

To account for differences in yaw manoeuvering during orbit noon and orbit midnight, knowledge of the actual yaw attitude models from the different ACs is required. As such, there is a proposal to extend the current RINEX clock format to include additional information such as yaw angle and phase/code biases (Donahue et al. 2016). The yaw information would allow for a phase wind-up correction to be applied to each solution for improved consistency, while the phase/code bias information accommodates the different integer-clock products including FCB.

Satellite combination of integer-clock products

The combination process of the integer clocks follows exactly the same parametrization and constraints, in addition to the integer constraints imposed on the satellite offset. For the combined products to be integer natured, it is imperative that the reference AC provide integer satellite clock products. Presented in equation (3) is the alignment of the widelane satellite hardware delay for each AC:

$$\delta^s_{a,WL} = \overline{\delta}^s_{WL} + B_{a,WL} + A^s_{a,WL} \qquad (3)$$

where $\delta^s_{a,WL}$ is the widelane hardware delay provided by each AC and $\overline{\delta}^s_{WL}$ is the combined widelane hardware delay and $A^s_{a,WL} = \lambda_{WL} N^s_{a,WL}$ with the term N having integer properties.

The alignment is necessary to reduce the differences between ACs, and most importantly, maintain the integer nature of the subsequent $A^s_{a,IF}$ parameters. In the second step, presented in equation (4), the rounded integer value of $N^s_{a,WL}$ is introduced as an additional correction. The equation for the integer clock combination reads:

$$dt^s_a - \psi^s_b - \frac{f_2^2}{f_1^2 - f_2^2}\lambda_2 [N^s_{a,WL}] = \overline{dt}^s + B_a + A^s_{a,IF} \quad (4)$$

where

$A^s_{a,IF} = \dfrac{f_1^2 - f_1 f_2}{f_1^2 - f_2^2}\lambda_1 N^s_{a,L1}$ and $[N^s_{a,WL}]$ represents rounding of the AC-satellite offset.

COMBINED INTEGER-CLOCK PRODUCTS

In the combination process of IRC and DCM products, each of the ACs were weighted equally. B_{IRC} , A^{s}_{IRC} (all satellites) and A^{1}_{DCM} were held fixed as minimal constraints in the adjustment. IRC was arbitrarily selected as the timing reference, and satellite PRN 01 was selected because it had the highest data availability. The results presented in this section were taken from day-of-year (DOY) 178 and 179 of 2016.

The first component analyzed in this section is the effect of yaw manoeuvers on the clock combination process. The expectation is that Block IIR and Block IIF satellites are able to keep their nominal attitude even when orbiting through the penumbra and the umbra. Because of the difficulties in determining the exact moment of exiting the umbra, modeling inconsistencies between ACs can be observed. For example, in Figure 4 when PRN 24, a Block IIF satellite, is in the Earth's shadow, discrepancies are present between the IRC and DCM products. According to the Jet Propulsion Lab (JPL) within their ".shad" file (JPL 2016), the time period the satellite transited through the umbra occurred from 03:28:43 to 04:24:09 and 15:27:18 to 16:22:43 and is shaded in green. The limitation of JPL's ".shad" file is only instances of midnight orbits are provided and it does not include the yaw rate. Highlighted in blue is the information presented in the DCM clock format, which indicates the time period of a critical yaw manoeuver within the umbra. In the DCM clock format instances of orbit noon are also provided but not illustrated as consistent modeling occurred during these manoeuvers.

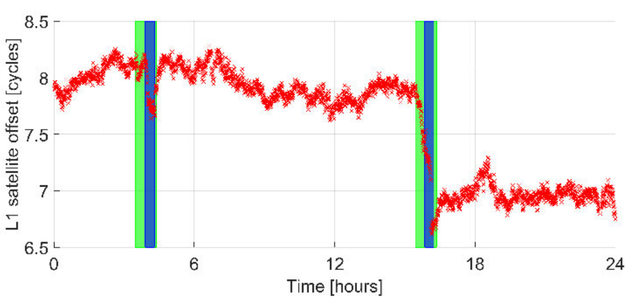


Figure 4: Inconsistent error modeling during a satellite eclipse for PRN 24, Block IIF on DOY 178 of 2016 between IRC and DCM. The red time series illustrates the unconstrained AC specific satellite offset with respect to PRN 1, the green box illustrates the shadow period provided by JPL and the blue box illustrates the critical yaw manoeuver provided by NRCan.

Presented in Figure 5 is the convergence of the DCM L1 satellite offset. The differences in yaw manoeuvers and antenna axis convention were taken into consideration. During the critical yaw manoeuvers the satellite offset of the eclipsing satellite in the DCM solution A^{s}_{DCM} was re-initialized.

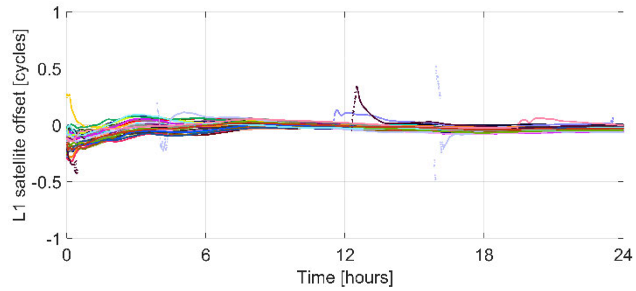


Figure 5: Convergence of the forward run of DCM L1 satellite offset with respect to the IRC on DOY 178, 2016 with the differences in yaw manoeuvers and axis convention taken into consideration. Each colour represents a different satellite with the integer component removed from each time series.

As mentioned previously, each analysis center must adopt a consistent satellite axis orientation definition. When ignoring the different axis conventions adopted by the DCM and IRC products, satellite-dependent offsets for the block IIR/IIR-M satellites converged to 0.5 cycles as opposed to integer values, as illustrated in Figure 6.

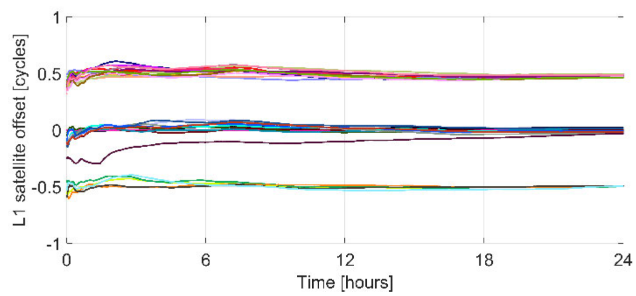


Figure 6: Convergence of the DCM L1 satellite offsets with respect to the IRC for DOY 179, 2016 with the differences in axis convention not account for. Each colour represents a different satellite with the integer component removed from each time series.

Hence, a 0.5 cycle correction term is applied to the measurements for ACs that adopted a different convention from the IGS. Presented in Figure 7 is the consistent integer natured satellite offset from DCM with respect to IRC on DOY 179, 2016 with an RMS error of 0.02 cycles.

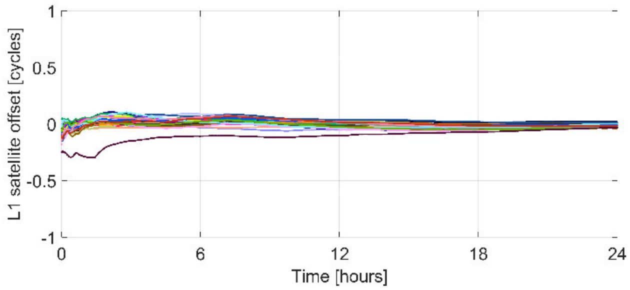


Figure 7: Convergence of the DCM L1 satellite offset with respect to the IRC on DOY 179, 2016 with the differences in axis convention account for. Each colour represents a different satellite with the integer component removed from each time series.

Figure 8 illustrates an example of the estimated widelane DCM satellite offset with respect to the IRC solution on DOY 178, 2016. Each line represents one satellite with the integer component removed. The final estimates of $N^{s}_{DCM,WL}$ have an RMS error of 0.03 cycles.

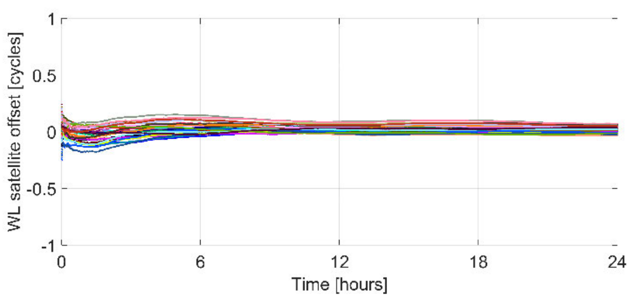


Figure 8: Convergence of the DCM widelane satellite offset with respect to the IRC on DOY 178, 2016. Each colour represents a different satellite with the integer component removed from each time series.

Presented in Figure 9 is the time reference parameter of the DCM solution (B_{DCM}). Since the term B_{IRC} was fixed, this offset effectively represents the offset between the DCM and IRC timing references.

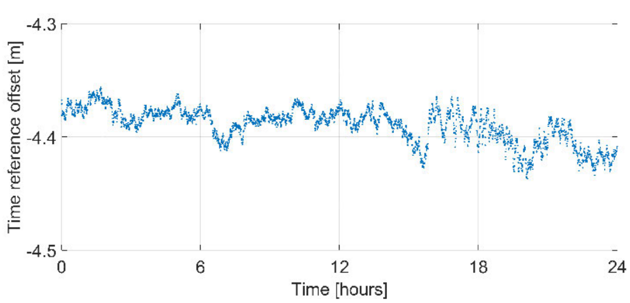


Figure 9: Time reference parameter of DCM with respect to IRC on DOY 178, 2016.

Post-fit residuals of the combined IRC+DCM clock with respect to the IRC clock products for DOY 178, 2016 is presented in Figure 10 with an RMS of 0.42 cm, where 98.85% of the residuals were within ± 1 cm.

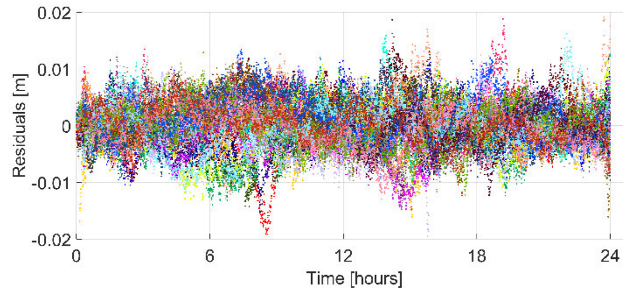


Figure 10: Post-fit residuals of the combined clock (IRC and DCM) with respect to the reference clock (IRC) on DOY 178, 2016.

ALIGNING IGS COMMON CLOCKS TO INTEGER CLOCKS

As a proof of concept, IGS common clocks were also aligned the IRC integer clocks to allow for ambiguity resolution with the (re-aligned) IGS clocks. Similar to the DCM and IRC combination, B_{IRC}, A^{s}_{IRC} (all satellites) and A^{1}_{IGS} were held fixed as minimal constraints in the adjustment. An infinite weight was assigned to the clocks provided by the IGS, and hence the combined clocks maintain the time variation of the IGS clocks. By assigning an infinite weight and combining the clocks relative to an integer clock solution, the combined clock product has the precision and stability of the original IGS common clocks while preserving the integer nature of the ambiguities at the user end. Presented in Figure 11 is the forward run of the IGS L1 satellite offsets with respect to the IRC clocks on DOY 178, 2016. As expected, because the IGS clocks are a combined common clock, satellite offsets are real-valued.

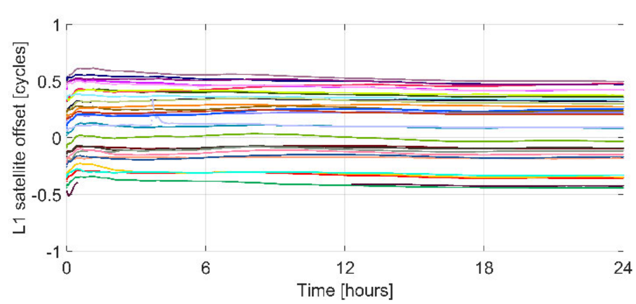


Figure 11: Convergence of the forward run of IGS L1 satellite offset with respect to the IRC on DOY 178, 2016. Each colour represents a different satellite with an integer component removed from each time series.

Presented in Figure 12 is the time reference offset of IGS with respect to the IRC solution.

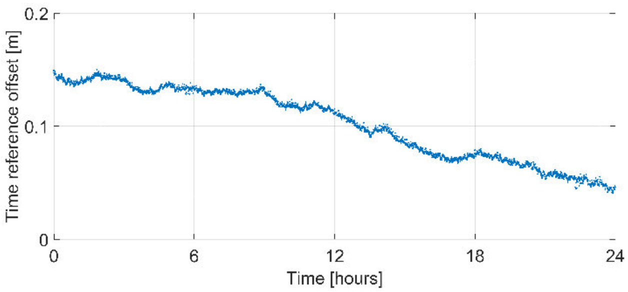


Figure 12: Time reference parameter of IGS with respect to IRC on DOY 178, 2016.

Post-fit residuals of the combined IRC+IGS clock with respect to the IRC clock products on DOY 178, 2016 is presented Figure 13 with an RMS of 0.3 cm, where 99.92% of the residuals were within ± 1 cm.

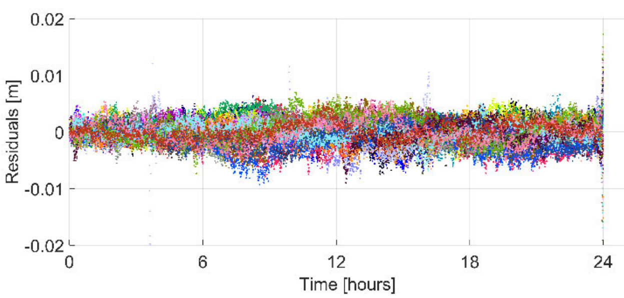


Figure 13: Post-fit residuals of the combined clock (IRC and IGS) with respect to the reference clock (IRC) on DOY 178, 2016.

PERFORMANCE OF COMBINED SATELLITE CLOCK PRODUCTS

The goal of this section is to evaluate the quality of integer satellite clock combinations in the position domain. Float ambiguity PPP solutions computed with the IGS clocks, (labeled 'IGS') and PPP-AR solutions obtained with the CNES IRC products (labeled 'IRC') are compared. Two sets of combined products are also included in the evaluation: 1) combined integer satellite clock products, labeled as 'IRC+DCM' and, 2) IGS clocks aligned to integer clocks, labeled as 'IGS-AR'.

GPS data from 29 IGS stations, observed during DOY 178 to 184 of 2016, were processed using a development version of NRCan's PPP software. A global station distribution was selected to assess the overall quality of the clock products. The distribution of the sites is illustrated in Figure 14. Dual-frequency uncombined observations were processed with a priori standard deviations of 1.0 m and 6 mm for pseudorange and carrier-phase observations, respectively. A cut-off angle 7.5° elevation was applied.

The reference stations were processed both in static and kinematic mode. Receiver clock parameters were estimated on an epoch-by-epoch basis. The zenith tropospheric delay was estimated with a random walk process noise of 3 mm/sqrt (hour). Slant ionospheric delays and uncalibrated signal delays were also estimated epoch-by-epoch in the PPP filter. Ambiguity resolution was performed for three solutions: 'IRC', 'IGS-AR' and 'IRC+DCM'. In static mode, the ambiguity resolution strategy adopted was a simple rounding strategy performed on a satellite-by-satellite basis, while an integer least-squares solution using the Best Integer Equivariant (BIE) estimator, computed following Banville (2016), was used in kinematic mode.

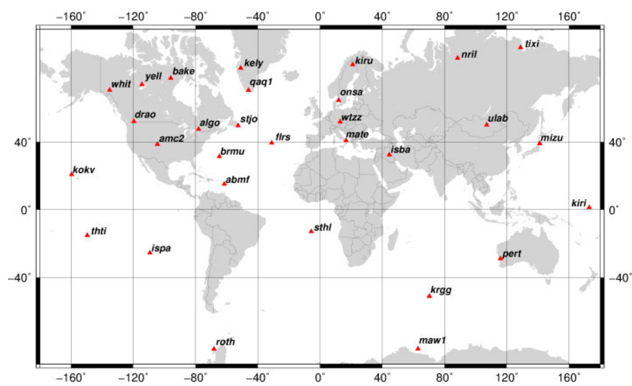


Figure 14: Global distribution of the selected 29 IGS stations observed during DOY 178 to 184, GPS week 1903, of 2016.

In static mode, we first examine position repeatability over the 7 days processed. For each station, the standard deviation of the 7 daily estimates for each component (latitude, longitude and height) was computed. These repeatability measures were then averaged over all 29 stations to yield the results presented in Figure 15. This process was repeated for every satellite clock product investigated. The impact of ambiguity resolution can clearly be seen in the longitude component, where all solutions with ambiguity resolution outperform the standard IGS clock solution in terms of the longitudinal repeatability. Aligning the IGS clocks to the IRC clocks has produced the best solutions, suggesting a benefit from both the robustness of the IGS combination and the integer properties of the integer clocks. Finally, the IRC+DCM solution provides repeatabilities that are marginally better than the IRC solution at the few mm-level.

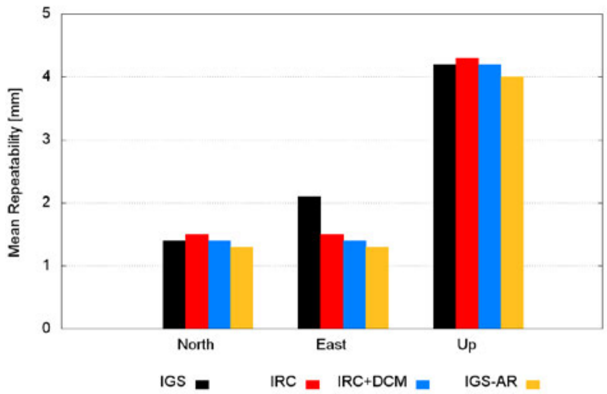


Figure 15: Examination of the repeatability of the PPP user solution in static mode utilizing different types of clock products. Statistics are based on GPS data from 29 IGS stations were observed during DOY 178 to 184, of 2016. All units are in millimetres.

Similarly, Figure 16 presents the results for kinematic processing. A different evaluation scheme was used in this case: for each daily station processing, the standard deviation of the latitude, longitude and height components were computed. The values for all 29 stations over the 7 days were then ordered and the 90th percentile values were extracted. This method was adopted as solution resets within the day (due to data gaps for example) can impact the mean value. Similar conclusions as in the static case can be made, where the contribution of ambiguity resolution significantly improves the solution. In this case, aligning the IGS clocks to the IRC clocks offered only marginal benefits over the original IRC solution.

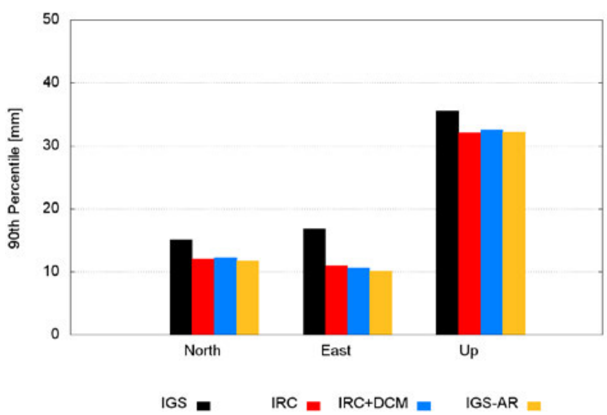


Figure 16: Examination of the repeatability of the PPP user solution in kinematic mode utilizing different types of clock products. Statistics are based on GPS data from 29 IGS stations were observed during DOY 178 to 184, of 2016. All units are in millimetres.

CONCLUSIONS

The satellite clock combinations routinely produced within the IGS currently disregard the integer nature of some AC products. Users have been expected to choose either a robust combined solution or select an individual AC solution that provides integer clocks allowing PPP-AR. The goal of our investigation was to develop and test a robust satellite clock combination preserving the integer nature of the carrier-phase ambiguities at the user end.

For a satellite clock combination to provide an integer-aligned clock, it is important that the different modeling utilized by the ACs are properly considered in the adjustment process. Two different types of modeling were addressed, namely: 1) different satellite axis conventions, and 2) differences in modeling of yaw manoeuvers. By not accounting for these differences in the combination process, the underlying integer nature of the clock products were compromised.

For GPS Block IIR/IIR-M satellites, the IGS axis convention and manufacturer specifications are not equivalent. The difference between the two axis representations for Block IIR/IIR-M satellites is the orientation of the X and Y axes. To account for the differences in antenna conventions, a 0.5 cycle correction term must be applied to the clocks for ACs that adopted a different convention from the IGS.

Different ACs have adopted different standards for modeling the yaw manoeuvers during orbit noon and orbit midnight. To account for the inconsistent yaw modeling between ACs. It is critical that additional information such as yaw angle and phase/code satellite hardware delays are provided at the same intervals as the clocks. The yaw information would allow for a phase wind-up correction to be applied to each solution for improved consistency, while the phase/code satellite hardware delays accommodates different product representations, such as FCB. To this end, we suggest an updated RINEX clock format.

Two sets of combined clock products were generated: 1) combined integer satellite clock products, and 2) IGS clocks aligned to integer clocks. The combined products were evaluated in the position domain by processing GPS data from 29 IGS stations, observed during DOY 178 to 184 of 2016. mm-level differences were noted, which was expected as the strength lies mainly in its reliability and stable median performance and the combined product is better than or equivalent to any single AC's product in the combination process. Aligning the actual IGS clock products to integer clocks yielded the best PPP-AR results, for both static and kinematic solutions.

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