Real-Time WADGPS Corrections from Undifferenced Carrier Phase

Paul Collins, François Lahaye, Jan Kouba and Pierre Héroux

Geodetic Survey Division, Geomatics Canada, Natural Resources Canada

BIOGRAPHIES

Paul Collins is a Research Officer in the Active Control Systems Section, Geodetic Survey Division of Geomatics Canada, Natural Resources Canada.

François Lahaye and Pierre Héroux are Senior Research Officers in the Active Control Systems Section, Geodetic Survey Division of Geomatics Canada, Natural Resources Canada.

Jan Kouba is actively retired from the Active Control Systems Section, Geodetic Survey Division of Geomatics Canada, Natural Resources Canada.

ABSTRACT

The Geodetic Survey Division (GSD) of Natural Resources Canada (NRCan) is currently enhancing its real-time Wide Area Differential GPS system with carrier phase processing. This development is aimed at improving the quality of GPS satellite clock corrections to facilitate real-time carrier phase Precise Point Positioning (PPP). By-products of this development are precise estimates of station clocks and tropospheric zenith delays both at the wide-area reference stations, and potentially at any user's site.

Preliminary results indicate that tropospheric zenith delays can be recovered with an RMS accuracy of approximately one centimetre, station clock corrections can be recovered with an RMS accuracy of 0.1-0.2 nanoseconds, and satellite clock corrections can be recovered with an RMS accuracy of approximately one nanosecond. Positioning tests with dual frequency data indicate that RMS accuracies between 10 and 30cm can be achieved in latitude, longitude and height.

INTRODUCTION

The Geodetic Survey Division (GSD) of Natural Resources Canada (NRCan) operates a 12-station real-time reference network and control system to compute wide-area differential corrections for GPS users. The locations of the stations throughout Canada are shown in Figure 1. This system is an extension of the GSD's Canadian Active Control System (CACS) [*Duval et al.*, 1996]. The stations are designated as Real-Time Active Control Points (RTACP's) and each is equipped with an atomic frequency standard and an Allen Osborne Associates *Benchmark* or *Turbo-Rogue(ACT)* dual frequency GPS receiver. Observation and ephemeris data is transmitted at 1 Hz rate via frame relay over terrestrial and satellite communications networks. A Master Active Control Station (MACS) in Ottawa receives the data, computes the wide-area corrections (known as GPS·C) and formats them for distribution. Technical information on the system architecture can be found in *Caissy et al.* [1996] and initial positioning results in *Lahaye et al.* [1997]. The current production system is reaching maturity in terms of robustness, and a plan is underway to broadcast the real-time GPS·C corrections by the Canadian Differential GPS (CDGPS) Service via the MSAT geostationary satellite. The CDGPS Service is a collaboration of provincial, federal and territorial government agencies. The GPS·C corrections will be broadcast at no cost to users

In the current production system, satellite and station clock corrections are estimated every two seconds from phase-smoothed ionosphere-free pseudoranges. These corrections are then formatted into RTCA-like messages for relay to the user. Single frequency users are also provided with a grid of ionospheric corrections, computed from the same data. In the current system, the Ultra-Rapid orbit product (IGU) of the International GPS Service (IGS) is used to provide an improvement over the broadcast orbit. The ephemeris for each satellite is

ION-NTM-2001, January 22-24, Long Beach, California.

transformed into the broadcast orbit format to allow efficient distribution to the users. This transformation occurs approximately once-per-hour to retain a centimetre level representation of the satellite coordinates. If the IGU product is not available, or is incomplete, a hierarchy is in place to select individual satellite ephemerides from other sources. These are consecutively: the IGS Predicted orbit (IGP), the GSD contribution to the IGP, and lastly, the most recent broadcast parameters. The primary source of satellite ephemerides will soon be augmented by the GSD contribution to the IGU so that more frequent updates (every three hours) can be applied. This will also maintain the current level of redundancy should the IGP product be discontinued.

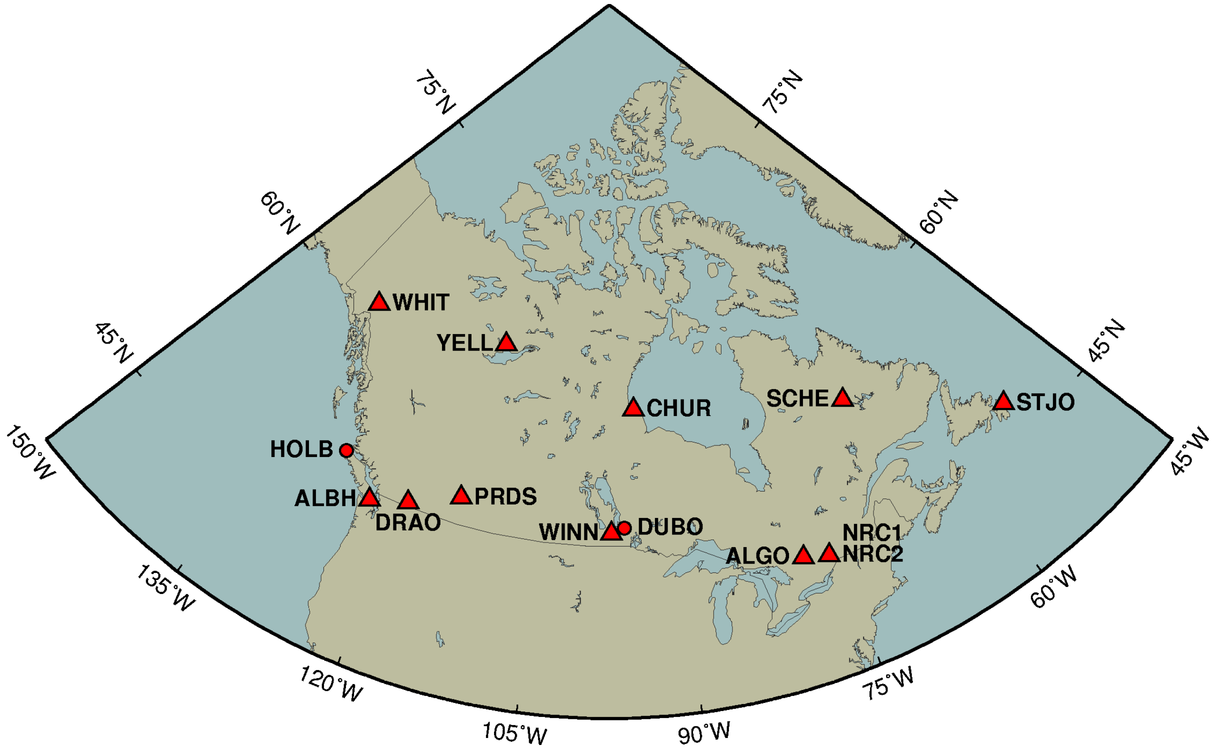

Figure 1. Current CACS network of real-time automated tracking stations (triangles), and validation stations used in this paper (circles).

For future MACS processing, we are investigating the use of the undifferenced carrier phase observable. The main reasons are twofold. The first reason is to enable decimetre level positioning in real-time for users across Canada equipped with dual-frequency receivers. The second reason is to continue to leverage products for other applications, i.e. more precise station clock estimates for high accuracy time transfer, and estimation of precipitable water content to further atmospheric investigations. It is also intended that these latter two parameters will be available to remote users as by-products of real-time Precise Point Positioning (PPP) undertaken with the wide-area corrections. This paper presents our initial experiences with processing carrier phase observations in real time at the MACS and the expected impact on real-time PPP.

METHODOLOGY

The carrier phase processing is based around the phase-smoothed code processing currently implemented. The least squares engine differs to a large extent due to the additional parameters required for phase processing and for sequential filtering with process noise.

Data pre-processing

Carrier phase data is retrieved from the network every second and filtered to detect cycle slips. The current technique uses single-station widelane and narrowlane phase-only combinations triple-differenced over time. This particular method is being investigated because initial testing indicated that filtering the two ‘usual’ combinations — the phase geometry-free delay and the code-phase widelane combination — was prone to excessive miss-detection of cycle slips. This alternative method has shown more constant, noise-like time series’ (see Figure 2 and Figure 3) than the other two combinations.

One advantage of using the widelane and narrowlane combinations in this way is that their complementary nature can be exploited. The noise on the narrowlane combination can often exceed the one-cycle level, especially over short gaps of several-seconds, and so the threshold is set to two cycles. The only cycle slips that will be missed at this level on the narrowlane always exceed the one cycle threshold on the widelane. Other advantages of this method include: no reliance on pseudorange data (that can often raise the detection threshold of the code-phase widelane combination above the one-cycle level), the possibility of detecting cycle slips several epochs afterward (due to amplification by the triple differencing), and no polynomial fitting or statistical windowing is necessary (which reduces execution time).

One disadvantage is that even comparatively short data gaps greater than several seconds long can trigger an apparent cycle slip and there is no way to distinguish between a clock jump and a common cycle slip. This method also relies on the fact that every station in our network is equipped with an atomic clock to control the residual geometric portion of the delay. It may be possible, now that Selective Availability has been turned off, to perform a secondary check by computing single differences between satellites to remove the common station clock portion. Finally, due to the real-time nature of the data flow, no attempt is made to distinguish between outliers and cycle slips. In effect, any outlier is flagged as a cycle slip, requiring the estimation of a new ambiguity parameter.

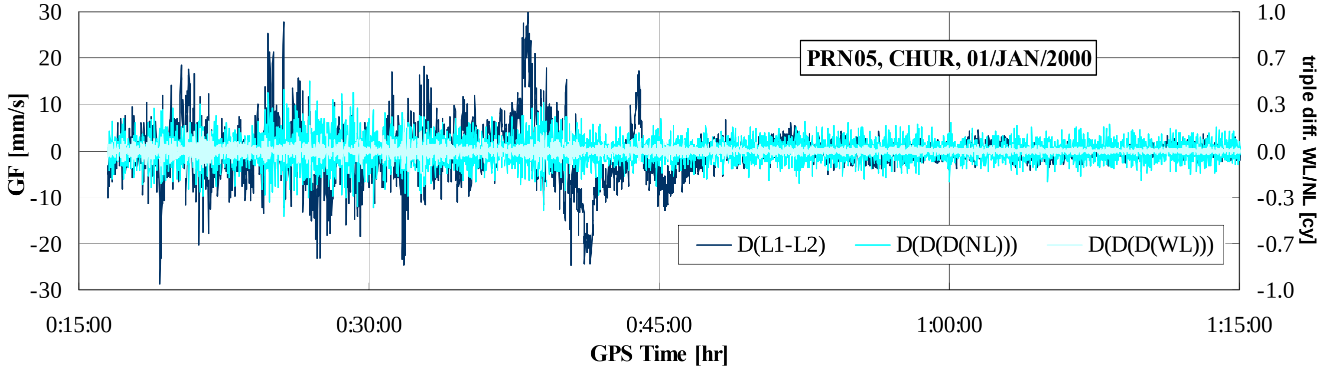

Figure 2. One-hour sample of widelane (WL) and narrowlane (NL) carrier phase data, triple-differenced in time compared to the geometry free (GF) delay.

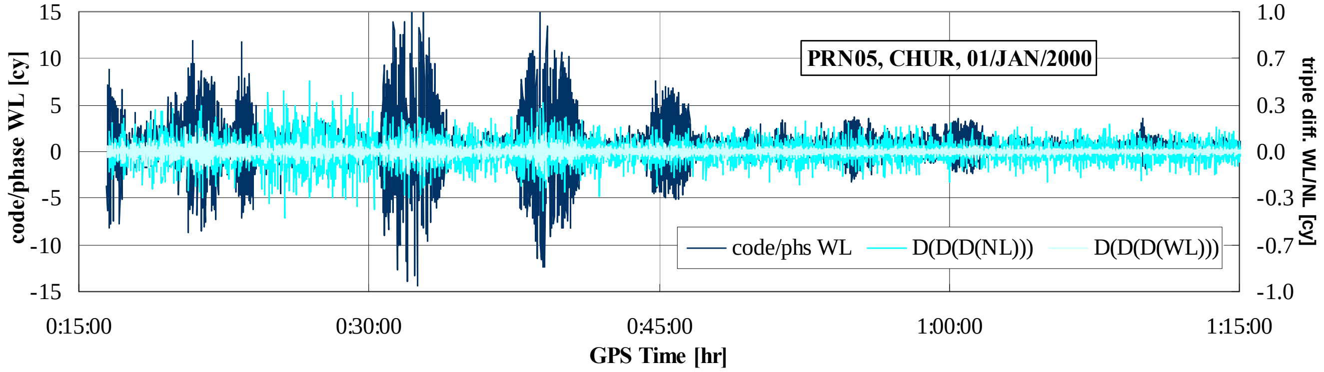

Figure 3. One-hour sample of widelane (WL) and narrowlane (NL) carrier phase data, triple-differenced in time compared to the code/phase widelane combination.

Parameter Computation

The least squares formulation and observation misclosure models closely parallel those required for the single-station PPP technique [see e.g. *Kouba and Héroux*, 2000]. Here however, we require additional partial derivatives in the design matrix for the satellite clock parameters. The current calibration models include the satellite antenna offsets, carrier phase wind-up, periodic special relativity, solid earth tides, ocean tide loading, and the sub-daily tidal earth rotation correction. These closely follow those models specified in the IERS Conventions [*McCarthy*, 1996] and represent the current standards used in IGS processing. Station and satellite coordinates are held fixed in the Canadian Spatial Reference System, NAD83(CSRS98) [*Craymer et al.*, 1998]. The observables are the ionosphere-free combinations of both the dual frequency pseudoranges and carrier phases weighted with an exponential function of elevation angle, scaled by an appropriate factor.

The parameters are computed every two seconds via a sequential least-squares filter. The weight matrix is used to propagate any required states between epochs. Station and satellite clocks are treated as random or white noise parameters, tropospheric zenith delays are treated as random walk processes, and the ambiguity parameters are treated as constant bias parameters. No attempt is currently made to fix the ambiguities to integer values. To minimise storage requirements while retaining a rigorous solution, any parameter deemed to have been deleted is eliminated by computing the reduced normal matrix [*Kouba*, 1972]. As such, the clock parameters are eliminated *en masse* at every epoch and individual ambiguity and zenith delay parameters are eliminated when the satellite or station is deemed to have dropped out (currently, after a 5 minute period of no observations).

Because of the simultaneous estimation of both station and satellite clock parameters, the inherent singular nature of the design matrix must be overcome. This is presently achieved by fixing the clock of one station, usually a hydrogen maser. However, the software is designed to allow *a-priori* weighting of all the clocks and to operate with a Virtual Reference Clock (VRC). The VRC is defined as a running mean of selected clocks in the solution. The *a-priori* least squares clock weights are chosen to reflect short-term noise levels, and weights for the VRC model are based on long-term clock behaviour. Discontinuities due to clock resets are closely monitored to allow for down weighting in the VRC solution. More details can be found in *Lahaye et al*. [1998].

RESULTS

Since November 2000 the phase processor has been running in real-time on our MACS development platform. The results presented here are extracted from one week of data between December 24 and 30, GPS week 1094. The clock and tropospheric parameters computed by the MACS real-time phase processor were compared to the same parameters extracted from the GSD contribution to the IGS final orbit product. These daily solutions (which we will designate as GSD Final or GSDF) are post-processed with a latency of one week-or-so using the GIPSY processing suite developed at JPL (Jet Propulsion Laboratory). The parameters are available every 7.5 minutes and are differenced directly with the phase parameters derived in real-time.

The timeliness of the GSDF solution makes it useful as an assessment tool, but because of the global nature of the solution, the scope for direct comparison can be limited. In general, only 4-6 RTACP stations are used in the GSDF solution, however for week 1094 seven stations were included. These were ALGO, CHUR, DRAO, NRC1, NRC2, STJO and YELL. Station NRC2 dropped out on December 27, day 3. Station ALGO was used as the reference clock in both solutions.

Station Troposphere Parameters

Figure 4 shows the results for the tropospheric zenith path delay differences with respect to the GSD Final solution. The overall RMS difference is 0.7cm. The seven stations are summarised individually in Table 1.

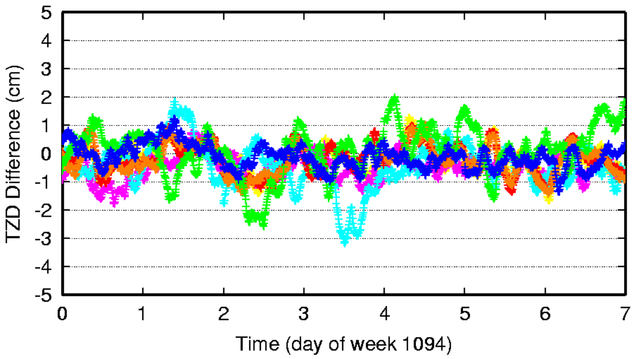

Figure 4. Tropospheric zenith path delay differences (GSDF–real-time) for week 1094. RMS = 0.7cm.

Table 1. Statistics for tropospheric zenith path delay differences (GSDF–real-time).

ΔTZD (cm)	**mean**	**std.dev.**
ALGO	–0.2	0.5
CHUR	–0.5	0.4
DRAO	–0.4	0.8
NRC1	–0.2	0.5
NRC2	–0.2	0.5
STJO	0.1	0.9
YELL	–0.1	0.4
Overall	–0.2	0.6

Station Clock Parameters

Interpreting the station and satellite clock results is less straightforward than for the troposphere delays. The primary reason is that the MACS processor currently uses the old pseudorange observation convention of CA and synthesised P2 to provide satellite clock corrections valid for single frequency pseudorange users. The GSDF solutions on the other hand, use the current IGS P1 and P2 pseudorange convention (see e.g., IGSMail #3160; http://igscb.jpl.nasa.gov/mail/igsmail/2001/msg00008.html). No corrections for the so-called <P1–C1> biases are made to the observations of either solution, so we must expect this to cause some differences which will primarily show up in the station and satellite clocks. In addition to this there are breaks at the day boundaries of the GSDF solutions due to the daily nature of the data processed.

Figure 5 shows the results for the station clocks. To mitigate the problems described above, daily straight-line trends have been removed from the results of each station. Some of the stations are corrupted due to jumps in the real-time solutions after data gaps of up to one or two minute's duration. For example, there is a common jump in day 2 where the real-time reference station dropped out for a short period. There are also several excursions in the real-time results (at a magnitude of 1ns) that occur after repeated data gaps. A few problems are due to the GSDF solution, such as station YELL where jumps in both solutions do not occur simultaneously. Where results are continuous however, the daily RMS difference between the two solutions is at the 0.1-0.2 ns level. The overall RMS difference of all the results is 0.4ns.

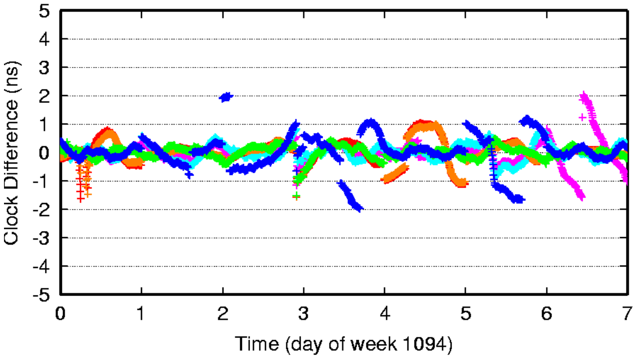

Figure 5. Station clock differences (GSDF–real-time) for week 1094. RMS = 0.4ns.

Satellite Clock Parameters

Figure 6 shows the satellite clock differences for week 1094. Again, daily straight-line trends have been removed from the results of each satellite. The overall RMS difference is 1.1ns. Satellites observed from only one station and satellites processed using broadcast orbits have been removed from the comparison. These satellites exhibit significant biases because of solution weakness due to observing from only one station and the poor accuracy of the broadcast orbits, respectively.

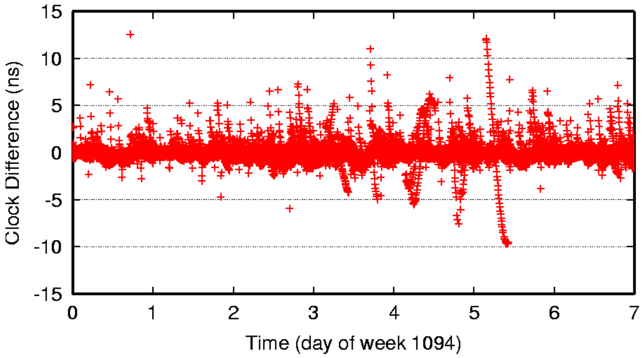

Figure 6. Satellite clock differences (GSDF–real-time) for week 1094. RMS = 1.1ns.

User Positioning Tests

Precise Point Positioning on independent station data provides a test of the real-time use of the wide area corrections. For this purpose, two IGS stations situated within our network footprint were used as validation sites. Stations HOLB (Holberg, B.C.) and DUBO (Lac du Bonnet, Manitoba) are part of the Western Canada Deformation Array, operated by the Geological Survey of Canada (Pacific), NRCan, Sidney, B.C. Figure 7 and Figure 8 show the differences with respect to known coordinates from the results of Precise-Point-Positioning (in kinematic mode) one day of 30-second data from each site. While there are several periods of metre level excursions, there are long periods of consistent decimetre level differences (see Table 2).

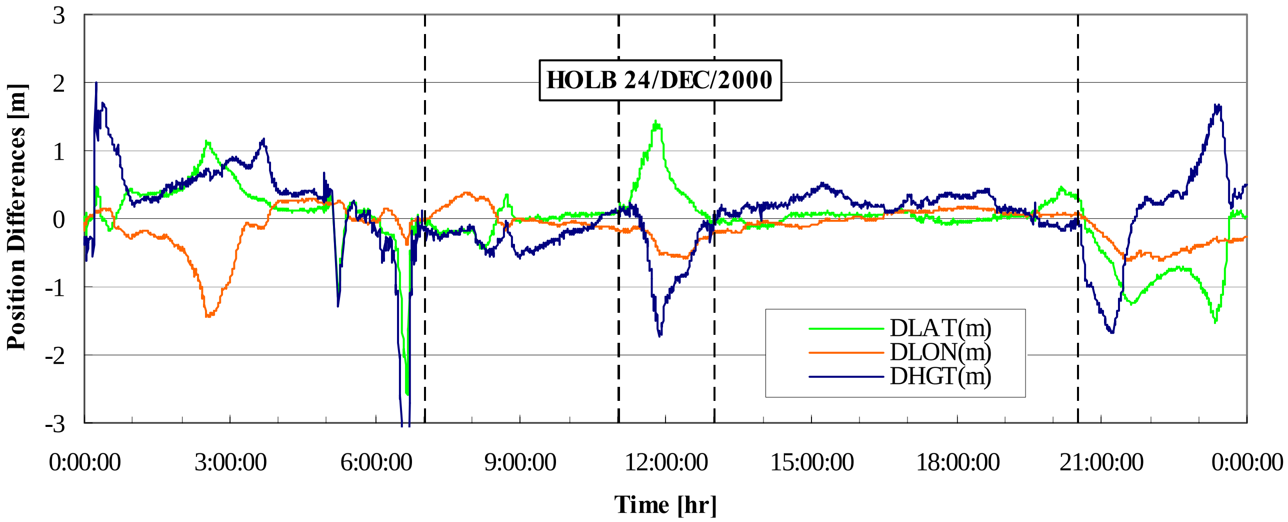

Figure 7. Dual frequency user positioning at HOLB.

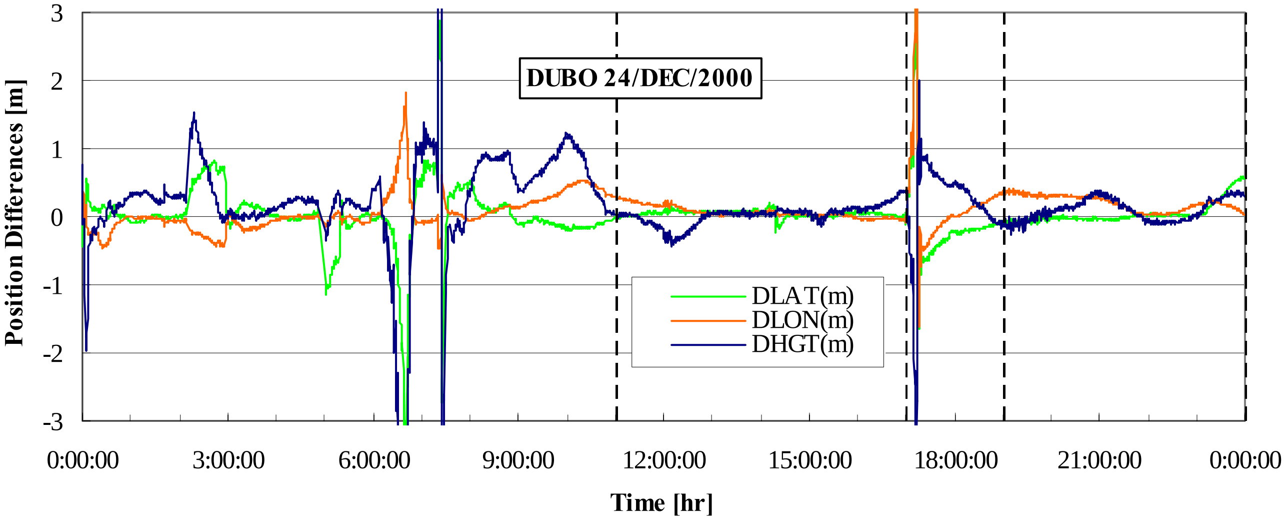

Figure 8. Dual frequency user positioning at DUBO.

Table 2. Dual frequency user positioning statistics.

HOLB 7hr-11hr	**lat.**	**lon.**	**hgt.**
mean (m)	–0.05	0.04	–0.25
std.dev. (m)	0.15	0.16	0.16
RMS (m)	0.16	0.17	0.30
HOLB 13hr-20½hr	**lat.**	**lon.**	**hgt.**
mean (m)	0.04	0.02	0.20
std.dev. (m)	0.11	0.10	0.15
RMS (m)	0.12	0.10	0.25
DUBO 11hr-17hr	**lat.**	**lon.**	**hgt.**
mean (m)	0.04	0.07	0.02
std.dev. (m)	0.05	0.08	0.14
RMS (m)	0.06	0.11	0.15
DUBO 19hr-24hr	**lat.**	**lon.**	**hgt.**
mean (m)	0.04	0.20	0.09
std.dev. (m)	0.15	0.11	0.16
RMS (m)	0.16	0.23	0.19

To obtain these results, satellites observed from only one station and satellites for which no IGU orbits were available were removed. Significant improvements were seen after removing the one satellite with an IGP ephemeris. This indicates that some of the positioning excursions could be due to the quality of the orbits and the related quality of clock corrections derived from those orbits.

CONCLUSIONS

The Geodetic Survey Division of Natural Resources Canada has implemented the initial testing and evaluation of a carrier phase wide-area differential GPS correction system. Initial results from both user positioning tests, and comparisons of the satellite clock, station clock, and station tropospheric parameters from the reference network, demonstrate the overall methodology and show that decimetre level positioning can be achieved for users with dual-frequency receivers.

Compared to a post-processed global solution, tropospheric zenith delays were recovered from the reference network in real-time with an RMS accuracy of 1cm or less. The station and satellite clock parameters were recovered at the 0.1-0.2ns and 1.1ns level respectively. Some of the differences in the station and satellite clock parameters are due to the different pseudorange convention of the post-processed solution, of which only the average effect can be removed. When these clock corrections were used in tests of real time Precise Point Positioning however, decimetre level positioning was achieved over 4-7 hour periods.

Further work is required to achieve decimetre level positioning continuously. Experience with the broadcast and predicted orbits indicates that the orbit quality for all satellites must be consistent throughout the computation and application of the wide area corrections. Therefore, the use of individual satellite weighting and real-time orbit improvement is currently being investigated.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the important contributions made by their colleagues in the Geodetic Survey Division towards the work presented here.

REFERENCES

Caissy, M., P. Héroux, F. Lahaye, K. MacLeod, J. Popelar, J. Blore, D. Decker, and R. Fong (1996). "Real-Time GPS Correction Service of the Canadian Active Control System." *Proceedings of ION GPS-96*, The 9th International Technical Meeting of the Satellite Division of the Institute of Navigation, Kansas City, Missouri, USA, September 17-20; pp. 1787-1791. (http://www.geod.nrcan.gc.ca/docs/PDF/Real-Time_Correction.pdf)

Craymer, M., R. Ferland and R. Snay (1998). "Realization and Unification of NAD83 in Canada and the U.S. via the ITRF." *Towards an Integrated Global Geodetic Observing System (IGGOS)*, Ed. R. Rummel et al., Proceedings of the IAG Section II Symposium, Munich, Germany, October 5-9, pp.118-121. (http://www.geod.nrcan.gc.ca/products/html-public/GSDpublications/Papers/English/Pdf/nad83csrs.pdf)

Duval, R., P. Héroux, N. Beck (1997). "Canadian Active Control System – Delivering the Canadian Spatial Reference System." Originally presented at GIS `96, Vancouver, Canada, March 1996. http://www.geod.nrcan.gc.ca/products/htmlpublic/GSDpublications/Delivering_the_CSRS/English/Delivering_CSRSe.html

Kouba, J. (1972). "Principal Property and Least Squares Adjustment Design." *The Canadian Surveyor*, Vol. 26, pp. 136-145.

Kouba, J. and P. Héroux (2000). "GPS Precise Point Positioning Using IGS Orbit Products." Submitted to *GPS Solutions*.

Lahaye, F., M. Caissy, P. Héroux, K. MacLeod and J. Popelar (1997). "Canadian Active Control System Real-Time GPS Correction Service Performance Review." *Proceedings of the National Technical Meeting of the Institute of Navigation*, Santa Monica, California, USA, January 14-16; pp. (http://www.geod.nrcan.gc.ca/html-public/GSDpublications/ION97paper/Jan97IONGPS_C.html)

Lahaye, F., M. Caissy, J. Popelar and R.J. Douglas (1998). "Real-Time GPS Monitoring of Atomic Frequency Standards in the Canadian Active Control System (CACS)." *Proceedings of the 30th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, Reston, Virginia, USA, December 1-3, pp. 187-198. (http://www.geod.nrcan.gc.ca/products/html-public/GSDpublications/Papers/English/RealTime_GPS_Monitoring/1998RealTimeGPS.html)

McCarthy, D.D. (Ed.) *IERS Conventions*. IERS Technical Note 21, Observatoire de Paris, 1996.