Online Precise Point Positioning

A New, Timely Service from Natural Resources Canada

By Yves Mireault, Pierre Tétreault, François Lahaye, Pierre Héroux, and Jan Kouba

MELIORA SEQUAMUR — let us strive to improve. The words that the Roman poet Virgil wrote some 2,000 years ago could well be the watchwords of those scientists and engineers who today work to improve the accuracy, coverage, and timeliness of GPS-based positioning. They are particularly appropriate for those seeking to improve the technique of precise point positioning or PPP.

INNOVATION INSIGHTS with Richard Langley

PPP uses undifferenced carrier-phase observations.

PPP is a single-receiver positioning technique just like conventional pseudorange-based positioning, which takes place inside a receiver. However, the similarity stops there. PPP uses the receiver's very precise undifferenced carrier-phase observations together with very precise (and accurate) satellite orbits and clocks to achieve positioning accuracies at the few centimeter level or better. And unlike differential techniques such as real-time kinematic (RTK) positioning, all of the physical phenomena affecting the measurements must be very accurately modeled. These include solid earth tides, ocean-tide loading, transmitting and receiving antenna phase-center offsets and variations, carrier-phase wind-up, relativistic effects, and so on. With differential techniques, such effects are greatly reduced and typically become insignificant, especially on short baselines. PPP can be used to process data collected at a fixed (static) site or along a trajectory in kinematic mode or a mixture of the two — "stop and go" PPP.

Although introduced in the late 1990s, PPP has only become more commonplace in the past few years, thanks, in part, to continued PPP development in government and university research labs. Several PPP processors are even available online.

The precise satellite orbits and clocks required are provided by the International GNSS Service (IGS) and its worldwide tracking network and analysis centers. These products are supplied with some latency resulting in PPP normally being used as a post-processing technique with observations being processed some time after they are collected. However, over the past year or so efforts have been made to reduce the latency of some high-precision products. In particular, the ultra-rapid orbit and clock product of the Geodetic Survey Division of Natural Resources Canada (NRCan) is now being produced with a delay of only 90 minutes. Coupled with NRCan's online PPP engine, it provides positioning accuracies almost as good as the IGS final product, which is only available with a delay of about two weeks.

In this month's column, we take a look at this new, timely service from the Great White North.

"Innovation" is a regular column that features discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who welcomes your comments and topic ideas. To contact him, see the "Contributing Editors" section on page 8.

Online precise point positioning (PPP) tools are an increasingly important means for GPS users to obtain position information in national or global reference frames. The Geodetic Survey Division (GSD) of Natural Resources Canada (NRCan) introduced the Canadian Spatial Reference System-PPP (CSRS-PPP) online service in November 2003. Since that time, the service improvement most frequently requested by users has been a reduction in the "wait time" for their results. In response, GSD has recently improved the timeliness of its online PPP service by introducing the use of near-real-time precise GPS orbits and clocks at 30-second intervals. The CSRS-PPP now enables absolute positioning worldwide as early as 90 minutes after data collection with centimeter or sub-decimeter accuracy level, depending on user dynamics (static or kinematic).

In this article, we describe the CSRS-PPP product and the development of NRCan's near-real-time satellite orbit and clock products that have had an important impact on the performance of this service.

CSRS-PPP

The point positioning method is a post-processing approach that uses undifferenced observations from a single geodetic-grade GPS receiver. Solutions are wide area, relying on precise satellite orbits and clocks as well as accurate models for all the physical phenomena affecting the observations. Depending on the type of GPS data processed, parameters normally estimated include the station positions (in static or kinematic mode), station-clock states, local tropospheric zenith delays, and carrier-phase ambiguities.

Before accurate GPS orbits and clocks were available, carrier-phase observations could only be used in a point-positioning context to smooth pseudorange observations. With the advent of the International

GNSS Service (IGS), accurate GPS products became available, making it possible to take advantage of the carrier-phase precision. Carrier-phase information transformed point positioning from a decimeter- to (for some applications) a few-millimeter-level technique, prompting the more recent PPP designation. NRCan's CSRS-PPP was introduced to provide users with the accuracy benefits of precise carrier-phase observations and the convenient access offered by the Internet.

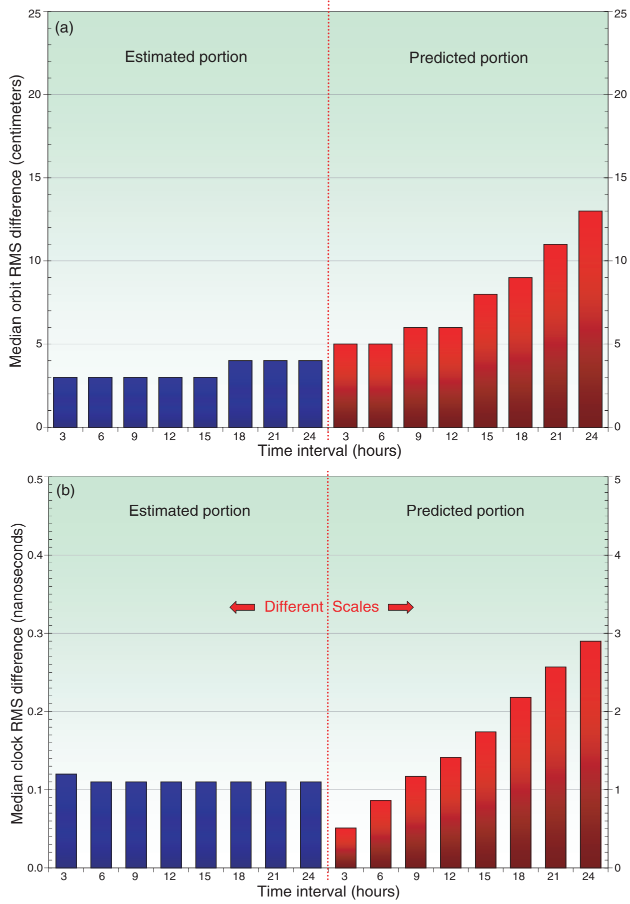
A detailed discussion of the PPP method including its parameterization and required modeling can be found in the paper by Jan Kouba and Pierre Héroux listed in Further Reading. It is worth pointing out two recent improvements to CSRS-PPP modeling: antenna phase variations and tropospheric delay mapping. CSRS-PPP uses the IGS absolute receiver and satellite antenna phase offset and variation values if available for the antenna model specified in the header of the submitted observation file. Otherwise, it defaults to relative antenna phase-center information. As for the tropospheric delay estimation, CSRS-PPP total tropospheric zenith delay estimates are now based on the Global Mapping Function derived from the European Centre for Medium-Range Weather Forecasts numerical weather model.

The online CSRS-PPP, which uses IGS and more recently NRCan hourly orbit and clock products, was developed and implemented to serve both geodetic positioning professionals as well as less demanding GPS users wishing to improve the quality of their positioning results for a variety of georeferencing requirements. The service, which can currently process pseudorange only or pseudorange and carrier-phase observations in either static or kinematic mode, was designed to be simple to use with minimal input. It is based on accepted international standards such as the Receiver INdependent EXchange (RINEX) format (and its more compact Hatanaka variation) for the GPS observation data and the IGS antenna phase calibration values and equipment-naming conventions.

Currently, the only required input to CSRS-PPP is the GPS observation file, desired reference frame (NAD83-CSRS or the International Terrestrial Reference Frame–ITRF), receiver dynamics (static or kinematic), and the user's e-mail address. Additional information required for processing, such as observation type, initial receiver coordinates, antenna height and model (for precise phase-center location), is obtained directly from the submitted GPS observation file. CSRS-PPP estimates are based on the best orbit and clock products and GPS observations available at submission time. This data submission process is unchanged with the introduction of ultra-rapid products, but the delay between the epoch of the last observation in users' datasets and the time they can access their results was reduced from 17 hours to 90 minutes.

CSRS-PPP results are made available via a URL link provided in an e-mail sent to the user once processing is completed. Results include comprehensive graphical and text outputs allowing users to clearly assess the PPP solution.

CSRS-PPP results are computed for an epoch corresponding to the mid-point of the submitted GPS observation session for



▲ **FIGURE 1** Current NRCan ultra-rapid orbit (EMU) median RMS (a) (after a 7-parameter Helmert transformation; see Table 1) and clock median RMS (b) (after clock offset and drift removal). The graphs are divided into 3-hour bins for both the estimated and the predicted portions of the ultra-rapid product. The comparisons were made with respect to the IGS rapid product (IGR) from January 1 to July 1, 2008.

static processing and the exact epochs of observation for kinematic processing. Care must therefore be exercised to properly account for any epoch differences when comparing or combining CSRS-PPP position estimates with estimates from other sources. In some areas of Canada, for example, centimeter-level height differences could exist between CSRS-PPP position estimates and older estimates due to crustal dynamics from glacial isostatic adjustment, with rates reaching 1 centimeter per year in some areas.

Although the achievable PPP accuracy is very much a function of the implementation and accuracy of the models used in the PPP software, it is also dependent on the quality and content of the submitted observation files. Particularly troublesome are the many non-standard ways in which 1-millisecond clock resets are represented in RINEX observations files. Failures in properly detecting and accounting for 1-millisecond clock resets can sometimes lead to unexpected behavior of the software and incorrect PPP estimation. Ensuring a valid PPP solution is challenging for an automated PPP service. In CSRS-PPP, quality control is accomplished by a series of automated verifications and the provision of an output that contains sufficient information to facilitate final validation by the end-user.

Geodetic Control Products. Statistics collected by NRCan over the past eight years on usage of geodetic control products in Canada show that since 2004, a decline in requests for passive control (monument coordinates) has occurred along with a steady increase in the use of active control (continuous tracking station data or precise orbit/clock products). The possibility of establishing high-precision control at low cost using active control products along with the limited accessibility and accuracy of aging monuments are likely the cause for this trend. Since it was introduced, CSRS-PPP usage has increased at a rate of about 50 percent per year. To date, over 90 percent of CSRS-PPP data submissions have been from dual-frequency users operating in static mode.

NRCan Ultra-Rapid Products. The key to a more timely CSRS-PPP service was the development of NRCan ultra-rapid GPS products, which would not be possible without the raw data contributions from a large number of agencies around the globe to the IGS.

NRCan was one of the original IGS collaborating agencies, participating as an analysis center as well as performing other functions over the years. The collaborative global tracking network of more than 300 continuously operating GPS stations provides a rich data set that enables IGS analysis centers to generate precise GPS satellite orbit and clock solutions, among other products. The IGS GPS orbit and clock products are combined from the analysis centers' individual contributions and come in three categories that differ mainly by their latency: final, rapid, and ultra-rapid. The IGS final products are available 13 days after the last observation while the rapid products are available 17 hours after the end of the UTC day. The different latencies result from the varying delays in IGS station data availability, given the wide variety of data acquisition and communication schemes in use. The evolution of the IGS over the past several years from a daily to an hourly data-availability model prompted the development of sub-daily ultra-rapid orbit and clock products in early 2000, with the reliability and precision to support real-time and near-real-time applications.

IGS ultra-rapid products consist of a 48-hour set of satellite orbits, clocks, and earth rotation parameters (ERPs), with the first 24-hour portion derived from observed GPS data and the remaining 24-hour portion extrapolated for near-real-time and real-time applications. Up to seven analysis centers, including NRCan (products referred to as "EMU"), contribute ultra-rapid products to the IGS for optimal combination (products referred to as "IGU," for IGS ultra-rapid). The IGU products have a latency of 3 hours and are released four times a day using a 6-hour production cycle (03:00, 09:00, 15:00, and 21:00 hours UTC). Note that the acronym "EMU" comes from NRCan's former name: Energy, Mines, and Resources Canada.

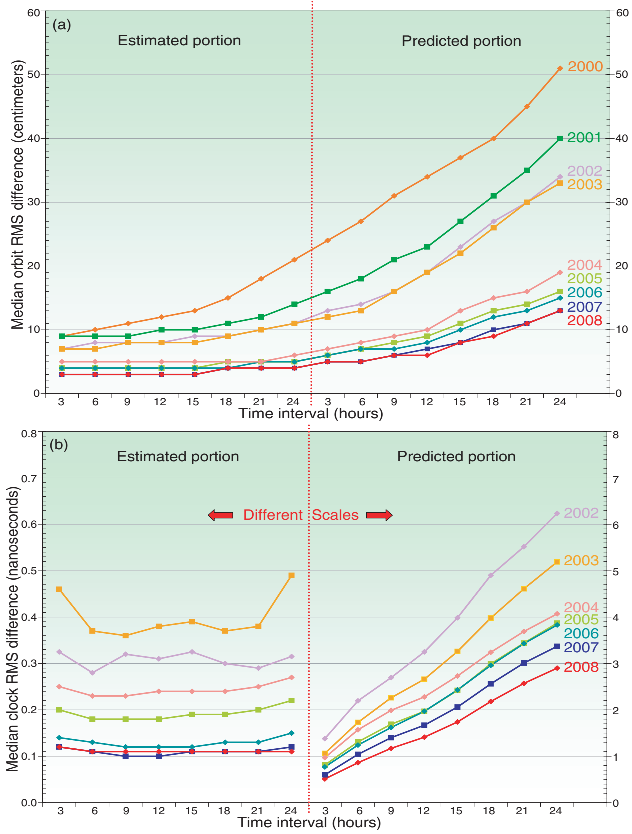
NRCan developed the EMU product starting in early 2000 using the Bernese v4.2 (later v5.0) software and implementing its own strategy within a highly automated system. The most important development milestones were computation of satellite clocks at 30-second intervals and moving from a 3-hour to a 1-hour production cycle.

Statistic	Translations (cm)			Rotations (mas)			Scale (ppb)
	X	Y	Z	X	Y	Z	
Mean	-0.11	-0.02	-0.04	-0.02	-0.01	0.01	-0.10
Std Deviation	±0.14	±0.17	±0.31	±0.13	±0.13	±0.22	±0.09
RMS	0.19	0.17	0.31	0.13	0.13	0.22	0.14
Minimum	-0.65	-0.70	-1.02	-0.45	-0.45	-0.77	-0.49
Maximum	0.52	0.65	1.44	0.53	0.45	0.85	0.28

▲ **TABLE 1** Overall statistics of the 7-parameter Helmert transformations between EMU and IGR (in units of centimeters, milliarcseconds, and parts per billion).

Within each hourly cycle, three basic steps are performed: data gathering, orbit computation, and clock computation. Given the availability of hourly observation files from about 200 globally distributed tracking stations at IGS data centers, about 100 are automatically selected and transferred locally. The file transfers are performed over the first 45 minutes of the hour, to maximize the number of stations available. Needless to say, the NRCan EMU process relies heavily on hourly IGS data files being made available in a timely manner at the end of each hour by the IGS data centers. From this dataset, 40 to 45 stations are included in the processing based on data span, data quality, and global coverage.

Orbit Products. For the orbit generation, our processing strategy is to form the normal equations (NEQ) from 3-hour independent batches of data and use these in a NEQ stacking (adding) scheme to generate orbits. Estimated parameters in each 3-hour processing batch include orbit parameters, station coordinates (some are constrained), station tropospheric zenith delay, and ERPs. A number of different sources of *a priori* orbits can be used to initiate the batch process, ranging from the previous EMU solution to the less precise broadcast ephemerides. *A priori* station coordinates and their associated standard deviations are taken from the IGS weekly combination (currently in the IGS05 reference frame) as computed by the IGS reference frame coordinator. The IGS05 reference frame is a GPS-only realization of the ITRF2005 frame and is updated on a weekly basis. For the *a priori* ERPs, the International Earth Rotation and Reference Systems Service Bulletin A is used. The procedure uses an elevation cutoff angle of 5 degrees. The Extended Center for Orbit Determination in Europe Orbit Model (ECOM) with six Keplerian elements and nine radiation pressure parameters is used. Integer ambiguity resolution is performed and unresolved ambiguities are left as real numbers. Each 3-hour session solution is followed by the stacking (or combination) of the previous ten 3-hour batch NEQ in order to generate more stable 30-hour orbital arcs and ERPs. Unconstrained station coordinates and tropospheric zenith delay estimates are combined as well. The orbit obtained via this process is then further validated with respect to the latest IGS combined orbit products in order to refine the EMU orbit prediction. The recent transition from a 3-hour to an hourly orbit processing scheme only required extending the last session by 1 hour (a 31-hour orbital arc) or 2 hours (a 32-hour orbital arc). No change was required for the clock processing strategy besides switching to the faster hourly computation cycle.



▲ **FIGURE 2** Historical NRCan ultra-rapid orbit (EMU) median RMS (a) and clock median RMS (b). The graphs are divided into 3-hour bins for both the estimated and the predicted portions of the ultra-rapid product. The comparisons were made with respect to the IGS rapid product (IGR).

As for any automated system, the ability to effectively deal with exceptions is paramount. Planned satellite maneuvers announced via the Notice Advisories to Navstar Users (NANUs) are accounted for by removing the unusable data periods and initiating a new independent orbital arc. On the other hand, unannounced satellite events (that is, any kind of spontaneous acceleration) cause real problems if not detected early enough and appropriately handled. In our current strategy, a separate process checks for problem satellites by estimating velocity pulses over several sessions. Very large changes in the pulse values indicate the approximate time an event has occurred. Problem satellite orbits are flagged and a new arc is started, similar to a planned maneuver. A better strategy, now in the planning stage, is to maintain a single arc while estimating a velocity pulse at the exact time of the event. For all planned and detected satellite maneuvers, the accuracy code of the problem satellite is adjusted and reported in the header of the orbit file, in Standard Product #3 (SP3) format according to IGS standards. In some cases, the arc for which we provide the satellite positions may be shortened to prevent user problems.

Clock Products. In the Bernese software, clock estimation is a separate process requiring orbits and ERPs to be held fixed. The last 24 hours of GPS data from 40 to 50 stations are gathered and the satellite and station clocks are estimated, fixing the orbits and ERPs to the most recent EMU solution. The network used for the clock estimation may slightly differ from the network used in generating orbits since it is further optimized to maximize the use of stations with stable (atomic) frequency standards (hydrogen maser, cesium, or rubidium). As in the orbit process, the elevation cutoff angle is set to 5 degrees, and station coordinates from the IGS weekly combination are constrained to their *a priori* standard deviations. Finally, satellite and station clocks along with station tropospheric zenith delays and real-valued ambiguities are estimated.

The hourly update of satellite clocks estimated on a shorter time interval (30 seconds) is an improvement that significantly affects the near-real-time usage of CSRS-PPP. After only a few months, we have noticed that almost 30 percent of the users requiring fast turnaround submit their data file on the same day as the data was collected, as opposed to the next one. The delay after which a new and complete EMU product is available is generally less than 90 minutes after its hour of applicability. This includes the 45-minute waiting time to gather station data, a 15-minute orbit/ERP processing time and a 30-minute clock processing time. The EMU hourly processing cycle combined with a 1.5-hour product latency means that the longest orbit prediction period for real-time use is actually 1.5 hours in comparison to a maximum of 9 hours, with the IGU 6-hour cycle. Although the majority of satellite orbit predictions are very good and do not require frequent updates, a faster cycle allows faster detection of marginal satellite orbits, thus reducing their impact and improving the general robustness of the product.

FIGURE 1 shows a comparison of the EMU orbit and clock products with respect to the IGS rapid solutions (IGR) for the period from January 1 to July 1, 2008. Results are shown after estimating and removing a 7-parameter Helmert transformation from the orbits and an offset and drift from the clocks. This is required for the clock products because the solutions compared are with respect to a different time reference. For the orbits, the 7-parameter Helmert transformation between the two products allows the evaluation and removal of systematic differences caused by reference frame realizations that are slightly different. Of course, users are directly affected by such differences. Figure 1a shows the cumulated time series of the 48-hour EMU orbit comparison with respect to IGR. This plot represents the precision users can expect when using a 48-hour EMU orbit. The graphic is split into two portions: 24 hours of estimated orbits (using real data) and 24 hours of predicted orbits, with each portion divided into 3-hour bins. Figure 1b shows a similar graphic but for EMU clock products. Notice the scale change between the estimated and predicted portions along the vertical axes. The estimated portion of the EMU product has a precision on the order of 3–4 centimeters for the orbits and about 0.12 nanoseconds for the clocks. EMU 3-hour and 6-hour orbit predictions are at the 5-centimeter level while the 12-hour and 24-hour orbit predictions are at the 6-centimeter and 13-centimeter levels respectively. Finally, the ultra-rapid clock prediction error grows linearly with time and can only be used for low-accuracy applications, since the ultra-rapid clock

Station	Days	Lat. (N)	Lon. (E)	Receiver	Antenna
ALIC	335-106	-23.6701	133.8855	ASHTECH UZ-12	AOAD/M_T
ALIC	122-136	-23.6701	133.8855	LEICA GRX1200GGPRO	AOAD/M_T
ALRT	335-136	82.4943	297.6595	ASHTECH UZ-12	ASH701945C_M
BAHR	335-136	44.3950	291.7783	ASHTECH Z-XII3	ASH700936B_M
GUAM	335-136	13.5893	144.8683	ASHTECH Z-XII3	ASH701945B_M
HARB	335-136	-25.8869	27.7075	ASHTECH UZ-12	TRM29659.00
KOKB	335-75	22.1263	200.3351	ASHTECH UZ-12	ASH701945G_M
NRIL	335-136	69.3618	88.3598	ASHTECH UZ-12	ASH701945C_M
STJO	335-136	47.5952	307.3223	AOA BENCHMARK ACT	AOAD/M_T
SYOG	335-62	-69.0070	39.5837	TRIMBLE NETRS	AOAD/M_T
THTI	335-136	-17.5769	210.3937	ASHTECH UZ-12	ASH701945E_M
USN3	335-136	38.9206	282.9337	ASHTECH Z-XII3T	AOAD/M_T
WHIT	335-136	60.7505	224.7779	AOA SNR-8000 ACT	AOAD/M_T

▲ **TABLE 2** Stations and day ranges in 2007 and 2008 used for evaluating the orbit and clock products in PPP

Product	Static (cm)		Kinematic (cm)	
	Horizontal	Vertical	Horizontal	Vertical
EMU 30-second clock	0.81	1.31	2.92	4.36
EMU 5-minute clock	0.89	1.41	10.18	14.17
IGR 5-minute clock	0.69	1.14	5.91	8.87
IGS 30-second clock	0.62	1.02	2.23	4.01
IGS 5-minute clock	0.67	1.13	6.75	9.47

▲ **TABLE 3** RMS of CSRS-PPP dual-frequency solutions with respect to IGS cumulative solutions using 132 24-hour, 30-second RINEX observation files and various orbit and clock products

Product	No. epochs	RMS error using 24h of 30-sec data for 12 stations (cm)			No. epochs	RMS error using 3h of 1-sec data for 3 stations (cm)		
		Lat.	Lon.	Ht.		Lat.	Lon.	Ht.
EMU 30-second clock	373964	1.73	2.35	4.36	32400	1.21	2.58	3.39
EMU 5-minute clock	373965	7.96	6.35	14.17	32400	4.20	5.29	11.51
IGS 30-second clock	373966	1.32	1.80	4.01	32400	1.38	2.94	3.29
IGS 5-minute clock	373966	4.45	5.08	9.47	32400	4.17	5.27	11.03

▲ **TABLE 4** Clock interpolation impact on kinematic PPP accuracy

product is generally only slightly better than (or at the same level as) the GPS broadcast clock parameters.

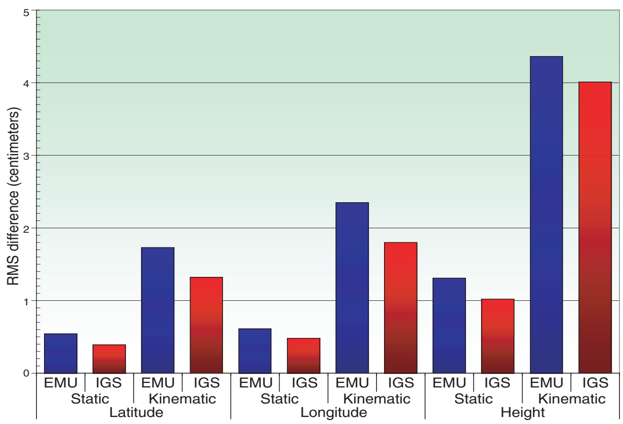
TABLE 1 shows the estimated 7-parameter Helmert transformations between EMU and IGR for the same period. Overall, the transformation parameter values are small with some exceptions. Comparisons without applying a 7-parameter Helmert transformation give a median orbit root-mean-square (RMS) difference similar to the ones found in Figure 1a, except for the longer prediction periods where increases of up to 2–3 centimeters are noticed. For completeness, **FIGURE 2** shows the constant progress made in terms of precision over the years for both the EMU orbit (2000–2008) and clock (2002–2008) products.

CSRS-PPP Accuracy Evaluation

Because CSRS-PPP uses different GPS orbit and clock products depending on the time of a user's data submission, it is worth assessing the accuracies of CSRS-PPP position estimates using the different products. We selected a 12-station global network (see **TABLE 2**) for the assessment based solely on a wide geographic distribution of the stations. Different products were used to process RINEX files with observations at 30-second intervals collected over 24 hours on the 1st and 15th day of each month, from December 2007 to May 2008. The matching orbit and clock products involved were the IGS final orbits with satellite clocks at 30-second and 5-minute intervals, IGS rapid orbits with 5-minute clocks, and NRCan hourly orbits with 5-minute and 30-second clocks. There are no 30-second clocks for the IGS rapid products. Data files spanning 24 hours were selected to ensure convergence of the carrier-phase ambiguities, which is essential for the highest accuracies of carrier-phase-based PPP solutions. CSRS-PPP settings used for the evaluation were identical to those used for the standard online service: the ionosphere-free combination of L1 and L2 data, 2-meter and 15-millimeter *a priori* standard deviations for pseudorange and carrier-phase observations, and 10-degree elevation cutoff angle. Dual-frequency receivers tracking either the C/A or P(Y) code on L1 were used.

To evaluate kinematic mode processing, the datasets observed in static mode were re-processed, since suitable kinematic datasets with known trajectories were not readily available. This represents a best-case scenario due to the absence of gaps in tracking that are more common in real kinematic datasets. We feel, however, that the kinematic results still represent a realistic estimate of the achievable kinematic PPP accuracies, since the tracking problems would more likely be related to receiver design and antenna placement issues rather than inherent to the PPP approach. For either the static or kinematic modes, IGS05 coordinates from the Solution INdependent EXchange (SINEX) formatted cumulative solution with the appropriate epoch correction were used in this analysis.

TABLE 3 lists the horizontal and vertical position RMS differences between CSRS-PPP estimates and the cumulative IGS estimates in both static and kinematic modes. No transformations were applied to either position sets. Out of the potential 144 RINEX files based on the 12 stations over the 12-day scenario, 132 were used in the analysis. Only two RINEX files (from station NRIL on days 32 and 122 in 2008) were screened out due to abnormal behavior in kinematic processing, which is under investigation. The other missing 10 datasets were simply not available or incomplete on the selected days. The significant differences in accuracies between the solutions based on 5-minute



▲ **FIGURE 3** RMS of CSRS-PPP position differences with respect to IGS cumulative solutions based on EMU 30-second orbits and clocks and IGS 30-second final orbits and clocks using 24-hour, 30-second dual-frequency pseudorange and carrier-phase RINEX data files (see also Table 4).

clocks and those using 30-second clocks are due to the interpolation of the 5-minute clocks down to the 30-second data rate.

To confirm that the performance improvement in PPP kinematic results with 30-second instead of 5-minute satellite clocks was indeed caused by interpolation — and not just an artifact of processing observations and clocks referred to a common epoch — we also performed a limited evaluation with 1-second datasets. For this purpose, we processed 3 hours of 1-second data from stations NRIL, STJO, and USN3 from April 1, 2008. **TABLE 4** lists the RMS of the position differences for both the 5-minute and 30-second clock products and 30- and 1-second data sampling. The similar ratios of the 5-minute versus 30-second-based PPP estimates for both EMU and IGS products clearly show that the improved performance is due to more frequent clock estimates.

The position differences listed in Tables 3 and 4 show how well the EMU products perform in CSRS-PPP when compared to the conventional IGS products. **FIGURE 3**, based on processing dual-frequency pseudorange and carrier-phase observations together with 30-second GPS clocks for the best PPP accuracies possible — reaching the subcentimeter level in horizontal coordinates and less than 2 centimeters in the vertical coordinate — highlights just how similar the accuracies obtained with the near-real-time EMU products are compared to IGS final products. This is encouraging given that EMU products are available within 90 minutes, as opposed to one or more days for IGS rapid and final products.

Although we have presented only dual-frequency, pseudorange, and carrier-phase PPP accuracy results in this article, a carrier-phase smoothed L1-only pseudorange solution that uses global IGS ionospheric total-electron-content grids is also available from CSRS-PPP. As expected, the accuracy of this solution is much lower than the dual-frequency solution reported here. Better suited for PPP is the L1 pseudorange and carrier-phase ionosphere-free combination. Accuracies obtained in static positioning using this single-frequency ionosphere-free combination with data from the network of Table 2, are about 4 centimeters and 8 centimeters RMS in the horizontal and vertical components, respectively. This represents a clear improvement over the current CSRS-PPP single-frequency-smoothed-pseudorange solution at about 25 centimeters and 65 centimeters. To work properly, however, the quality of the pseudoranges used in the combination must be good (usually well below the meter level). An L1 ionosphere-free solution could eventually be offered in the online version of CSRS-PPP after more thorough evaluation and testing demonstrates that it can perform reliably and in an automated fashion.

Summary

We have provided a brief overview of the performance of NRCan's PPP solution based on the recent release of NRCan ultra-rapid orbit and clock products (EMU). These low-latency hourly products with centimeter-level precision are produced on a continuous basis, 24 times a day, seven days a week. They enable the computation of CSRS-PPP results only 90 minutes after users complete their data collection, providing horizontal and vertical positioning accuracies at the sub-centimeter and centimeter level (respectively) in static mode, and at the sub-decimeter level in kinematic. This performance level, along with the relative simplicity for the user, makes PPP a tool of choice to gain access to global and related national reference frames from products created collaboratively with IGS. For the user, all that is needed is a RINEX file with good quality GPS data of sufficient duration to ensure proper estimation of the carrier-phase ambiguities.

While we limited our discussion to the evaluation of GPS orbit and clock products from a positioning perspective using the PPP methodology, it is worth mentioning that total zenith tropospheric delay and receiver clock estimates may also be parameters of interest to some user groups. These groups may also benefit from the availability, in near real time, of products and services now offered by NRCan. The CSRS-PPP online service can be found at *http://www.geod.nrcan.gc.ca/online_data_e.php*.

Acknowledgments

The authors are grateful to all IGS contributing agencies and to the individuals who initiated the ultra-rapid product in 2000. Continued scientific collaboration within IGS and public access to its reliable data and products were key in achieving the results presented.

YVES MIREAULT, PIERRE TÉTREAULT, FRANÇOIS LAHAYE, and **PIERRE HÉROUX** develop GPS solutions to improve reference frame realization and access at the Geodetic Survey Division, Natural Resources Canada, Ottawa, Ontario.

JAN KOUBA is a former IGS analysis center coordinator and emeritus scientist at the Geodetic Survey Division, Natural Resources Canada, from where he retired in 1998.

MORE ONLINE

Further Reading

For references related to this article, go to *gpsworld.com* and click on **Innovation** under **Resources** in the left-hand navigation bar.

FURTHER READING

• Precise Point Positioning

"GPS Time Transfer: Using Precise Point Positioning for Clock Comparisons by F. Lahaye, D. Orgiazzi, P. Tavella, and G. Cerretto in *GPS World,* Vol. 17, No. 11, November 2006, pp. 44–49.

Precise Point Positioning Using Un-Differenced Code and Carrier Phase Observations by M. Abdel-Salam, Ph.D. dissertation, UCGE Report 20229, University of Calgary, Alberta, Canada, 2005.

"Products and Applications for Precise Point Positioning–Moving Towards Real-Time" by P. Héroux, Y. Gao, J. Kouba, F. Lahaye, Y. Mirault, P. Collins, K. MacLeod, P. Tétreault, and K. Chen in *Proceedings of ION GNSS 2004,* the 17th International Technical Meeting of the Satellite Division of The Institute of Navigation, Long Beach, California, September 21–24, 2004, pp. 1832–1843.

"Precise Point Positioning Using IGS Orbit and Clock Products" by J. Kouba and P. Héroux in *GPS Solutions, Vol. 5, No. 2, 2001, pp. 12–28.*

• Canadian Spatial Reference System

"Space Geodetic Techniques and the Canadian Spatial Reference System Evolution, Status and Possibilities" by P. Héroux, J. Kouba, N. Beck, F. Lahaye, Y. Mireault, P. Tétreault, P. Collins, K. MacLeod, and M. Caissy in Geomatica, *Canadian Spatial Reference System special issue,* Vol. 60, No. 2, 2006, pp. 137–150.

• IGS Products

"The International GNSS Service: Any Questions?" by A.W. Moore in *GPS World,* Vol. 18, No. 1, January 2007, pp. 58–64.

"Guide to Using International GPS Service (IGS) Products" by J. Kouba, online publication http://igscb.jpl.nasa.gov/igscb/resource/pubs/GuidetoUsingIGSProducts.pdf, 2003.

"Moving IGS Products Towards Real-Time" by G. Gendt, P. Fang, and J. F. Zumberge in *IGS 1999 Technical Reports,* published by the IGS Central Bureau, Jet Propulsion Laboratory, Pasadena, California, November 2000, pp. 391–403.