CANADIAN ACTIVE CONTROL SYSTEM-- DELIVERING THE CANADIAN SPATIAL REFERENCE SYSTEM[1]

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The Geodetic Survey Division (GSD)'s primary role is to maintain the Canadian Spatial Reference System (CSRS), ensure its compatibility with current positioning technology, and to facilitate efficient access to it. For over 80 years, GSD has been providing a system for referencing horizontal and vertical coordinates for Canadians. With the advent of GPS and the subsequent demands of a rapidly expanding positioning and navigation community, GSD has upgraded the traditional reference service by developing and operating the Canadian Active Control System (CACS) in collaboration with Geological Survey of Canada. Current plans allow for the Canadian Active Control System to play a key role in the delivery of integrated GPS services across Canada through efficient access to the Canadian Spatial Reference System and by improving the effectiveness and accuracy of GPS applications.

Canadian Active Control System products are already used for post-processing applications requiring accuracies ranging from a centimetre to a few metres. The Canadian Geodetic Bulletin Board Service (CGBBS) provides subscribers with on-line access to these products. New post-processing positioning approaches provide metre-level accuracy economically and efficiently anywhere in Canada with a single GPS receiver for many applications, including GIS.

GSD is developing this technology further to provide similar capabilities in real-time. Current developments will combine real-time acquisition of data from the Canadian Active Control System network of stations, the prediction of GPS orbits, and the real-time evaluation and distribution of corrections for the satellite clocks. Additional stations are being added to the existing network with the collaboration of partners such as British Columbia's Geographic Data BC and Geological Survey to further improve the efficiency and reliability of the system. The real-time service is expected to support metre-level positioning accuracies for any location in Canada. The prototype GPS Correction service, *GPS•C*, will be introduced in the spring of 1996.

INTRODUCTION

Since its inception, the primary role of the Geodetic Survey Division (GSD) has been to establish the basic infrastructure for a national spatial reference system, and to maintain and improve it as surveying technology evolves. The reference system is fundamental for ensuring

[1] Revised February 1997. Document originally presented at GIS '96, Vancouver, Canada, March 1996.

compatibility of all geomatics, navigation and other spatial information from various sources, allowing it to be exchanged and merged in a seamless and economical fashion. Traditionally, access to the national spatial reference system was provided through the use of monumented geodetic control points established by various government agencies throughout the country and then used by surveyors for integration of local or regional surveys. Today, the Global Positioning System (GPS)-based Canadian Active Control System not only allows for efficient access to the national reference system without occupying monumented control, but also improves the effectiveness and accuracy of end user GPS applications.

The Canadian Active Control System is supported by a network of ten unattended tracking stations (Figure 1), referred to as Active Control Points (ACPs), which continuously record carrier phase and pseudo-range measurements for all GPS satellites within station view. A Master Active Control Station (MACS), operated by GSD in Ottawa, assures the coordination of the system (Kouba et al. 1993). It facilitates GPS integrity and performance monitoring; computation of precise satellite ephemerides (GPS orbits) and precise satellite clock corrections (NRCan 1995); generation of accurate GPS corrections (*GPS•C*) applicable to the Canadian landmass; and other applications, such as geodynamics and precise time transfer. Through participation in the International GPS Service for Geodynamics (IGS), the Canadian Active Control System also contributes to the maintenance of the International Terrestrial Reference Frame (ITRF) and the improvement of the NAD83 national reference system (Kouba and Popelar 1994). Likewise it ensures global consistency and accuracy at the centimetre level to meet current and future positioning requirements in Canada.

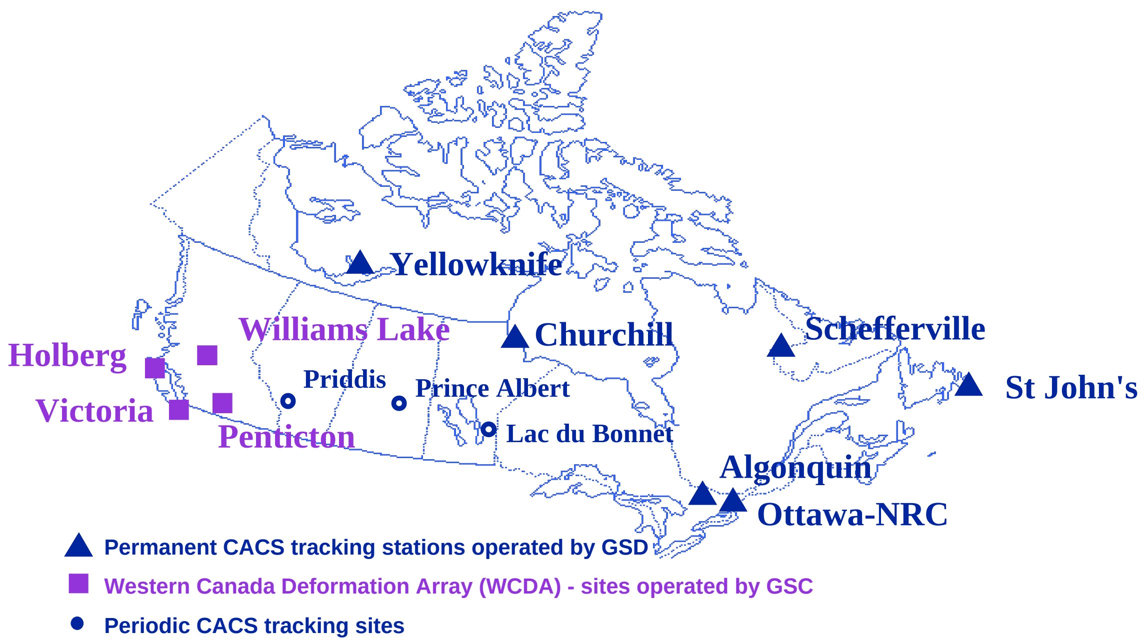

Figure 1: CACS network of automated tracking stations.

The following brief description of the Canadian Spatial Reference System is provided as background for understanding the significance and role of the Canadian Active Control System.

THE CANADIAN SPATIAL REFERENCE SYSTEM

The Canadian Spatial Reference System (CSRS) is being continuously improved and maintained in collaboration with federal, provincial and local government agencies, industry and the user community to support positioning applications whether they relate to geomatics (land management, geodesy, mapping, Geographic Information Systems, etc.), navigation or scientific studies.

The Very Long Baseline Interferometry (VLBI) network provides the highest layer of the Canadian Spatial Reference System hierarchy (Figure 2). VLBI is a radio astronomical technique using extragalactic radio sources providing the inertial reference frame to determine direction and inter-station distances on a global scale with millimetre accuracy. The VLBI sites, collocated with ACPs, are used as fiducial reference to provide the orientation and scale for the terrestrial reference networks. Repeated VLBI observations are used for the determination of earth orientation parameters and station velocities due to crustal motion. VLBI observations have been carried out at five sites in Canada with international cooperation. These are located at Whitehorse, Yukon; Yellowknife, Northwest Territories; Penticton and Victoria , British Columbia; and Algonquin Park, Ontario. The last four sites are collocated with ACPs.

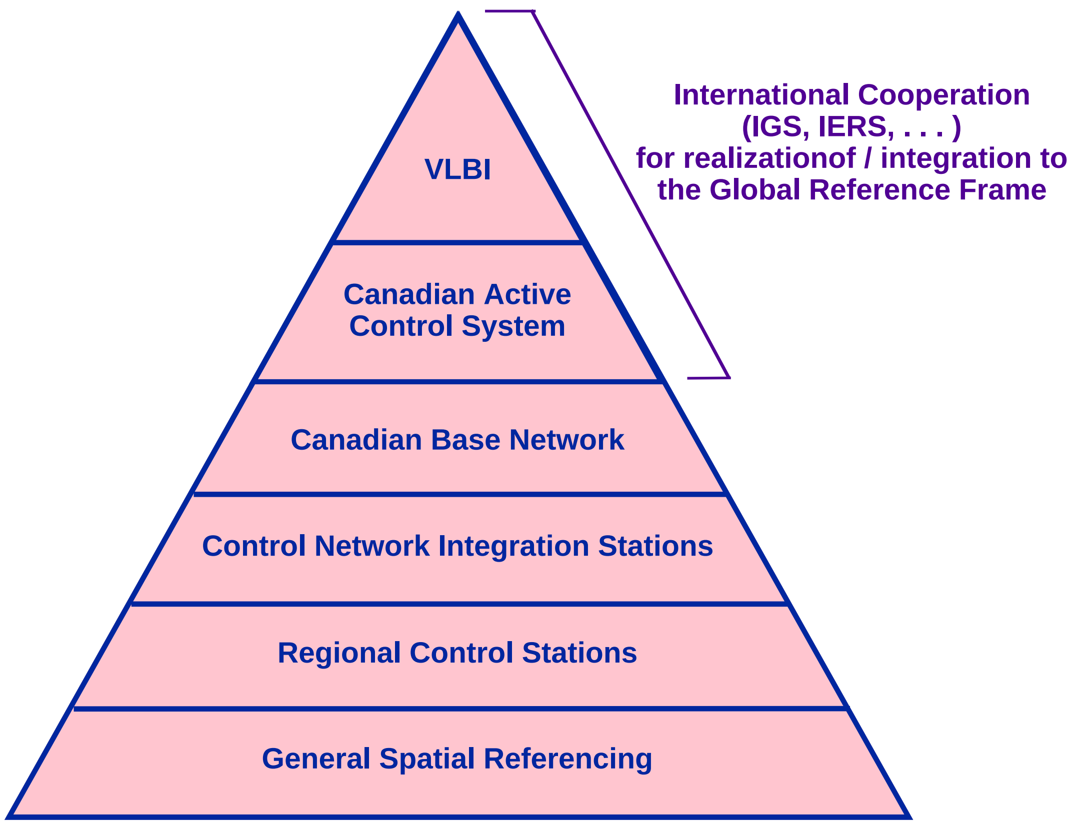

Figure 2: The Canadian Spatial Reference System hierarchy.

The second most important layer of the Canadian Spatial Reference System is the Canadian Active Control System. It contributes to the refinement of the national reference system assuring its stability, accuracy and compatibility with international standards through continuous observation and cooperation at the international level. It also provides the means for end users of

GPS to directly integrate their spatially referenced data to the Canadian Spatial Reference System (Kouba et al. 1994).

The Canadian Base Network program was initiated in 1994, in cooperation with the provinces, to complement the Canadian Active Control System network. With a nominal spacing of 200 kilometres in the southern latitudes, it provides easily accessible high accuracy control (at centimetre accuracy with respect to the Canadian Active Control System). It also provides the means to evaluate the lower layers of traditional monumented control points established throughout the years by various government agencies. As Canadian Active Control System data products gain acceptance, the need for large numbers of these monumented control points should be greatly reduced.

International Cooperation

The Geodetic Survey Division also contributes Canadian Active Control System data to the International GPS Service for Geodynamics (IGS) and participates as an analysis centre (IGS 1995). In return, the Division has access to data from globally distributed fiducial sites for use in the computation of precise satellite ephemerides. Through the IGS, Geodetic Survey Division data are included in global adjustments for the realization of the ITRF which ensures integration and compatibility of the Canadian Spatial Reference System at a global scale. Canadian Active Control System data and related products are also made available to international organizations such as NASA Crustal Dynamics Data Information System, the U.S. National Geodetic Survey, the U.S. Naval Observatory and many other organizations around the world studying Earth dynamics, natural hazards and global change.

The IGS currently has seven contributing international analysis centres. Since 1994, the Geodetic Survey Division has assumed, at the request of the IGS Governing Board, the international role of coordinator of analysis centres. This includes the computation of the final IGS combined precise GPS satellite ephemerides and other products derived from data submitted by the seven international centres.

The Canadian Active Control System data products are based on the products submitted to the IGS.

CANADIAN ACTIVE CONTROL SYSTEM DATA PRODUCTS

Observational Data

The ACPs are presently collecting dual frequency pseudo-range and carrier phase observations at a 30 second sampling interval by continuously tracking all GPS satellites in station view. Data are normally retrieved from the sites by the Master Active Control Station every four hours. They are then run through a validation process (Héroux et al. 1993) to ensure that they are complete and that ACP operations are normal. Data are then archived in daily files in RINEX format (Gurtner 1994). Data files for each ACP are currently made available on-line 4 hours after the end of the day.

Precise Ephemerides

The precise ephemerides are computed from data collected at ACPs augmented by up to 24 globally distributed core GPS tracking stations of the IGS. Based on IGS orbit comparisons, the NRCan precise ephemerides have a precision at the 10 cm level (one sigma) in each coordinate. Precise ephemerides are provided as daily files and are available typically within 2 to 5 days following the observations. They are currently distributed in the internationally accepted NGS-SP3 format (Remondi 1989) containing X, Y, Z positions along with clock information for all satellites at 15 minute intervals. A CACS rapid orbit solution is available within 36 hours following observation.

Precise Satellite Clock Corrections

Precise offsets between individual GPS satellite clocks and the Canadian Active Control System reference clock are computed for satellite arcs visible in Canada based on the precise ephemerides and ACP observational data. These precise satellite clock corrections also account for the dithering effect introduced by selective availability (SA). Although the clock corrections are archived at 30 second intervals, they can be interpolated to an higher rate - (i.e.) one second intervals - with no significant degradation in the resulting pseudo-range positioning accuracy. Precise clock corrections are archived in an ASCII format. Each complete file contains the clock corrections for each satellite for a 24-hour period. They are currently available on-line within 2-5 days following the observation. Rapid clock corrections based on the CACS rapid orbit solution are available within 36 hours following observation.

HOW TO USE CANADIAN ACTIVE CONTROL SYSTEM PRODUCTS

The availability of precise ephemerides, precise satellite clock corrections and observational data from the ACPs can offer significant benefits for GPS applications in Canada. These products make it possible to position any point in the country, with a precision ranging from a centimetre to a few metres, in relation to the Canadian Spatial Reference System, without actually occupying an existing control monument or base station.

For the Most Precise Applications

For applications requiring the highest precision and using carrier phase measurements, the utilization of the precise ephemerides during the data processing reduces orbit-related errors in baseline determinations to less than 0.05 parts per million. These errors can reach 3 parts per million or more when ephemerides broadcast by the satellites are used. Scale and orientation are provided for the resulting coordinates through the precise ephemerides. Furthermore, by including observational data from the ACPs in the data processing, a direct tie to the Canadian Spatial Reference System is established without occupying any monumented control point. This increases the efficiency of field operations and data processing. Depending on the GPS software, further advantages may be realized, such as improved cycle slip detection and correction capability, enhanced carrier phase ambiguity resolution as well as improved and more consistent aposteriori error estimates. Recent surveys, combining Canadian Active Control System station data and precise ephemerides, have shown static positioning precision at the centimetre level in each of the three-dimensional components for distances over 1000 kilometres, when appropriate software and procedures are used.

Precise Point Positioning with a Single Receiver

Positioning at the metre level from pseudo-range (code) observations without the use of a base station is possible with precise satellite clock corrections. These corrections can be applied anywhere in Canada to correct the user's observed ranges, and together with precise ephemerides, provide positioning accuracies at the one-metre level depending on the user's receiver measurement noise, multipath, satellite geometry and residual atmospheric effects.

The accuracies normally achievable using single-point positioning are 100 metres (2 DRMS) horizontally and 156 metres vertically assuming favourable satellite geometry. The error sources that limit the accuracy can be grouped under three categories (Figure 3) (Erickson 1993): those that are satellite-related (inaccuracies of the broadcast satellite orbital and clock information); those that originate as the signal travels through the atmosphere (ionospheric and tropospheric biases); and those that are site-related (user's receiver measurement noise and multipath). Currently, the largest error source is Selective Availability which is introduced by dithering of GPS clocks. Selective Availability appears as a random process having a period of a few minutes and an amplitude of about 100 nanoseconds or 30 metres in the direction of the range measured to the satellite.

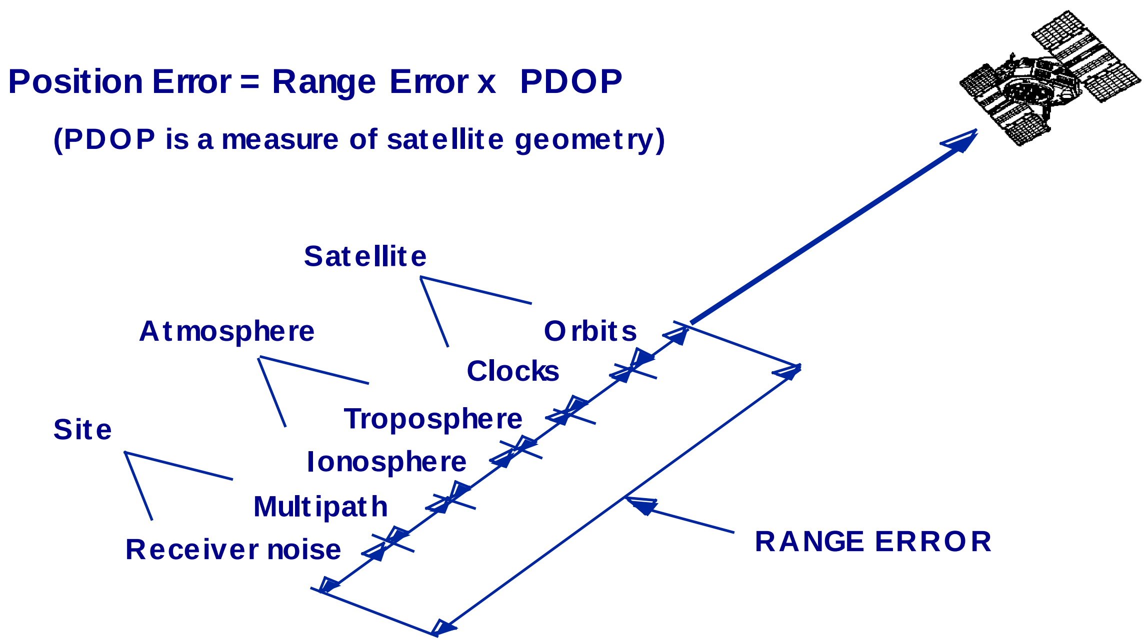

Figure 3: GPS Positioning Error Sources

Local differential GPS techniques provide a method to reduce errors introduced by Selective Availability, orbital errors and atmospheric effects. With this approach, the combined effect of these errors is determined at a base station of 'known' coordinates. The difference between the observed pseudo-range measurements and the expected ranges for the known coordinate are applied to roving receiver measurements under the assumption that the observed errors are common to receivers operating in the same area. As the distance between reference and roving receivers increases, the correlation of these errors is reduced and applying pseudo-range corrections from a single base station does not produce optimal results. Site-related errors are not reduced through differential corrections and may be propagated to the network if they exist at the base station.

Alternatively, similar positioning accuracies are achieved with a single receiver by directly applying a correction for each of the error sources. Broadcast orbits and clock parameters are replaced by precise orbits and precise clock corrections, which are available products of the Canadian Active Control System. The Canadian Active Control System orbits have an accuracy of approximately 10 centimetres, compared to the 5-20-metre accuracy of the broadcast orbits (Figure 4). Similarly, the Canadian Active Control System precise clocks are accurate at the one nanosecond (30 cm) level, whereas the broadcast clocks are only accurate to 70-100 nanoseconds (21-30 m). This represents an improvement in satellite data accuracy of about 100 times.

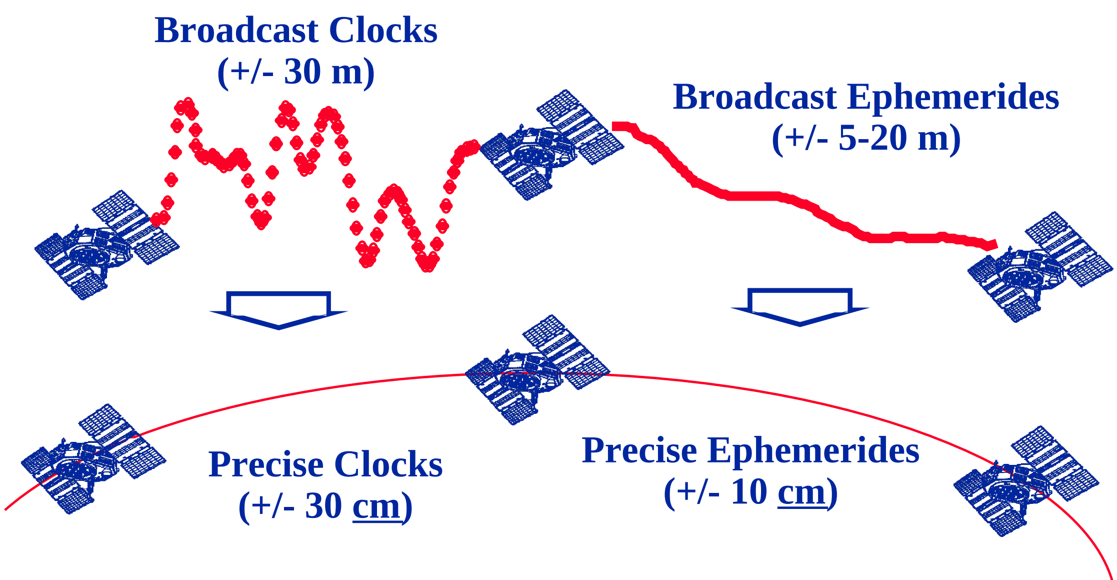

Figure 4: Satellite data improvements resulting from CACS processing.

Dual-frequency users can take advantage of the dispersive nature of the ionosphere to correct the ionospheric delay from their observations. For single-frequency users, Geodetic Survey Division is presently developing a single-layer ionospheric model based on the Canadian Active Control System data to improve ionospheric delay corrections. As for the tropospheric error, it is reduced through the use of standard mapping functions and input of surface meteorological data.

Since the Canadian Active Control System products are based on a network of accurately known reference points equipped with high performance GPS receivers, the uncertainty associated with using coordinates and data from a single base station is effectively removed. The well distributed stations of the Canadian Active Control System also ensure complete satellite visibility to users at any Canadian location at any time of day. This eliminates the problem of "matching" observations between remote and reference sites sometimes associated with local differential GPS. The use of Canadian Active Control System products results in positions automatically linked to the Canadian Spatial Reference System.

GPSPace Software

Single-point positioning with precise Canadian Active Control System orbits and clocks, as described above, was recently introduced in the GPS community (Lachapelle et al. 1994; Erickson and Héroux 1994; Héroux and Kouba 1995). To demonstrate and facilitate its application, GSD has developed the program GPSPace (GPS Positioning from ACS Clocks and Ephemerides) as an interface program for Canadian Active Control System products. Any user with the capability to convert GPS observation data, collected in static or kinematic mode, into the standard RINEX format (Gurtner 1994), can use GPSPace for data reduction. This software is now being licensed to value added re-sellers. Several commercial point positioning software suites are also compatible with Canadian Active Control System data.

Figures 5 and 6 compare the quality of positioning from a single receiver using precise orbits and clocks versus one using broadcast information. Independent positions were computed every second over a 25 minute period using program GPSPace in post-processing. The data was collected via a NovAtel single frequency receiver.

Using broadcast information, the variations (RMS) of each independent determination, with respect to the known position (Figure 5), are 27 metres in latitude and 13 metres in longitude. After applying precise satellite ephemerides and clocks, the variations (RMS) are reduced to 0.45 metres in latitude and 0.42 metres in longitude.

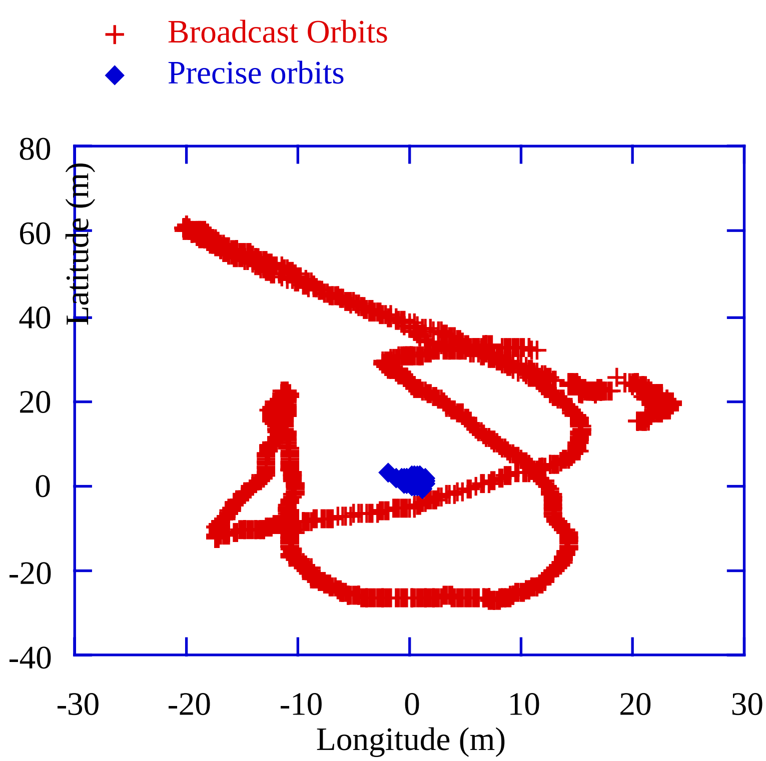

Figure 5: Comparison of latitude and longitude from single point positioning using broadcast orbits and clocks and CACS precise orbits and clocks.

Similarly, the variations (RMS) with respect to the known ellipsoidal height (Figure 6) is 65 metres when using broadcast information. After applying Canadian Active Control System precise satellite ephemerides and clocks, the variation (RMS) is 1.5 metres.

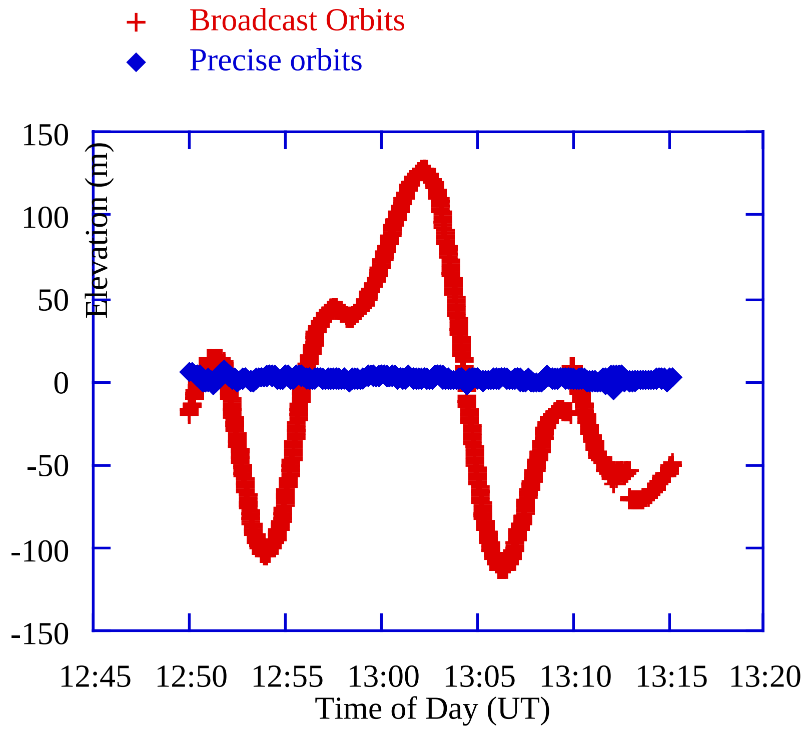

Figure 6: Comparison of heights from single point positioning using broadcast orbits and clocks and CACS precise orbits and clocks.

Real Time GPS Corrections

The precise GPS satellite and clock information provided by the Canadian Active Control System, available since 1992, has been obtainable from the Canadian Geodetic Bulletin Board Service since the spring of 1995. The Canadian Geodetic Bulletin Board Service can be accessed:

- on Internet via telnet -- ‘bbs.geod.nrcan.gc.ca’;
- on the World Wide Web at URL-- ‘http://www.geod.nrcan.gc.ca’; or,
- by dial-up modem-- (613) 947-7660.

Many users and agencies now subscribe to this service, download the orbit and clock information from the electronic bulletin board, use post-processing techniques, and improve the accuracy of their point positioning results from a single receiver to the metre level or better. This same technology and capability is reaching a level of maturity and is being developed into a real-time service.

The prototype operation of this real-time component is now operational with GPS corrections available for distribution by industry. This new GPS Correction service, called *GPS•C*, supports metre-level or better positioning accuracies for any location in Canada. It will continue to provide the advantages offered by the post-processing service but with the additional advantage of being provided to users in real-time.

While Geodetic Survey Division is establishing this real-time capability with collaboration from other agencies such as Geographic Data BC, it does not intend to directly distribute this information itself. GSD is relying on private and public sector partners to develop the real-time distribution and support systems to serve the vast GPS application user base (Figure 7). Geodetic Survey Division is committed to maintaining the basic infrastructure required to support and facilitate spatial referencing and to collaborating with companies or agencies wishing to develop and offer, to end users, services based on the national Canadian Active Control System. Geodetic Survey Division will provide a real-time data stream of accurate satellite orbits and clocks and other GPS error corrections, and will work with collaborators to distribute this information and transform it into local GPS corrections for their users. Software to perform this transformation and conversion will be made available to service providers.

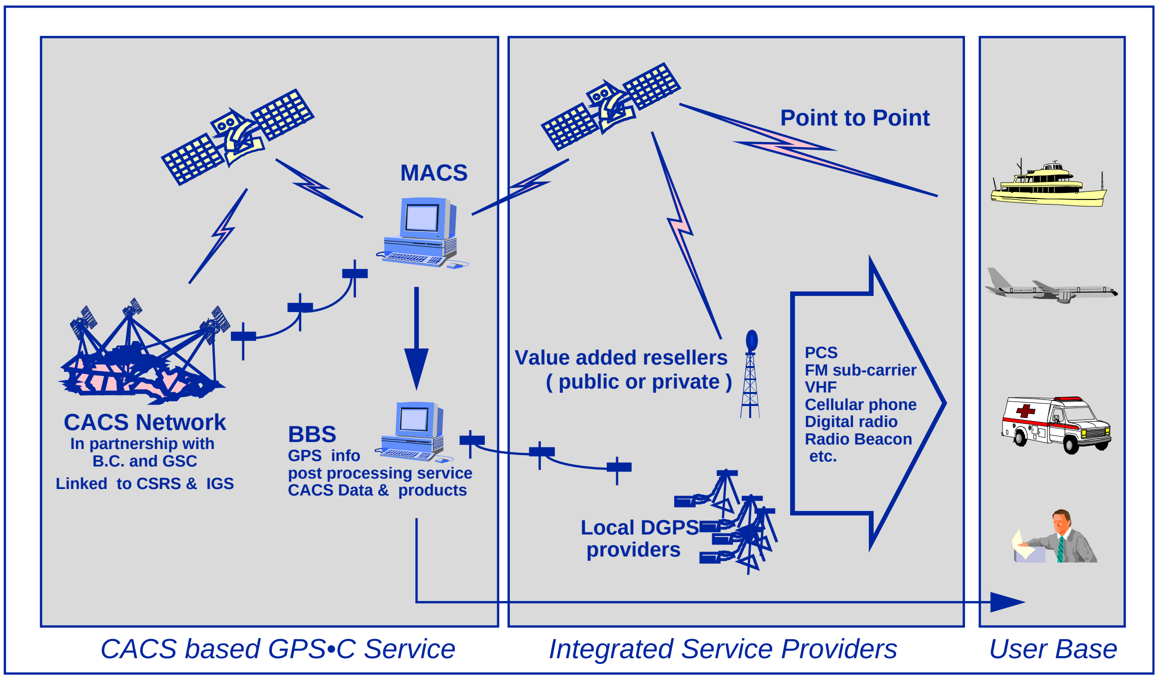

Figure 7: Integrated GPS Correction Services

GPS•C information can complement local differential or wide-area differential correction services by offering these service providers the opportunity to validate and enhance their products, provide independent quality assurance, and directly tie into the national reference system in real-time. The present differential GPS market is generally characterized by considerable activity and variety, but to a certain degree, lacks standards, compatibility and quality assurance, and offers limited coverage. Many of these deficiencies can be addressed by the *GPS•C* service, which can also potentially reduce a service provider's total operating costs while increasing the system's reliability and integrity.

In the future, it is expected that there will be a combination of integrated service provision systems including: local differential GPS systems to satisfy local niche markets, wide-area differential systems to provide wider area coverage with networked differential technology, and the internationally-based *GPS•C* service providing more global coverage (without differential corrections) and positioning accuracies at the sub-metre level.

This real-time information will provide unparalleled opportunities for Canadian industry. Demands for real-time services have been growing rapidly since GPS became fully operational in 1993 with studies estimating GPS-related worldwide revenues at $30 billion (U.S.) by the year 2005 (NAPA and NRC 1995).

SUMMARY

The Canadian Active Control System is part of a national infrastructure that supports georeferencing applications and the progression towards a spatial reference system that is no longer based solely on a network of monumented stations, but increasingly on satellite-based positioning technology. The Canadian Active Control System provides current users with a simple means of relating their positioning information to an accurate and stable reference frame while being well suited for continuous improvement of the national spatial reference system.

Access to Canadian Active Control System products through the CGBBS supports GPS post-processing applications requiring centimetre to metre accuracy. Availability of the real-time *GPS•C* service will further meet evolving user needs and enhance the system by ensuring lower end-user costs through shared infrastructure. Other benefits to Canadians will be realized in terms of validated and quality-assured data, improved accuracy, and a standard and accessible spatial reference system.

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