GPS Precise Point Positioning with a Difference*

Pierre Héroux and Jan Kouba
Geodetic Survey Division, Geomatics Canada
Natural Resources Canada
615 Booth Street
Ottawa, Ontario
K1A 0E9

heroux@geod.nrcan.gc.ca
kouba@geod.nrcan.gc.ca

Abstract

The introduction of Selective Availability (SA) has degraded the precision attainable using the Global Positioning System (GPS) at a single epoch with a single receiver to about 100 metres. Most GPS users who require higher precision now operate differentially with respect to a known reference to eliminate the effects of SA and significantly reduce common station errors. As the distance between a roving receiver and its reference increases, the commonality of errors is reduced and applying range corrections from a single reference station may not provide optimal results. This problem is usually addressed by operating differentially with respect to a network of reference stations.
[1]

The 'difference' this paper proposes is the use of precise satellite orbits and clocks for point positioning. Daily, the Geodetic Survey Division (GSD), Natural Resources Canada (NRCan) generates precise GPS satellite orbits and clocks in a standard format which are contributed to the International GPS Service for Geodynamics (IGS). Higher frequency satellite clocks are subsequently computed from the Canadian Active Control System (CACS). These products can be included in a point positioning software interface and provide high precision to users operating a single GPS receiver. With the use of quality receivers, this rather simple approach can offer precision of one metre or better and satisfy a wide range of spatial referencing requirements.

---

[1] **Presented at : Geomatics '95, Ottawa, Ontario, Canada, June 13-15, 1995**

1. Introduction

A global network of GPS tracking stations has been established over the past few years through the formation of the International GPS Service for Geodynamics (IGS) (Neilan, 1993). The IGS presently collects GPS data at about 65 globally distributed tracking stations. The Geodetic Survey Division (GSD), Natural Resources Canada (NRCan), in collaboration with the Geological Survey of Canada (GSC) has established the Canadian Active Control System (CACS). It is an essential component of a modern fully integrated spatial reference system to support geodetic positioning, navigation and general purpose spatial referencing. The system consists of unattended tracking stations, referred to as Active Control Points (ACPs), which continuously record carrier phase and pseudorange measurements for all GPS satellites within station view (Figure 1). Presently, ACPs are located in Algonquin Park, Ont., Yellowknife, N.W.T., Penticton, Victoria, Williams Lake and Holberg, B.C., St. John's, Nfld., Schefferville, Qué., and Churchill, Man. Each ACP is equipped with a high precision dual frequency GPS receiver and an atomic frequency standard. Temperature, pressure and humidity data are also collected at selected ACP sites. The data collected at each ACP is retrieved on a daily basis by a central processing facility in Ottawa.

Data from five CACS stations is contributed daily to the global IGS network. As an IGS Analysis centre, NRCan also computes daily precise GPS satellite orbits and clocks to facilitate positioning with the highest precision for geodetic control networks and crustal dynamic studies. The CACS precise satellite orbit and clock products can also be used for precise point positioning to satisfy a wide range of spatial referencing requirements.

The following reviews the steps leading to the production of precise GPS satellite orbits and clocks. It also describes the CACS single-point positioning interface. Finally, positioning results attained using this approach are analyzed.

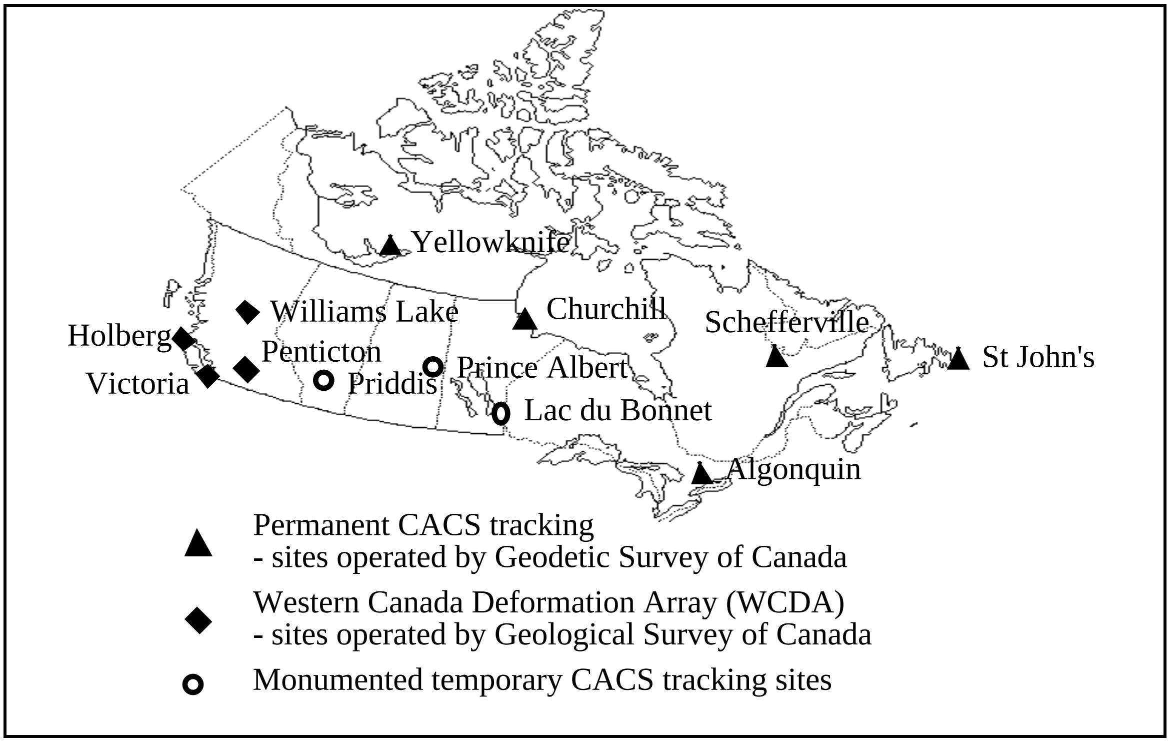

Figure 1. Canadian Active Control System Network Configuration

2. CACS precise orbits and clocks.

Since August 1992, the GSD has been processing data from a number of CACS stations augmented with 12 to 18 stations of the IGS global core network to compute precise GPS orbits. For this purpose, the GIPSY II / OASIS system developed by the Jet Propulsion Laboratory is used on an HP9000/700 series UNIX platform. The estimation strategy is based on undifferenced phase and smoothed pseudorange data. The satellite states, earth orientation parameters, station and satellite clocks as well as station coordinates and tropospheric delay are estimated daily for 24 hour arcs. The reference frame is realized by constraining a number of selected tracking station coordinates to their adopted values in the International Earth Rotation Service (IERS) Terrestrial Reference Frame of 1992 (ITRF92). All constrained station coordinates, constants, gravity and radiation pressure models conform to IGS/IERS standards. A more complete description of the NRCan processing strategy may be found in Kouba et al., 1993.

On a daily basis, NRCan has been contributing to IGS/IERS precise GPS satellite orbits, clocks and Earth Orientation Parameters (EOP) (NRCan, 1994). At the present time, precise satellite orbits and clocks are produced every 15 minutes and archived in the standard SP3 format (Remondi,1989). NRCan is one of seven IGS Analysis Centres that carry out independent computations of GPS satellite orbits, clocks and EOP. Quality control is insured through comparison of results between centres. This operation is conducted routinely through the IGS orbit combination (Beutler at al., 1993) and has shown a precision of 10 cm, 1 nanosecond and 0.5 mas respectively for the NRCan orbit, clock and EOP results (Kouba et al., 1993). An alternate way to verify the quality of precise orbits and clocks is to use them for pseudorange single-point positioning. Results obtained using this approach show absolute positioning precision at the sub-meter level (Héroux et al., 1993).

3. CACS satellite clock computation.

Selective Availability (SA) is presently the main source of error in GPS single point positioning and is carried out through the dithering of GPS satellite clocks using a random process that has a period of a few minutes and an amplitude of about 100 nanoseconds. Once we have an accurate representation of the GPS satellite clock, it is possible, in post processing, to remove satellite clock errors from the pseudorange measurements. At the present time, precise satellite orbits and clocks are generated in SP3 format at 15 minute intervals. To be useful to users interested in short site occupancy or kinematic operations, the 15 minute precise satellite clocks need to be computed at a higher rate.

Since all CACS stations observe GPS satellites at 30 second intervals and are equipped with high precision atomic clocks that can be precisely monitored, CACS data can be used to observe the higher frequency variations of the GPS satellite clocks. At a given epoch, a particular satellite is tracked by several CACS stations and multiple satellite clock samples are available and combined into a single GPS satellite clock estimate. This effectively reduces station dependent errors (mainly multipath) and atmospheric model uncertainties while connecting the visibility period of a particular satellite between stations. This results in precise satellite clocks at 30 second intervals for long and continuous satellite arcs. It assures precise positioning in any Canadian location without the requirement to 'match' satellite coverage with a reference station as is the case in conventional differential operations.

Daily satellite clock files at 30 second intervals applicable Canada wide are presently being produced routinely by combining range data from CACS sites. Global clocks may also be produced if required. The format under which the clock estimates are being archived is in agreement with a proposed IGS standard (Zumberge,1993). The fields in each record are:

Table 1
Precise satellite clock file field description

Field #	*Field Description (code or units)*
1	Record type (c=clock)
2	Processing centre (emr)
3	Satellite identifier (prn number)
4	Time of satellite clock estimate (year, month, day, hour, minute, second)
5	Estimated satellite clock offset (seconds)
6	Precision of clock offset (seconds).

A sample from a daily clock file is given in Table 2. The clock estimates for all CACS visible satellites are stored sequentially in time for a one day period. The estimated satellite clock offsets vary widely from one satellite to another. This is to be expected given the varying drift rates of the satellite clocks. Since the satellite clocks are estimated from all CACS stations from which the satellite is visible, a precision estimate can be derived at each epoch from the differences in the satellite clock estimates from the contributing stations. Generally, these values are in the 1-3 nanosecond range and are a reflection of the varying multipath and tropospheric conditions prevailing at the different stations, the ionosphere being eliminated with a dual-frequency model. This 1 nanosecond precision in satellite clock corresponds to 30 centimetre uncertainty in range. This is the level at which it is presently possible, using carrier-smoothed code observations, to estimate satellite clocks.

Table 2
Precise satellite clock file sample

```
 t pc sat   yr   mm dd hr mn     sec   clk offset(s)  precision(s)

c emr prn15 1993 09 16 00 00    .0000  .000028707423  .000000001501
c emr prn28 1993 09 16 00 00    .0000  .000032778384  .000000001043
c emr prn12 1993 09 16 00 00    .0000  .000690244138  .000000001604
c emr prn23 1993 09 16 00 00    .0000  .000000952164  .000000000532
c emr prn01 1993 09 16 00 00    .0000 -.000056312352  .000000000908
c emr prn21 1993 09 16 00 00    .0000 -.000005793945  .000000000327
c emr prn09 1993 09 16 00 00    .0000 -.000002618134  .000000002030
c emr prn31 1993 09 16 00 00    .0000  .000038487659  .000000000965
c emr prn26 1993 09 16 00 00    .0000 -.000008515005  .000000001026
c emr prn17 1993 09 16 00 00    .0000 -.000032398715  .000000000222
c emr prn15 1993 09 16 00 00  30.0000  .000028705458  .000000001237
c emr prn28 1993 09 16 00 00  30.0000  .000032819140  .000000001110
c emr prn12 1993 09 16 00 00  30.0000  .000690241405  .000000001064
c emr prn23 1993 09 16 00 00  30.0000  .000000966630  .000000000635
c emr prn01 1993 09 16 00 00  30.0000 -.000056322265  .000000000636
c emr prn21 1993 09 16 00 00  30.0000 -.000005812782  .000000000464
```

The effects of SA on GPS satellite clocks can be observed in the time variation of Block II satellite clock estimates. Figure 2 shows satellite clock variations with respect to an initial epoch at 30 second intervals over a 30 minute period. Satellites prn 12 and 31 are respectively Block I and Block II satellites. For prn 12, not affected by SA, the clock varies linearly by -30 nanoseconds over the 30 minute period, mainly due to the drift of the satellite time standard. Departures from a straight line reflect the precision of the CACS satellite clock estimates. For prn 31, the clock variations are within a band of +/- 150 nanoseconds reflecting the clock dithering effects typical of SA. In this instance, it is difficult to appreciate that the satellite clock estimates for prn 31 are as precise as for prn 12 because of the large periodical variations caused by SA. Nevertheless, it is confirmed through comparison of satellite clocks estimated from different CACS stations.

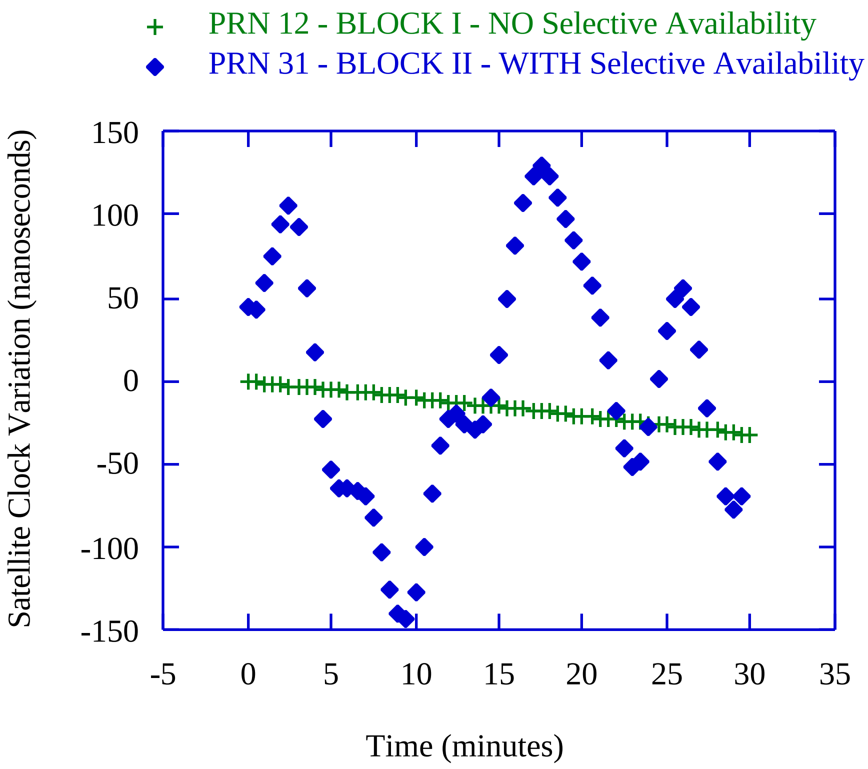

Figure 2. Satellite clock variations

4. Point Positioning with CACS Products - A Precision Analysis

Any user with the ability to convert his GPS observation data, collected in static or kinematic mode, into the standard RINEX format (Gurtner, 1994), can use point positioning software which interfaces with CACS products for data reduction. The precision of the positioning results will depend mainly, as stated earlier, on the ability to compensate for ionospheric delay, the code resolution of the receiver and the multipath rejection characteristics of the antenna. The following sections look at a few different scenarios involving receivers with different capabilities.

4.1 Dual-Frequency

To assess the quality of results attainable in pseudorange point positioning with precise orbits and clocks, a data file from a station in Churchill observed on October 22, 1994 was processed. The positions resulting from the processing were used to create figures 4 and 5 which show the consistency of independent position determinations in Churchill for the horizontal and vertical components. In this case, data was collected at a 30 second rate and we could therefore obtain position estimates at that interval. Each one of the positions presented here is independent, meaning that no filtering or constraints were applied to either observations or parameters. Obviously, during the day a number of different satellite combinations of varying geometry were used. The daily mean position derived from 2874 independent estimates differs from the known position of Churchill by -4, -20 and -17 centimeters in latitude, longitude and height respectively.

The more interesting result is the consistency of the single epoch position determinations in the horizontal and vertical components. The standard deviations from the daily mean are 43 and 27 centimeters in latitude and longitude and 80 centimetres in height. This represents the level of precision that can be attained at a single epoch by any Canadian user operating a single dual-frequency receiver when he uses CACS precise satellite orbits and clocks. These results were obtained with a high quality dual-frequency code tracking receiver (Turbo-Rogue) in static mode. Obviously, ionospheric delays were well compensated using the dual-frequency model.

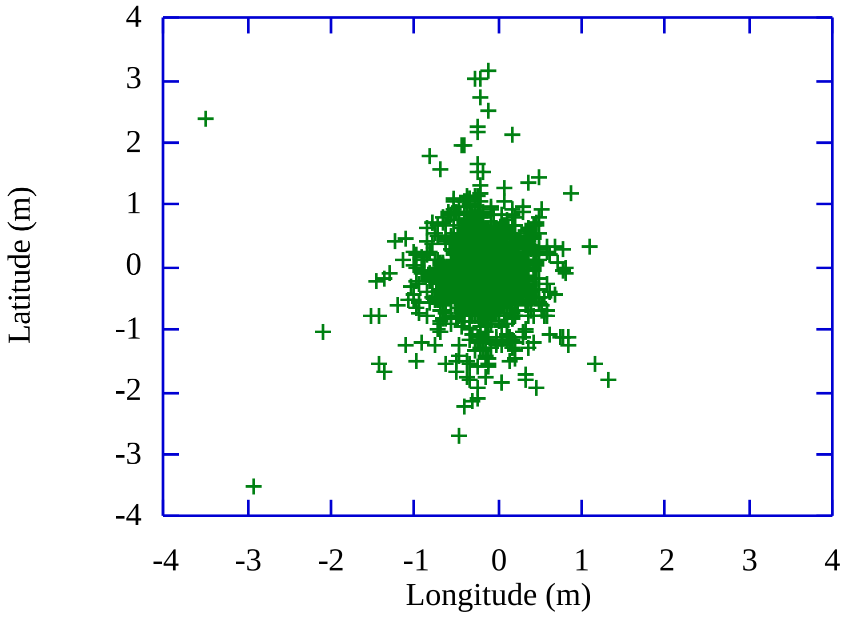

Figure 4. Churchill Horizontal Components
DUAL FREQUENCY

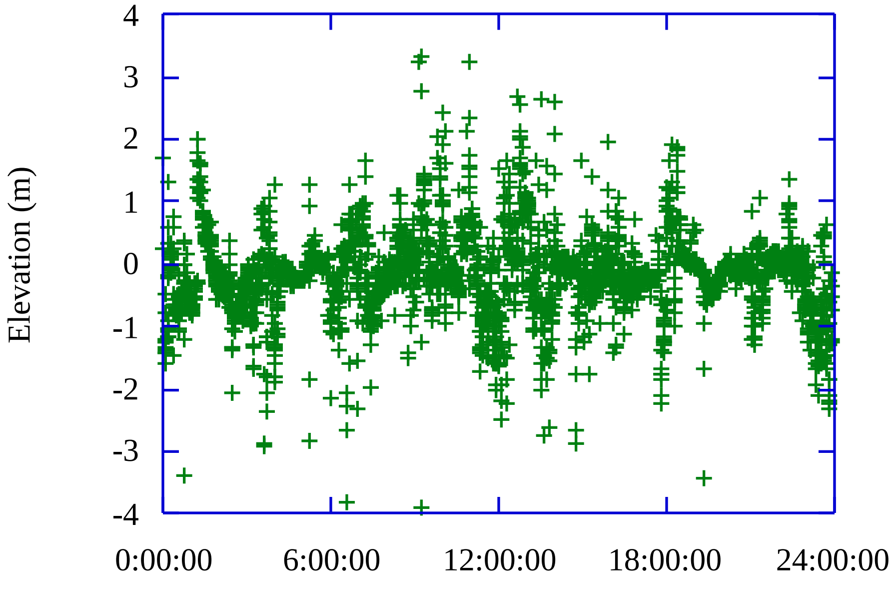

Figure 5. Churchill Vertical Component
DUAL FREQUENCY

4.2 Single-frequency.

Many users with single frequency equipment will also be interested in using precise orbits and clocks while operating a single receiver. It is therefore interesting to consider the influence of not applying ionospheric corrections. For comparison, the same daily data file from Churchill at 30 seconds interval is used, but only the L1 observations are considered and processed using precise satellite orbits and clocks. The positions resulting from the single frequency point positioning were used to create figures 6 and 7 which show the consistency of independent position determinations in Churchill along the horizontal and vertical components.

The RMS of the 2874 position determinations about the mean is 1.09, 0.53 and 2.13 metres respectively in latitude, longitude and height. This daily mean position is different from the known position of Churchill by 15 and -15 centimeters in latitude and longitude and 2.29 metres in height. As can be expected the vertical component is the most affected by neglecting the ionospheric delay. Height variation with respect to time is presented in Figure 7 and differences of up to 7 metres are noticeable at certain times of day. Along the horizontal components, there are no apparent biases introduced at this level of precision.

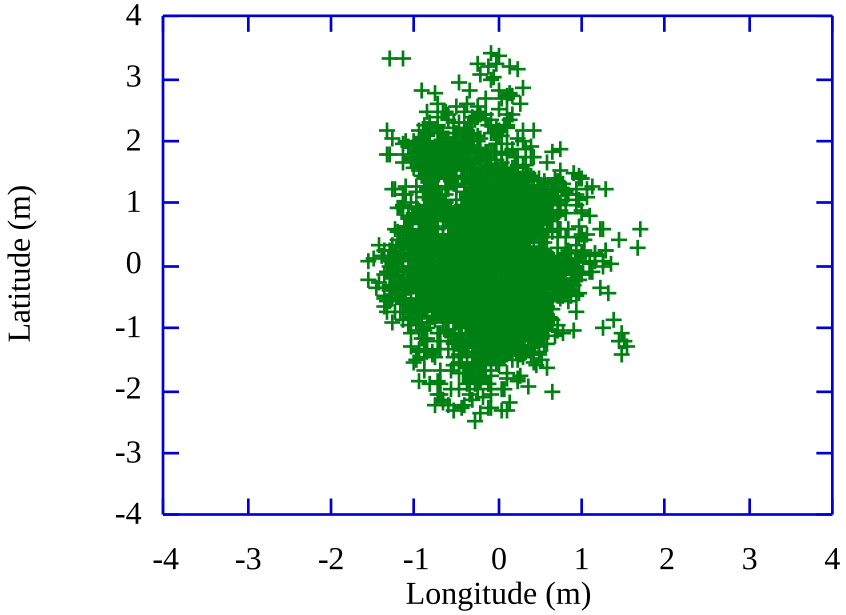

Figure 6. Churchill Horizontal Components
SINGLE FREQUENCY

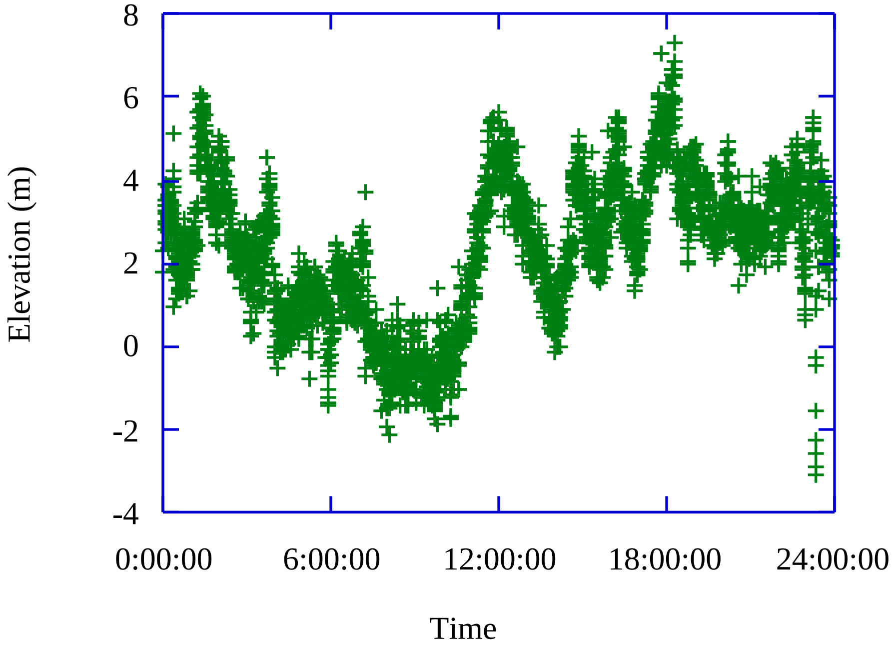

Figure 7. Churchill Vertical Component
SINGLE FREQUENCY

A daily single-layer model grid of vertical ionospheric delays, based on dual-frequency CACS observed path delays, can be used to correct observed single frequency ranges for ionospheric effects (Gao, 1994). The CACS positioning interface program provides users the option of applying this ionospheric grid. When applying modeled ionospheric corrections to the L1 ranges at Churchill, we obtain a mean daily position that differs from the truth by -6 and -18 centimeters in latitude and longitude and -42 centimetres in height. Along the horizontal components, these results compare well with the ionospherically corrected results. Along the height component, the 2.29 meter daily mean bias that was present using L1 ranges without the model has now been reduced to 42 centimetres. As for the RMS about the mean for the 2874 position estimates, they are now 1.75, 0.82 and 2.72 metres in latitude, longitude and height respectively. The RMS of the height component is still high at 2.7 metres, indicating that refinements to the single layer model are still required.

Table 3.
Single-Point Positioning Results (m)

	Dual Frequency		**Single Frequency**		**Single Frequency Ionospheric Model**	
	DIFF	**RMS**	**DIFF**	**RMS**	**DIFF**	**RMS**
Latitude	-0.04	0.43	0.15	1.09	-0.06	1.75
Longitude	-0.20	0.27	-0.15	0.53	-0.18	0.82
Height	-0.17	0.80	2.29	2.13	-0.42	2.72

4.3 Pseudorange resolution and multipath reduction.

The previous sections have demonstrated that horizontal positioning with precision of one metre could be achieved with single or dual frequency GPS receivers and precise CACS orbits and clocks. These precisions were also reached with a receiver operating in kinematic mode in a marine navigation environment as reported in Lachapelle et al, 1994. When using precise orbits and clocks, the errors in the user's position originate mainly from the quality of the pseudorange measurements and the multipath rejection capabilities of the GPS receiver. The benefits of using quality code tracking GPS receivers with CACS precise orbits and clocks are clearly illustrated in Figures 8 and 9.

First, positions are computed at one second intervals with a high quality single-frequency receiver using the GPS broadcast orbits and clocks. During the 25 minute time segment considered here, the RMS of the variations about the mean in latitude, longitude and height are 22, 15 and 65 metres. In this instance, positioning is affected mainly by SA (errors in broadcast orbit and effects of satellite clock dither) which causes the position to vary systematically with respect to time. Secondly, precise CACS orbits and clocks are used for positioning with pseudorange observations from a low quality GPS receiver. The RMS of the variations in latitude, longitude and height are now reduced to 7.2, 6.4 and 13 metres . A more random distribution of positions about the mean is now apparent since the systematic effects of SA have been removed. Finally, precise CACS orbits and clocks are used with pseudorange observations from a high quality GPS receiver, lowering the RMS of the variations in latitude, longitude and height to 0.45, 0.42 and 1.5 metres

This short analysis shows the wide range of precisions that can be obtained with similar data and emphasizes the need to assess the quality of the GPS equipment before performing a survey. When occupying known control stations to validate equipment and procedures, care must be given to assure compatibility of the coordinate systems used for comparison (Erickson,1994).

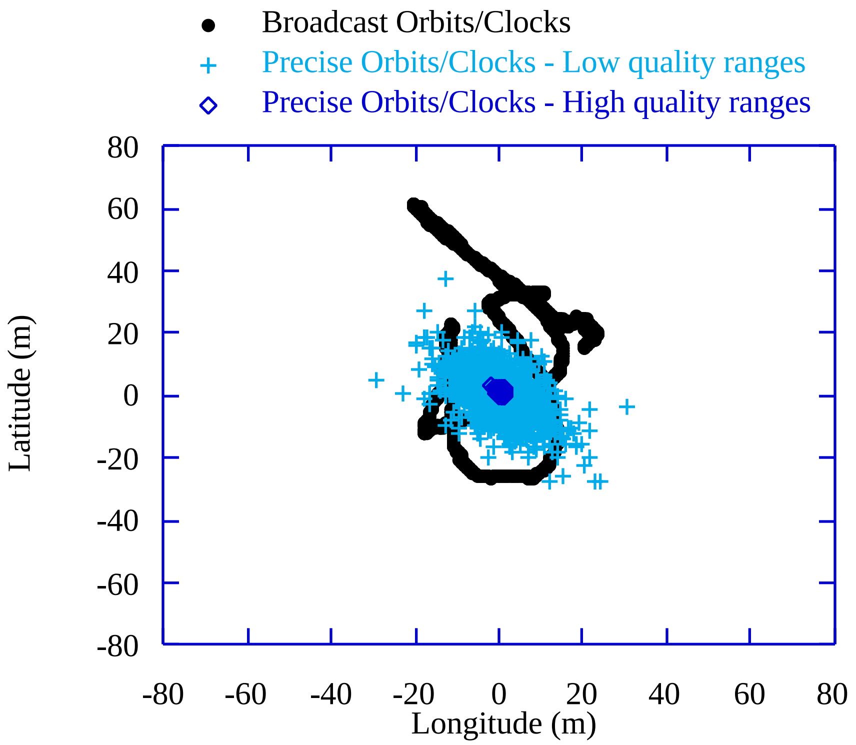

Figure 8. Horizontal Positioning Precision Comparison

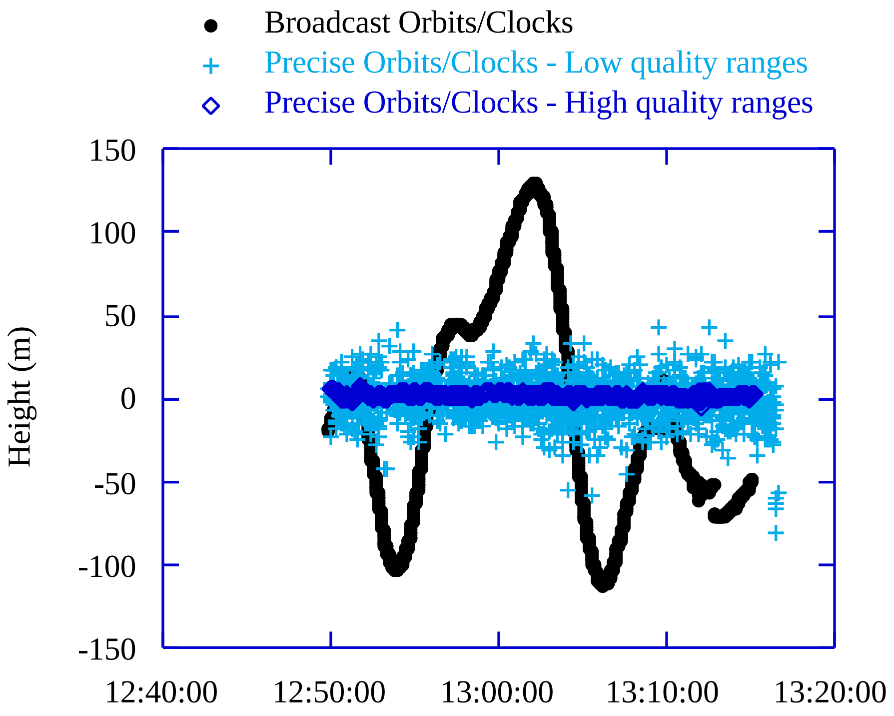

Figure 9. Vertical Positioning Precision Comparison

5. Conclusion

Precise GPS satellite orbits and clocks are produced daily by NRCan as an Analysis Center contributing to IGS. High frequency (30 seconds) satellite clocks are also computed over Canada from the CACS. A point positioning software interface was developed to use CACS products to provide enhanced precision to users operating a single GPS receiver. With the use of quality receivers, it is shown that this rather simple approach can offer precision of one metre or better and satisfy a wide range of spatial referencing requirements.

References

Beutler, G., J. Kouba, T. Springer (1993), Combining the orbits of the IGS Processing centers, Proceedings of the 1993 IGS (International GPS Service for Geodynamics) Workshop, University of Bern, pp. 20-56.

Erickson, C. and P. Héroux (1994), GPS Locations for GIS: Getting them Right the First Time, Paper presented at Decision 2001, Toronto, Canada, September 12-16.

Gao, Y., P. Héroux and J. Kouba (1994), Estimation of GPS Receiver and Satellite L1/L2 Signal Delay Biases Using Data from CACS, Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation, Banff, Canada, August 30-September 2, pp. 109-117

Gurtner, W. (1994), RINEX: The receiver-Independent Exchange Format, GPS World, July, pp. 48-52.

Héroux, P., M. Caissy, and J. Gallace (1993), Canadian Active Control System Data Acquisition and Validation, Proceedings of the 1993 IGS (International GPS Service for Geodynamics) Workshop, University of Bern, pp. 49-58.

Kouba, J. , P. Tetrault, R. Ferland and F. Lahaye (1993), IGS data processing at the EMR Master Active Control System Centre, Proceedings of the 1993 IGS (International GPS Service for Geodynamics) Workshop, University of Bern, pp. 123-132.

Lachapelle, G., Klukas, R., Qiu, W. and Melgard, T.E. (1994), Single Point Satellite Navigation Accuracy - What the Future May Bring. Presented at IEEE PLANS94, Las Vegas, April 11-15 .

Neilan, R.E., W.G. Melbourne and T.P. Yunck (1993), The Future Role of the IGS Central Bureau: Proposed Functions, Organization and Responsibilities, Proceedings of the 1993 IGS (International GPS Service for Geodynamics) Workshop, University of Bern, pp. 15-24.

NRCan (1994), Canadian Active Control System Products, Geodetic Survey Division, Geomatics Canada, Natural Resources Canada, Ottawa, August.

Remondi, B.(1989), Extending the National Geodetic Survey Standard for GPS Orbit Formats, NOAA Technical Report NOS 133 NGS 46, National Geodetic Information Branch, NOAA, Rockville, MD, 20852, November.

Zumberge, J. and C. Goad (1993), IGS Processing Center standard report requirements and product formats, Proceedings of the 1993 IGS (International GPS Service for Geodynamics) Analysis Center Workshop, Ottawa, Canada, pp. 6-19.