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Ensuring compatibility with the Canadian Spatial Reference System

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Draft

Abstract

There are currently over 700 hundred Global Navigation Satellite System (GNSS) reference stations actively broadcasting corrections (Active Control Stations – ACSs) in Canada. This number has been consistently growing since the early 2000s. In 2009, the federal, provincial and territorial members of the Canadian Council on Geomatics (CCOG) recognized that consumers of GNSS corrections data had very little ability to verify that service providers were following best practices to ensure the quality of their work. It is common for surveyors to delineate property boundaries or to define the location of civil infrastructure with significant economic value, so being dependent upon another party without quality assurance was perceived as a major risk. Additionally, this new dependence upon commercial ACSs for GNSS corrections posed a threat to the consistency of position values in Canada.

To address this concern, CCOG tasked its Canadian Geodetic Reference System Committee (CGRSC) with developing a plan to describe, validate and provide certification of the GNSS corrections services consumed by industry. This paper summarizes the development of Natural Resources Canada's (NRCan) Compliance Program for High Accuracy, GNSS Services and how it can benefit professional surveyors across Canada.

Keywords: GNSS, RTK, Compliance Agreement, Surveying

Introduction

Differential Global Navigation Satellite Systems (D-GNSS) have been widely embraced for surveying, construction and engineering applications. Real-Time, Kinematic (RTK) D-GNSS surveys have introduced efficiencies in these sectors by providing instantaneous access to centimetre level positioning. D-GNSS surveys require at least one reference station to generate GNSS corrections. When a polygon of reference stations are used around a region, D-GNSS performance can be enhanced. In this scenario, D-GNSS corrections can be interpolated between stations rather than extrapolated from a single location [InsideGNSS 2011].

The establishment of a reference station requires careful consideration for site location. Good satellite visibility is needed to maximize the number of commonly viewed satellites when a user is in the field, a condition that is required for differential data processing [Leick 1990]. Equipment must be located in a secure location. Power and telemetry options must also be considered. Finding suitable reference locations can take time.

Organizations within the private sector, public sector and academia have recognized the value of continuously operating, GNSS reference stations. Such investments can significantly reduce the time required to conduct a survey by eliminating the setup and tear down of a temporary reference station. Additionally, positioning accuracy and ambiguity resolution time can be improved by leveraging a polygon of permanent reference stations.

Currently, there are over 700 hundred GNSS reference stations actively broadcasting corrections (Active Control Stations – ACSs) in Canada. This number has been consistently growing since the early 2000s. In 2009, the federal, provincial and territorial members of the Canadian Council on Geomatics (CCOG)

recognized that consumers of GNSS corrections data had very little ability to verify that service providers were following best practices to ensure the quality of their work. It is common for surveyors to delineate property boundaries or to define the location of civil infrastructure with significant economic value, so being dependent upon another party without quality assurance was perceived as a major risk. Additionally, this new dependence upon commercial ACSs for GNSS corrections posed a threat to the consistency of position values in Canada.

To address this concern, CCOG tasked its Canadian Geodetic Reference System Committee (CGRSC) with developing a plan to describe, validate and provide certification of the D-GNSS RTK corrections services consumed by industry. This paper summarizes the development of NRCan's Compliance Program for High Accuracy, GNSS Services and how it can benefit professional surveyors across Canada.

Solution Considerations

In devising a solution to address the concerns of CCOG, several considerations needed to be addressed.

These included:

- a. **Ensuring tight integration of ACSs into the Canadian Spatial Reference System (CSRS):** Canadian Geodetic Survey (CGS) is responsible for the definition, maintenance, and access to the Canadian Spatial Reference System (CSRS). The CSRS currently uses the North American Datum of 1983 (NAD83) at epoch 2010 as the official datum for determining horizontal position and ellipsoidal heights. The Canadian Geodetic Vertical Datum of 2013 is the official CSRS vertical datum. To allow access to the CSRS, CGS maintains a national network of ACSs whose GNSS data is made freely available. The CSRS can also be accessed through passive geodetic control monuments for

which coordinates have been published. The increased use of commercial services for accessing position information has necessitated a means to ensure their compatibility with the CSRS. This can be achieved by applying a common methodology to computing coordinates for commercial reference stations. These coordinates can then be assigned by commercial service providers so that all derived surveys are compatible with the CSRS.

Additionally, ACSs must seamlessly integrate with passive geodetic control monuments for various reasons including:

- Passive control monuments provide users of real-time services the independent ability to confirm system performance (albeit at an instant in time);
- Passive control monuments allow for traditional reference/rover RTK setups to be employed when cellular service is not available. Coordinates determined using this approach should agree with those calculated using real-time services; and
- Historic surveys derived from passive control monuments should have position values that can be directly compared with those derived from real-time services.

It is also important to note that corrections enabled by an ACS may originate in one province but extend into another. It is critical that a homogenous national referencing system is achieved by leveraging coordinate values of consistent quality for all reference stations across the country.

- b. **Making end users aware when a reference station's true position no longer matches its published coordinate value:** If the coordinates assigned to a reference station do not reflect its true position, positioning biases equivalent to the discrepancy size can occur for end users in the

field. Amongst other causes, discrepancies between actual and published values can be introduced by:

- i. Thermal expansion of the materials used to construct the reference station or of the structure to which the reference station's antenna is attached
- ii. Seasonal thermal effects such as freeze/thaw cycles of the ground where a monument is embedded
- iii. Unstable monument construction
- iv. Unstable ground where the reference station is located
- v. Changes in station hardware (e.g., antenna or antenna mount) without proper bookkeeping
- vi. Accumulation of snow on a reference station's antenna
- vii. Natural (e.g., bird's nest on the antenna) or human induced (e.g., placement of an object on the antenna) changes at the reference station
- viii. Environmental changes near the site (e.g., vegetation growth)

- c. **Making end users aware when a station is offline:** In Network RTK (NRTK), a polygon of reference stations is used to generate corrections. The closest reference station generally has the most influence on the calculated GNSS correction since it should have the highest error correlation. If the closest reference station goes offline, reference stations further away have greater influence on the received correction value. Depending upon reference station spacing, accuracies may degrade from ± 2 cm to ± 4 cm or more. For applications such as road construction, this degradation in performance may not meet project requirements. It is important that end users are able to verify station uptime during the course of a survey.

- d. **Providing recommendations to service providers on how to meet stability and uptime needs:**

There is never a guarantee that a reference station will behave as expected, but by following certain best practices, performance anomalies can be minimized. This is critical in an industry where end users are dependent on another party for accurate results.

Stakeholders

Key stakeholders in the delivery of high accuracy, GNSS positioning services include:

- a. **High Accuracy, GNSS Service Providers:** There are presently at least six companies offering high accuracy, GNSS corrections services in Canada. Their target markets include the surveying, construction and agriculture industries. Technological advances have opened up new opportunities in machine automation and artificial intelligence applications, increasing the likelihood of new entrants to this market.
- b. **End Users (e.g., Surveyors, Survey Technologists, and Construction Workers):** There are currently more than 2,000 professional surveyors in Canada and more than 10,000 survey technologists. These consumers of high accuracy GNSS corrections depend upon GNSS Service Providers to provide reliable data. Erroneous data can have significant liability implications for subscribers due to the nature of their work.
- c. **Canadian Geodetic Survey:** CGS is responsible for defining, maintaining, and providing access to the national referencing system – the CSRS. Access to the CSRS is provided in several ways including:

- i. Maintaining a national network of passive geodetic control monuments having published coordinates that can be accessed by industry;
 - ii. Maintaining a national network of active geodetic reference stations whose data can be accessed for D-GNSS positioning
 - iii. Offering online Precise Point Positioning (absolute) services that can determine a user's position in the CSRS by submitting GNSS data for the location of interest.
- d. **Provinces:** Provincial geodetic agencies are responsible for defining, maintaining, and providing access to provincial coordinate referencing systems, which should integrate with the national system. Access to provincial coordinate referencing systems is provided by:
 - i. Maintaining a provincial network of passive geodetic control monuments having published coordinates that can be accessed by industry (many provinces are no longer do this); and
 - ii. Maintaining a provincial network of active geodetic reference stations whose data can be accessed for D-GNSS positioning (half of the provinces are currently doing this).
- e. **Cities & Municipalities:** Cities and municipalities have also recognized the value of having access to high accuracy, GNSS positioning and many have invested in one or more continuously operating reference stations to broadcast GNSS corrections. Some cities and municipalities also define, maintain and provide access to a local coordinate referencing system. Some maintain networks of passive geodetic reference stations.
- f. **Academia:** Some universities and colleges with geomatics programs have installed continuously operating reference stations.

Tools

In response to the previously described solution considerations, tools have been developed to help address industry needs as subsequently described. The tools have been in development since 2011, through ongoing consultations between CGRSC and service providers.

Best Practices for GNSS Service Providers

There is never a guarantee that a reference station will behave as expected, but by following certain best practices, performance anomalies can be minimized. To assist GNSS service providers in installing stable reference stations having high uptime, best practices were compiled. The best practices are based upon the installation experiences of CGS and other provincial geodetic agencies and best practices developed by other nations. Topics such as choice of construction materials, antenna mast design, and data handling are discussed [CGS 2017].

Coordinate Calculation Services

CGS now offers coordinate calculation services at no charge for organizations operating reference stations whose data is consumed by a third party. As subsequently described, it is expected that the organization will commit to making the station's data available for analysis on an ongoing basis. Interested

organizations must provide sufficient data (2 weeks or more) to facilitate initial coordinate calculations. By offering such a service, it is hoped that the integrity of the CSRS will be maintained.

Currently, CGS routinely processes data from several commercial RTK networks, most of whom provide reference station data on a daily basis. Rigorous, geodetic, processing techniques are employed to achieve the highest accuracy. Each network is processed separately in combination with a set of global reference frame stations (e.g., the Canadian Active Control Stations) to provide network constraints.

Daily data files for each network are processed following the International GNSS Service (IGS) processing standards. Bernese GNSS Software, absolute, antenna phase centre, calibration models and IGS Final precise ephemerides are used. Each daily solution is integrated directly into the current version of the geodetic reference frame by using the global reference frame stations as constraints. These daily, Bernese coordinate solutions are then combined into a weekly solution that is used for monitoring the stability of the reference stations (see next section).

Each month, all of the weekly solutions (coordinates and full covariance matrices) are combined into a cumulative solution. At this stage, coordinates at the official epoch (currently 2010.0) and their velocities are estimated. Station velocities are estimated only for stations that have more than one year of data. Experience has shown that using less data can result in unreliable velocity estimates.

For a station with less than one year of data, coordinates are estimated at the mean epoch of the weekly solutions in which the station is included and then propagated to the official epoch using CGS's velocity model. These coordinates are supplied to the RTK network operators for adoption at their reference stations. The cumulative solution at the end of each year is considered the latest official or published solution for adoption. Since frequent changes to reference station coordinates can cause confusion, service providers are only required to update their reference station coordinates to the new

official solution if they have changed by more than 2 cm horizontally or 3 cm vertically. These thresholds reflect values that can be detected using RTK.

When new stations are added or existing stations are relocated, new coordinates are needed quickly by service providers. In such cases, CGS will provide preliminary coordinates from the latest monthly cumulative solution where the new or relocated stations have more than 2 weeks of data. CGS uses IGS Final ephemerides that have up to a 14-day latency after the end of the week. It takes approximately 1 week to estimate the new weekly coordinate solutions and to combine it into an updated cumulative solution. Consequently, preliminary coordinates from the monthly cumulative solutions typically take a minimum of 3 weeks to generate once 2 weeks of data is made available for processing.

Reference Station Position Monitoring

As described, a reference station's position may vary or change for a number of reasons. At some point, the difference between the true and published coordinate values will exceed the user's error tolerance, negatively impacting survey results. For monitoring purposes, thresholds of 2 cm horizontally and 3 cm vertically were deemed to be the maximum tolerable errors before RTK results become negatively affected, while at the same time not putting too onerous demands on service providers to constantly update coordinate values.

As described in the previous section, weekly solutions are used to monitor the stability of a reference station. Figure 1 gives an example of a detected horizontal discontinuity that could be caused, for example, by a sudden shift in reference station location or by a change in the antenna mounting hardware.

In such circumstances, it is often necessary to estimate a new reference station position after the discontinuity.

Figure 2 illustrates a station exhibiting large seasonal variations in the vertical position. Such variations can cause a station to exceed agreement thresholds during specific times of year (often during the winter months). Thermal expansion of the antenna mast, thermal expansion of the building on which the antenna mast is mounted, snow and ice on the antenna, and other environmental effects can cause this type of behaviour. In such cases, it is advisable to find and mitigate the source of the variation, which may involve moving to another site.

A reference station may also illustrate a runaway trend, as illustrated in Figure 3. In this scenario, a reference station illustrates a velocity that may be caused by an unstable monument or a geophysical effect, for example. A new coordinate can be generated for the station, but unless the underlying cause of the velocity is addressed, the problem will continue to occur. This may mean relocating the station to a less precarious geophysical region or stabilizing the monument's construction.

The majority of reference stations monitored by CGS illustrate behaviour similar to that illustrated in Figure 4. The reference stations are relatively stable over time, illustrating only small variations from the published position and minimal data outages. It is impossible to predict how a reference station will behave once installed and to prevent all data outages, but by following best practices and implementing monitoring tools like the ones developed by CGS, the needs of industry can be protected.

Data Availability Monitoring

In the best practices for GNSS service providers, it is recommended that service providers promptly advise subscribers when a station goes offline. It is also recommended that service providers make available station uptime plots so that subscribers can verify reference station uptime for the duration of a survey. By service providers agreeing to transfer daily GNSS data files to CGS, CGS can also determine when data outages occur over a longer term, adding a further level of protection for users of the technology.

GNSS Reference Station Status Web Site

A web page was developed that allows users of the technology to query the status of GNSS reference stations in Canada (Figure 5). Information regarding reference station stability and data availability can be obtained. Information is available for reference stations of organizations that willingly participate in an *NRCan Compliance Program for High Accuracy, GNSS Services*, subsequently described.

Compliance Program

In 2014, CGS began entering into formal agreements with interested service providers to address the concerns of CCOG. CGS is a key member of CGRSC, having the largest resource capacity to undertake such an endeavour. Through the agreement, NRCan agrees to:

1. Provide official CGS generated reference station coordinates, integrated into the CSRS;
2. Maintain a public record of these official coordinates; and
3. Monitor and display publically the differences between the current (weekly) coordinates and the official published coordinates.

At the same time, the service provider agrees to:

1. Provide continuous access to reference station GNSS observation data using open Internet protocols;
2. Maintain station metadata in the format prescribed by the International GNSS Service's (IGS) site log (or other mutually agreed upon) format; and
3. Adopt the official CGS supplied coordinates for their reference stations.

Once the provider confirms that they have adopted the official coordinates for their reference stations, their GNSS reference station network is added to the CGS GNSS reference stations monitoring website. Each service provider's network is shown separately on a map of Canada. The web page displays each station in green, yellow, or red depending on the station's status (Figure 6) using the following criteria:

- A station's status is considered "Compliant" and displayed in green if both their GNSS data has been made available to CGS for coordinate estimation and the latest weekly estimated position propagated to epoch 2010 is within the agreed tolerance level from the official published coordinate.

- A station's status is considered "Unknown" and displayed in yellow if there are no coordinate estimates in the previous two weekly solutions, (which normally indicates there is no GNSS data available for those weeks).
- A station is considered "Non-Compliant" and displayed in red if either there are no coordinate estimates in the previous three weekly solutions, or the latest weekly coordinate estimate at the reference epoch is outside the tolerance level.

Other Considerations

Adoption into Standards of Practice by Professional Surveyors' Associations

Seeing that the Compliance Program protects the best interests of consumers of GNSS corrections, professional surveyors' associations are encouraged to update their standards of practice to only allow GNSS corrections to be consumed from service providers who have entered into a Compliance Agreement with CGS. This will acknowledge the voluntary efforts of the service providers that are currently compliant and add incentive for others to become compliant. It will also ensure that the services that surveyors rely upon are compatible with the CSRS.

Public Network Integration

Although the original target of the Compliance Program was commercial GNSS service providers, it is clear that there is benefit to including any organization offering high accuracy GNSS corrections services to another party. For example, the Compliance Program can apply to public infrastructure operated by provinces, municipalities or cities. Such an effort will also help to ensure that surveyors relying upon services from this infrastructure will obtain results compatible with the CSRS.

Real-time, Precise Point Positioning Services

In recent years, Real-time, Precise Point Positioning Services have emerged as an alternative approach to D-GNSS for high accuracy GNSS surveys. Although the GNSS reference station infrastructure is hidden from the user with this approach, similar concerns for station stability and data availability exist when generating GNSS corrections. There is therefore also value to service providers of such services to have their reference stations monitored through the Compliance Program.

Outlook

High accuracy, real-time position information caters to the rapidly growing global geospatial technologies market, which is forecasted to hit \$439.2 billion by 2020 [GeoBuiz 2018]. Satellite positioning has become a worldwide utility. It is predicted that GNSS will enable over eight billion devices by 2020 [ESA 2017]. High accuracy, real-time GNSS corrections are automating the guidance of lawn mowers, haul trucks in mining, cargo ships, gantry cranes, shuttle buses and other vehicles. Although the focus of this discussion has

primarily been on applications in surveying, it is clear that the technology is becoming embedded in our daily lives and the need for quality control and quality assurance in this industry has never been greater. It is anticipated that the services offered by CGS will continue to evolve as new applications for the technology emerge and tighter requirements for quality control are needed.

Conclusion

In response to concerns raised by CCOG regarding the provision of commercial GNSS positioning services, a compliance agreement has been created. The agreement is voluntarily entered into with CGS by organizations providing access to high accuracy, GNSS corrections. Through the agreement, CGS provides coordinates to the service provider for their reference stations and monitors the stability and uptime of the stations. The service provider provides CGS with access to the stations' data, maintains an accurate site log and implements the CGS generated coordinates for the site. Through this relationship, the integrity of positioning in Canada can be upheld by ensuring that service providers are compatible with the CSRS. It is anticipated that the services offered by CGS will continue to evolve as new applications for the technology emerge and tighter requirements for quality control are required. The full benefits of this service will only be realized when professional associations relying upon positioning services embrace the agreement in their standards of practice.

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Further Reading

Guidelines for RTK/RTN GNSS Surveying in Canada available for download from NRCan website at:

<http://www.nrcan.gc.ca/earth-sciences/geomatics/geodetic-reference-systems/9056>

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Figures

Figure 1: Example of a station exhibiting a horizontal position discontinuity. Green circles indicate when the calculated position agrees with the published position; red triangles indicate when they do not agree.

Figure 2: Example of a station exhibiting large seasonal variations in the vertical. Green circles indicate when the calculated position agrees with the published position; red triangles indicate when they do not agree.

Figure 3: Example of a station exhibiting an unexpected change in horizontal velocity. Green circles indicate when the calculated position agrees with the published position; red triangles indicate when they do not agree.

Figure 4: Example of a 'good' reference station, illustrating only small seasonal vertical variations and few discontinuities in its data. Green circles indicate when the calculated position agrees with the published position.

Figure 6: Example GNSS Reference Station web page display. Compliant stations are displayed in green indicating that both their GNSS data has been made available to NRCan for coordinate estimation and the latest weekly estimated position propagated to the reference epoch is within the agreed tolerance level from the official published coordinate. Stations with an Unknown status are displayed in yellow when there are no coordinate estimates in the previous two weekly solutions, which normally indicates there is no GNSS data available for those weeks. Non-compliant stations are displayed in red when either there are no coordinate estimates in the previous three weekly solutions, or the latest weekly coordinate estimate at the reference epoch is outside the tolerance level [NRCan 2019].