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Utilization of Network RTK GPS in MTO Highway Surveys

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Project #14: Utilization of Network RTK GPS in MTO Highway Surveys

(Final Report)

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Executive Summary

The requirement to use newer methods of precise positioning is an ever growing need. Network Real-Time Kinematic (RTK) GPS (GNSS) in particular, can provide centimetre-level positioning accuracy in real-time using only one user receiver and access to a wireless network, which is a significant improvement over traditional RTK and other static relative positioning methods. Network RTK has caught the interest of the Ministry of Transportation of Ontario (MTO) as a replacement of static relative positioning methods for certain classes of control surveying. This report is essentially a feasibility study of network RTK performance in the context of MTO specifications.

Two extensive field campaigns have been carried out to collect hundreds of hours of raw and network RTK data from three different service providers, in order to analyze the performance of network RTK in terms of: availability, time-to-first-fix (TTFF), precision, accuracy, integrity and long-term repeatability. The availability results have shown that service performance can vary, but solution availability of 82% to 97% can be expected. TTFF of 30 seconds on average can be expected with extreme cases of 100 seconds or longer. The results indicate an overall precision of ~2.5 cm (95%) or lower, horizontally. However, solution biases do exist and can be up to 4 cm (horizontally) in isolated cases, which can severely undermine the accuracy of services and solutions. In terms of long-term repeatability, biases and precision levels in the solutions are repeatable at the 1 centimetre-level. Moving average filtering was employed to determine the observation period that is needed to meet MTO specifications, and the results show that a 5 minute observation window increases the precision of the solution by up to 25% and maximum error is reduced by up to 40% over the original 1 Hz data sets. Also, simulation of a control survey using network RTK shows misclosure error of ~2 cm horizontally within MTO specifications. However, the results of the analyses have not been uniform and each service network possesses individual characteristics, specifically coordinate biases, which could be address by regulatory guidelines for performance and quality of the services provided.

From the results of the analyses and the control survey simulation, network RTK services can meet MTO specifications for third-order horizontal (5 cm, 95% uncertainty) or lower order of control surveys. A set of practical considerations and procedures have been devised in this report for use of network RTK that are based on the issues and outcomes of the survey campaigns performed for this study and existing MTO RTK guidelines. Control surveys should be divided into sections and primary control points should be identified. More than one set of observations needs to be taken at each control point using an observation window in excess of 5 minutes with 1 Hz data rate. Different observation sessions for the same point should be separated by a period of at least several hours in order to take advantage of the change in satellite geometry and ensure the solution integrity. The quality of the network RTK solution should be checked in the area by collecting observations over the primary control points and checking the precision of the solution against the authorized public coordinates. Because the network RTK solutions are provided as absolute coordinates, relative baselines between two adjoining control points need to be deduced and used to check the quality of the solutions by statistically testing loop closure errors or against the specified tolerances. In case of measurement rejection, more observation sessions may be needed. With the qualified baseline measurements, the closure errors can be distributed and the coordinates of each new control point can further be estimated.

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1 Introduction

Over the past two decades, the Global Positioning System (GPS) has become ubiquitous in outdoor positioning and navigation. Other Global Navigation Satellite Systems (GNSSs), such as GLONASS, can also provide similar positioning and navigation services. While GPS has been popularized in consumer applications, it is used in a wide variety of scientific and engineering applications; one such very precise application is land surveying. The highest quality GPS receivers and antennas are used to determine the relative distance and orientation (vector) between survey monuments that are metres to thousands of kilometres apart with accuracies of millimetres to centimetres. Relative GPS requires that two sets of GPS equipment be set up at either ends of a baseline to be determined. One end of the baseline has known coordinates (reference stations), and with the GPS-determined vector, the unknown coordinates of the other end of the baseline can be calculated. Relative GPS has been augmented in different ways to improve its operational capabilities. One such change is known as real-time kinematic (RTK) that provides real-time few centimetres positioning after seconds to tens of seconds of data collection. However, RTK has its limitations, such as degradation of performance with longer baseline distances (>10-15 km), so network RTK was developed to reduce some of these limitations.

1.1 Network RTK

Network RTK was developed to effectively pool the measurements from a set of RTK reference stations, generally interpolated GPS error source corrections, to produce RTK-like performance over a larger area. A positive consequence is that reference stations can be spaced few tens of kilometres apart, making network RTK even more efficient. For a user, no RTK base station needs to be erected and therefore manned, and only one set of GPS equipment needs to be employed – through a radio receiver (typically in the form of a cellular modem) is needed to disseminate the network RTK corrections.

The network RTK corrections can be generated by means of a number of different approaches, including the virtual reference station (VRS) (Cansel, 2010), master auxiliary concept (MAC) (Leica, 2010) and FKP approaches. VRS is a very popular approach for utilization of network RTK corrections. Figure 1-1 shows the network architecture for the VRS network RTK method. When the user logs into the VRS network with their receiver, the approximate location of the survey is sent via NTRIP (Network Transportation of RTCM Internet Protocol) (Lenz, 2004) over the Internet using a wireless cellular modem that is normally embedded within the rover receiver to the central server. This location is treated as the VRS and the corrections for this location are computed using the reference station's satellite observations in the central server. The corrections for a virtual station near the rover are then provided to the user in RTCM data transmission standard (Lenz, 2004) or CMR (Compact Measurement Record) (Talbot, 1996) format. Another popular method of network RTK is the Master Auxiliary Concept (MAC). This method is very similar to the structure of the VRS network. In the MAC network structure, as it can be seen from Figure 1-2, the master station's direct observations and the auxiliary station's ambiguity-reduced observations and coordinate differences (to the master station) are used to compute the corrections for the rover's location.

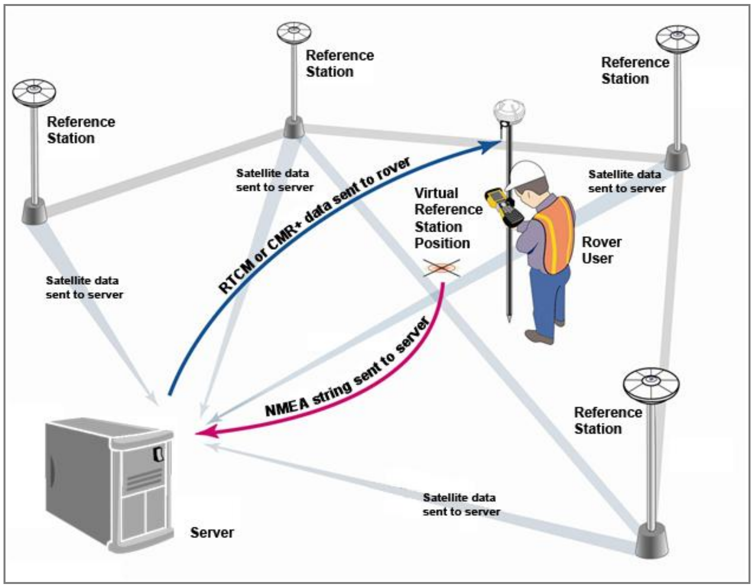

Figure 1-1. VRS network architecture (modified from Cansel, 2010)

One of the major differences between the two methods is that MAC does not utilize a virtual reference station and the solutions provided to the rover are founded on baselines formed directly with respect to the Master reference station. Like VRS, the corrections for the MAC network are provided to the rover over the Internet using the RTCM format. Also there is an extension to the MAC system, i-MAC (Leica, 2010), that accommodates older receivers that are not compatible with the MAC method.

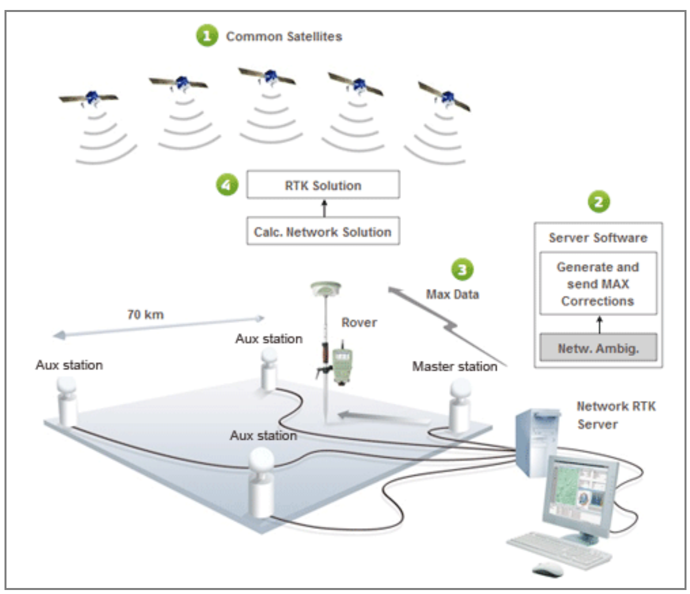

Figure 1-2. Network architecture of MAC used by Leica Geosystems (Leica, 2010)

There are also other effective methods of network RTK such as FKP which uses a series of area correction parameters as simple planes that are valid for a limited area around a single reference station. This method does not require a two way communication between the server and the rover. The correction parameters that are broadcast by the network's reference stations are received by the rover and are used to compute its position (Park and Changdon, 2010).

1.2 Objectives

Currently, in Ontario, MAC and VRS are both utilized by three different private companies. The Ministry of Transportation of Ontario is interested in how these recently developed commercial network RTK services may be used for control and engineering surveys. The overall focus of this report is to investigate the performance of these network RTK services in southern Ontario for use in MTO control and engineering surveys. This goal will be achieved via the following specific objectives:

- Evaluate the performance of network RTK services as a whole in Ontario.
- Develop specifications and guidelines for the use of network RTK in MTO control and engineering surveys.

A series of specific tasks have been defined to directly and efficiently research each objective. These tasks are further explained in §2.3, which discusses the parameters that will be used to characterize the performance of network RTK in relation to control and engineering surveys.

1.3 Similar Research

There have been similar studies performed that have investigated the performance of network RTK in various locations around the world. An example is Edwards et al. (2008) which evaluated network RTK services in Great Britain. Commercial network RTK has been available in Great Britain since 2006 and network RTK services were basically an expansion of the Ordnance Survey OS Net (OS Net). Leica and Trimble are the two companies that are licensed to provide network RTK solutions operating 'SmartNet' and 'VRSNOW', respectively. This study focused on the performance of these privately-run networks in terms of accuracy and repeatability of the solutions, the improvement of the solutions with the integration of additional satellite constellations and performance of the networks at the extents and in presence of significant height differences. A series of tests were completed in this study in March 2008 and solutions of the networks were recorded at each of the chosen test sites. A rather interesting test set up is employed (Figure 1-3), which utilized a horizontal bar that holds three antennas; the antenna in the centre is connected to a geodetic receiver and the outer network RTK antennas are each at a distance of 25 cm away from the centre. Coordinates for the test locations are determined independently using raw data from the central antenna in Bernese v5.0 and relative positioning for the two outer antennas with respect to precisely determined central antenna coordinates using Leica GeoOffice software. Filtering of the solutions is employed prior to the analyses using CQ (Coordinate Quality), as well as DOP (Dilution Of Precision). Some of the results revealed that both private companies are operating at the same level of accuracy. Also, it is shown that the coordinate quality values indicated by the equipment under more extreme conditions (limited visibility and large multipath) tend to be overestimated. The study also concluded that, in general, the accuracies (1σ) of network RTK in Great Britain range from 10 to 20 mm in the horizontal and 15 to 35 mm in the height. A set of “proper” field practices for the use of network RTK are demonstrated based on the results of the study.

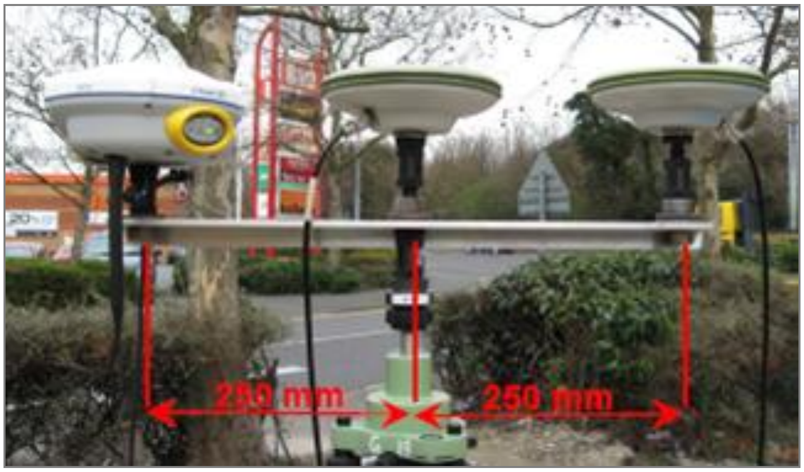

Figure 1-3. Test set up used by Edwards et al. (2008)

Another similar study by Rubinov et al. (2011) is based in Victoria, Australia. There are three different networks currently operating in Victoria: VRSNet, using Trimble network software; TopNet, using Topcon software suite; and Checkpoint, provided by GLOBAL CORS. Three test sites are chosen at various distances. Control points are established at each test site at nominal distances of 250 m and rigorous and extended static occupations are performed to determine coordinates for the control points using Trimble Geo Office (TGO) post-processing software. The main focus of the study is the quality of height at various test locations; however, similar results are shown for the horizontal solution qualities as well. The testing procedure was devised to evaluate the performance of network RTK for two separate applications: general surveying (static testing) and machine guidance applications (kinematic testing). A Temporary Reference Station (TRS) was also introduced to densify the existing CORS network and to evaluate the benefits, if any, of its inclusion on the results. The results showed general height error of 25 mm (1σ) which was reduced to 20 mm by application of the TRS. The study also shows the performance of the mentioned networks at various distances from primary reference stations in both horizontal and height accuracy. Generally, a decrease in the absolute accuracy was demonstrated with an increase of the baseline length.

2 Methodology and Fieldwork

In this section, the methodology and fieldwork that were performed as part of this study will be discussed. The evaluation methodology was designed to accommodate three different makes of equipment and their respective characteristics. Careful pre-planning and logistics were considered due to the volume of the tasks undertaken. Field practice simulations were held to ensure stability of the proposed methodology and reduce problems during the data collection process. Also, for the thorough evaluation of network RTK services, two separate field campaigns were performed: in December 2010 and in July 2011. The goal of the fieldwork campaigns have been to collect as much raw GPS data and network RTK solutions as possible for all active service providers. The fieldwork campaign in July 2011 was performed to test the issue of long-term repeatability and also to perform additional tests that were deemed necessary after reviewing the results of December 2011 campaign, such as static timed tests and a control survey test.

2.1 Data Collection

Two sets of field surveys were performed in December 2010 and July 2011. The tests performed in each field survey are summarized here:

December of 2010 (winter):
- 9 static sites visited (Figure 2-3)
- ~ 8 hours of raw and network RTK data collected from each receiver at each site.
- Time-to-first-fix tests performed
- ~ 50 hours of kinematic network RTK data collected

July of 2011 (summer):
- 4 sites revisited
- ~6 hours of raw and network RTK data collected from each receiver at each site.
- Additional tests performed
- Static solution[1] tests
- Control survey tests (Figure 2-4)

Table 2-1 shows the amount of data collected as part of the field surveys performed for this study.

Table 2-1. Data types collected during the field campaigns

Field Survey	Data type	Duration	Total
Winter (Dec. 2010)	Static NRTK	8 hours	288 hrs. (1 Hz, fixed)
	Raw GPS	8 hours	288 hrs. (1 Hz, fixed)
	TTFF	5 trials	135 trials
	Kinematic NRTK	10 hours	50 hrs. (1 Hz, fixed)
Summer (July 2011)	NRTK	6 hours	80 hrs. (1 Hz, fixed)
	Raw GPS	6 hours	80 hrs. (1 Hz, fixed)
	Static solutions	5 trials	369 trials

[1] Static solution is used to describe the "survey" or "topo" measurement option on Network RTK equipment for manually starting the measurement process.

The additional tests performed in the summer were planned after an interim report of the winter results, and it was decided between our team and MTO.

2.1.1 Test Configuration

The three network RTK rovers were set-up as per Figure 2-1; one receiver / antenna was set up on the selected reference station, which was a forced-centering monument or a brass cap, and the other two receivers / antennas were set up on tripods within a few metres of the reference monument over temporary markers. Network RTK solutions, the associated quality control information and raw measurements (for post-processing) were recorded for at least 8 hours in the winter campaign and 6 hours in the summer campaign using the auto static solution[2] surveying method, which automatically records network RTK fixed solutions. The configuration in Figure 2-1 should minimize biases due to geometrical differences by keeping the geometry and surrounding environment the same.

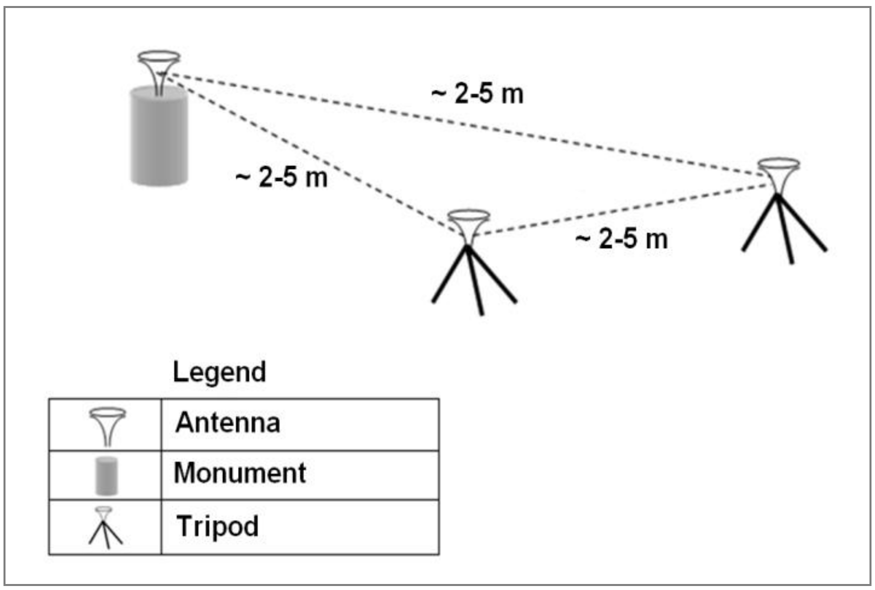

Figure 2-1. Test set up used at each test site

Time-to-first-fix tests were also performed and the measurement for each trial was recorded to be analyzed as metric of network RTK service performance. The time-to-first-fix was measured time from the moment the receiver was fully connected to the internet to the first network RTK fixed solution. For each trial the receiver was fully restarted to simulate a cold start.

2.1.2 Control Survey

The data collection for the control survey followed a different procedure. Each set of equipment were set up over monuments (Figure 2-4) and three sets of static timed measurements were performed. One, two and five minute static solutions were collected to

[2] Auto static solution is used to describe the "auto-survey" or "auto-topo" option on Network RTK equipment, which involves the equipment automatically collecting solutions until stopped by user.

simulate what the average surveyor would experience when using the equipment. These network RTK solutions were then compared with the computed and published reference coordinates. The determination process of the reference coordinates is given in § 2.5.

2.1.3 Quality Control Settings

In the winter campaign, in order to be able to obtain as much network RTK data as possible, it was decided to turn off all possible internal quality control and outlier detection options in each set of equipment. Provided that each set of equipment offers the user with a different level of authority over the internal quality control and internal outlier detection, this was done to the best knowledge of the service providers and the testing team. The outlier detection process was completed using MATLAB scripts which read in all the unique solutions from each record and remove those solutions that have a horizontal (or 2D CQ) covariance above 5 cm. Note that no attention was paid to the vertical quality of the solutions (or 3D CQ) as the main objective of this report is to evaluate the horizontal quality of network RTK solutions.

In contrast, during the summer campaign, after reviewing the results from all the previous fieldwork, it was considered necessary to have all possible outlier detection and quality control options enabled to display discrepancies, if any, with respect to the winter campaign's solution qualities. All the horizontal quality control settings in the equipment sets were enabled to filter out any solution above 5 cm horizontal. As part of the summer campaign, the control survey also utilizes the same settings for internal quality control. This was done to study what the average user would experience when using the network RTK services.

2.1.4 Difficulties Encountered

A few problems were encountered during the course of fieldwork. The cell phone GSM network at times "dropped" connections at which point the connections needed to be reset manually for two of the service providers. A few instances of data corruptions were encountered, for which the raw GPS data and network RTK records could not be obtained. These particular encounters can be seen in the data availability analysis. The large gaps shown in the network RTK data or raw data are due to connection/hardware and also network unavailability that were encountered. Two instances of unavailable networks were encountered due to network software upgrades. Battery life is a constraint for long period surveys (sometimes up to 10 hours), especially in frigid winter conditions. This created various instances when the battery needed to be switched on a particular set of equipment. As a part of the study only Bluetooth connections were used, when possible, to communicate between data collectors and receiver/antenna to test the equipments reliability as experienced by the average user. Bluetooth can become unstable even over very short distances and sometimes, depending on the equipment, cause the receiver to shut down its modem, which consequently closes the Internet connection.

As a result of some of the difficulties encountered, some isolate cases of missing data were stumbled upon, which is to be expected in a field work of this magnitude. The network RTK data for company 'B' at the Belleville site were irretrievable due to a hardware corruption issue, in the winter. Also, for company 'C' there is no available data for sites Ottawa and St. Catharines due to network being down for maintenance, during the winter campaign. These missing solutions for the parties mentioned will be noted in the results section.

2.2 Site Locations

Figure 2-2 shows the dense network RTK reference station distribution in southern Ontario. There are over a total of 70 stations covering a span of 900 km from southwestern to eastern Ontario.

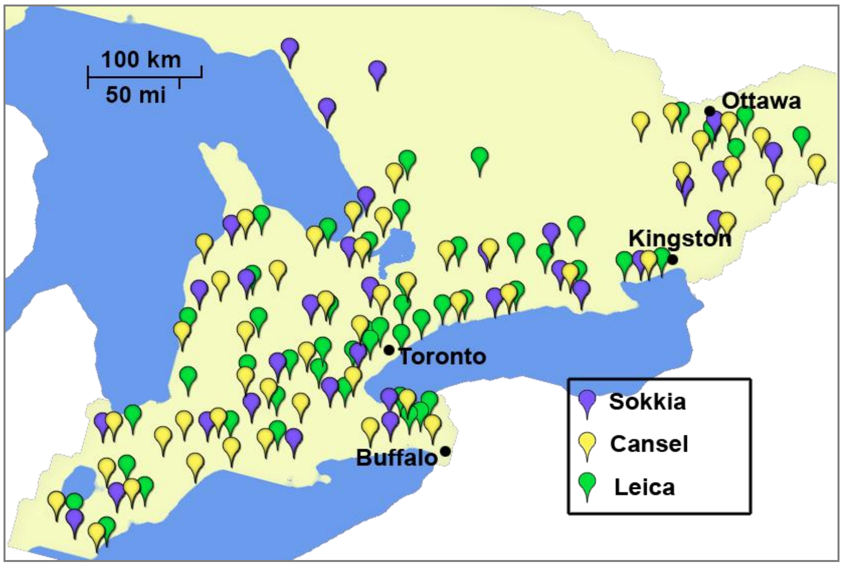

Figure 2-2. Network RTK reference stations in southern Ontario - 2010

The locations of the nine sites visited during fieldwork for this study are shown in Figure 2-3: Peterborough, Belleville, Kingston, Ottawa, Kitchener, Windsor, London, St. Catharines and Barrie. Each location has a high order forced-centering monument or a brass cap and they have been chosen in a manner to cover most areas of interest in southern and eastern Ontario, as seen in Figure 2-3.

The site names are merely chosen based on the closest large municipality and may not represent the actual location of each site. Details of each monument can be seen in Table 2-2, which shows the type and class of the monument occupied. The COSINE station numbers, which are provided in Table 2-2, refer to the monument numbers provided on Ontario's COSINE (Control Survey Information Exchange) database. Published coordinates and other details of the abovementioned monuments can be viewed using that database.

Figure 2-3. Test locations used in southern Ontario

Table 2-2. Test site information

Name of testing points	Type of monument	Order	COSINE station numbers	Site code
Peterborough	CBN	Class A	00119973002	pet
Belleville	CBN	Class A	00119823033	bel
Kingston	CBN	Class A	00119973001	kin
Ottawa	CBN	Class A	00119833001	ott
Kitchener	CBN	Class A	00119843025	kit
Windsor	CAP	Class C	00819980491	win
London	CBN	Class A	00119813041	lon
St. Catharines	CAP	Class C	00819980031	stc
Barrie	CAP	Class D	00819798415	bar

2.2.1 Winter and Summer Campaigns

For the winter campaign all of the monuments shown in Table 2-2 were visited. All equipment was set up in a special configuration, as explained in detail in §2.1, and raw and network RTK GPS data were collected for approximately eight hours.

For the summer campaign only four of the monuments shown in Table 2-2 were visited: Kitchener, London, Belleville and Barrie. All equipment was set up in a special configuration, as explained in detail in §2.1, and raw and network RTK GPS data were collected for approximately six hours. In addition to the regular data collection procedure, a set of static solutions were collected to be analyzed further as a test of the equipments' internal filtering process.

2.2.2 Control Survey

A separate control survey was performed with seven monuments along Highway 9 in Orangeville during the summer campaign (Figure 2-4). The test procedure for the control survey is explained in § 2.1.2. These seven monuments were recently surveyed by MTO and the preliminary coordinates were provided to the project to perform these tests. For the purpose of this study, the monuments were named points 1 to 7, with point 1 being the closest point from Highway 400 and point 7 being the farthest. The control survey tests were performed to simulate and analyze the results of an actual control survey and to use the results to help complete the guidelines and specifications for use of network RTK in MTO's control and engineering surveys.

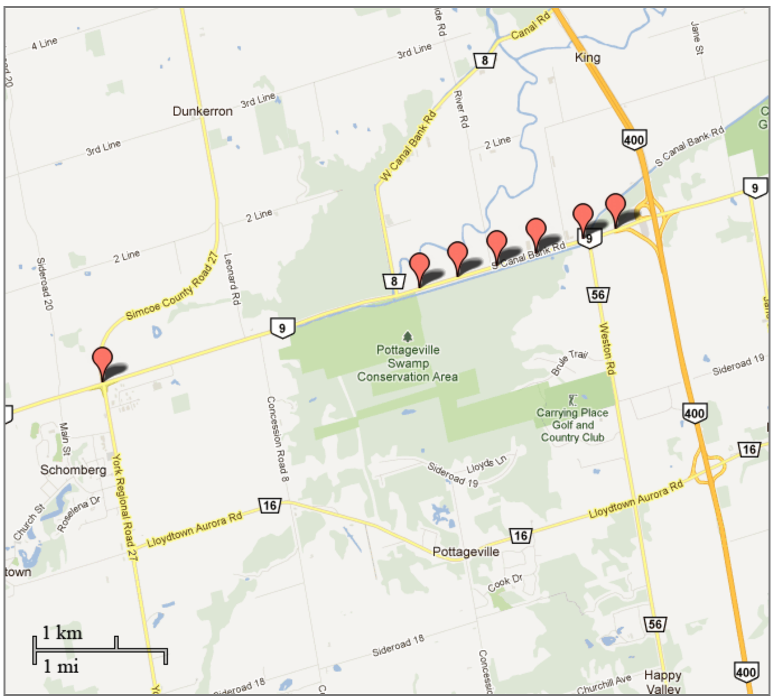

Figure 2-4. Control survey test locations

2.3 Service Providers and Equipment

The three major service providers that are operating in Ontario are: SmartNet, PowerNet and Can-net from Leica Geosystems, SOKKIA Corporation and Cansel Survey Equipment Inc., respectively. The service providers will be referred to as Companies 'A', 'B' and 'C' in a random order for anonymity throughout this report. As the service providers are continuously upgrading their software and hardware and improving the coverage of their network by adding reference stations, there have been some changes in equipments and the networks during the course of the seven month gap between the winter and summer campaigns. The project was provided with the equipment deemed most stable and widely used by each service provider.

2.3.1 Equipment Models

The winter campaign was performed from December 2, 2010 to December 15, 2010. Nine sites were visited that are outlined in detail in § 2.2. All three service providers participated in this fieldwork campaign. The tested equipment from each service provider is given in Table 2-3.

Table 2-3. Models of equipment used for the fieldwork

Service Provider	Manufacturer	Receiver/Antenna
Sokkia	Sokkia	GSR2700 ISX
Leica	Leica	GS15
Cansel	Trimble	R8 Model 2

The summer campaign was performed from July 1, 2011 to July 26, 2011. There were a few equipment changes with some of the service providers, where a variation of the equipment models mentioned in Table 2-3 were used for testing. These changes in the summer were either due to the unavailability of the exact receiver model used at the equipment rental high-season, or due to the request of the service provider.

2.4 Summary of Analyses

This section of the report will focus on demonstrating the details of the analyses that have been performed as part of this study on the network RTK solutions. Also, the reference coordinate determination process is presented. In order to define 'performance' of network RTK, performance metrics need to be defined. Each sub-section focuses on a different set of performance metrics with respect to determined reference coordinates. For the purpose of this analysis, the metrics selected are: availability, time-to-first-fix, precision, accuracy and solution integrity. Also, the effect of moving average filtering is studied on precision and maximum error.

Availability

The purpose of the availability analysis is to show the amount of usable data that were collected for each test site. The network RTK availability percentage is computed by comparing the number of network RTK records available against the number of records that should be available at the 1 Hz data collection interval over the period of observation. Detailed discussions of these results is given in §3.2.

Time-To-First-Fix

The time-to-first-fix (TTFF) analysis shows the average time to first network RTK position fix for each service provider at each test site. The TTFFs were recorded from a "cold start" to the time when the first fixed solution is obtained. This test was repeated multiple times. The results for TTFF analysis is presented in §3.3.

Precision

The purpose of the precision analysis is to compare the collected 1 Hz data with respect to its own mean, using the auto static solution setting for network RTK position fixes. The standard deviations of the time series characterize the data as "precise" or "imprecise" within 1σ of the normal distribution. The results of the precision analysis can be seen in §3.4.

Accuracy

The accuracy analysis compares the network RTK solutions from service providers against the published and determined (refer to §2.5 for more details on coordinate determination) coordinates. For these analyses, the service provider's internal quality control variances are used to filter the network RTK solutions the results are shown in NEU components. The results and discussions on accuracy are presented in §3.5.

Solution Integrity

The solution integrity analysis is an in-depth look at coordinate quality covariances and attempts to determine the reliability of the coordinate quality values that are given by equipment processing outputs. This study will provide comparisons of absolute errors against coordinate quality values, and correlation plots. Solution integrity analysis results are shown in §3.6.

Moving Average Filtering

The moving average filtering analysis compares different size averaging windows of the 'raw' network RTK solution with respect to each determined coordinate. An average of the 1 sec filtered network RTK solutions collected for the service providers with different sized time bins (5 sec, 10 sec, 30 sec, 60 sec, 5 min) shows how this "moving average" can be used to filter the solutions further and obtain better results. The main purpose of this analysis is to determine what minimum length of time data needs to be collected to fit MTO accuracy/precision specifications for the common user.

2.5 Reference Coordinates

The monument coordinates used in this study are official coordinates published by Natural Resources Canada (NRCan) and COSINE, the latter of which is a public service provided by the Ontario Ministry of Natural Resources. All of the post-processing of the collected raw GPS data was completed using Bernese v5.0. For coordinate determination, the raw data were used to determine the vectors from the monument to each of the temporary markers. Approximately eight hours of raw data were available from each antenna. The double-differenced vectors were then used with the officially published coordinates (COSINE and NRCan) to determine the coordinates of each temporary marker. Also, each high order monument's coordinates were re-determined and compared to guarantee the quality of these coordinates using raw data from nearby CACS (Canadian Active Control System) reference stations and the eight hours of raw GPS data that was collected over each monument. Table 2-4 shows the CACS sites that were used to determine the monument coordinates. These sites were chosen based on the closest pair of active control points to each test site.

Table 2-4. CACS sites used in processing and proximity to test sites

Test site	CACS used	Approximate distance from site (respectively)
Peterborough	Kingston & Peterborough	140 km & 170km
Belleville	Kingston & Ottawa (NRC1)	50 km & 185 km
Kingston	Kingston & Ottawa (NRC1)	30 km & 130 km
Ottawa	Gatineau & Ottawa (NRC1)	20 km & 25 km
Kitchener	Goderich & Port Weller	100 km &110 km
Windsor	Goderich & Port Weller	200 km & 310 km
London	Goderich & Port Weller	105 km & 110 km
St. Catharines	Goderich & Port Weller	165 km & 80 km
Barrie	Parry Sound & Port Weller	130 km & 115 km

For the control survey monuments the coordinates were determined by occupying each point for approximately one hour and simultaneously setting up a separate receiver over a nearby, higher-order monument. This process was repeated twice and the results were averaged for the control survey adjustment. Also, the relative baselines between the points were surveyed by "leap-frogging" along the traverse. Using Bernese v5.0, a full network adjustment was done to determine coordinates of each monument. Figure 2-5 shows the data collection process that was used for the coordinate determination for the seven control survey points.

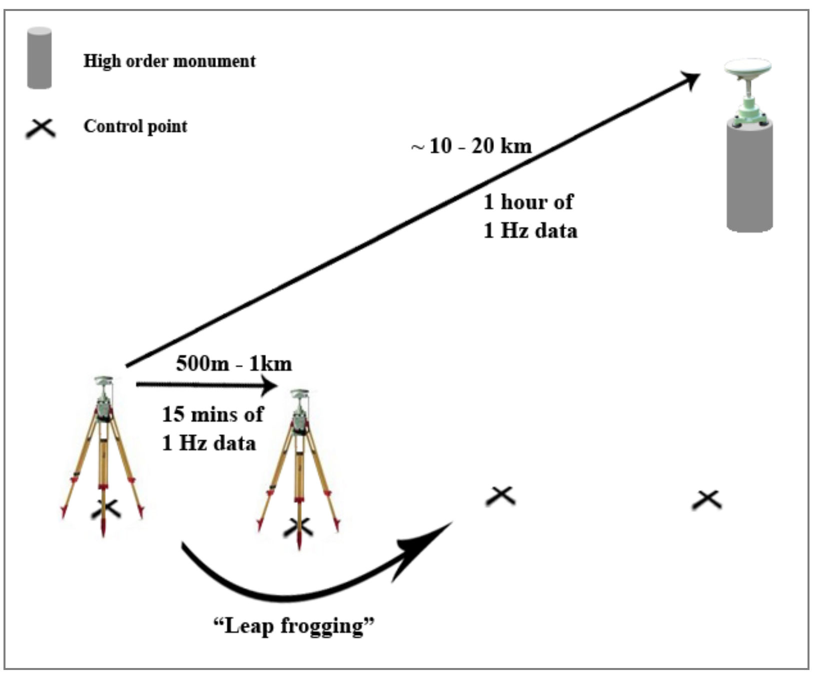

Figure 2-5. Control survey data collection procedure for coordinate determination

3 Results and Discussions

The aim of this section is to quantify the major performance metrics of the network RTK services available in Ontario. The results of the analysis shown here will be used later in this report to set guidelines and specifications for using network RTK in control surveys.

3.1 Solution Quality

This section focuses on time series of the network RTK solutions with respect to reference coordinates over a period of approximately 8 hours. Figure 3-1 shows a "good" solution set with solution error versus local time. Horizontally, a maximum error of ~1 cm can be seen and the time series shows very little variation. Statistically, there are no significant positional biases seen in the solution with the current scale. As expected the up component shows twice as much absolute error as the horizontal components. For 8 hours of network RTK records a standard deviation of 0.6 cm in the horizontal and 0.8 cm in the height. Also, solution means of 0.1 cm and 0.2 cm in the north and east component, respectively, and 0.8 cm bias can be seen for the height. Upon closer inspection a sinusoidal behaviour is revealed in all components of the solution.

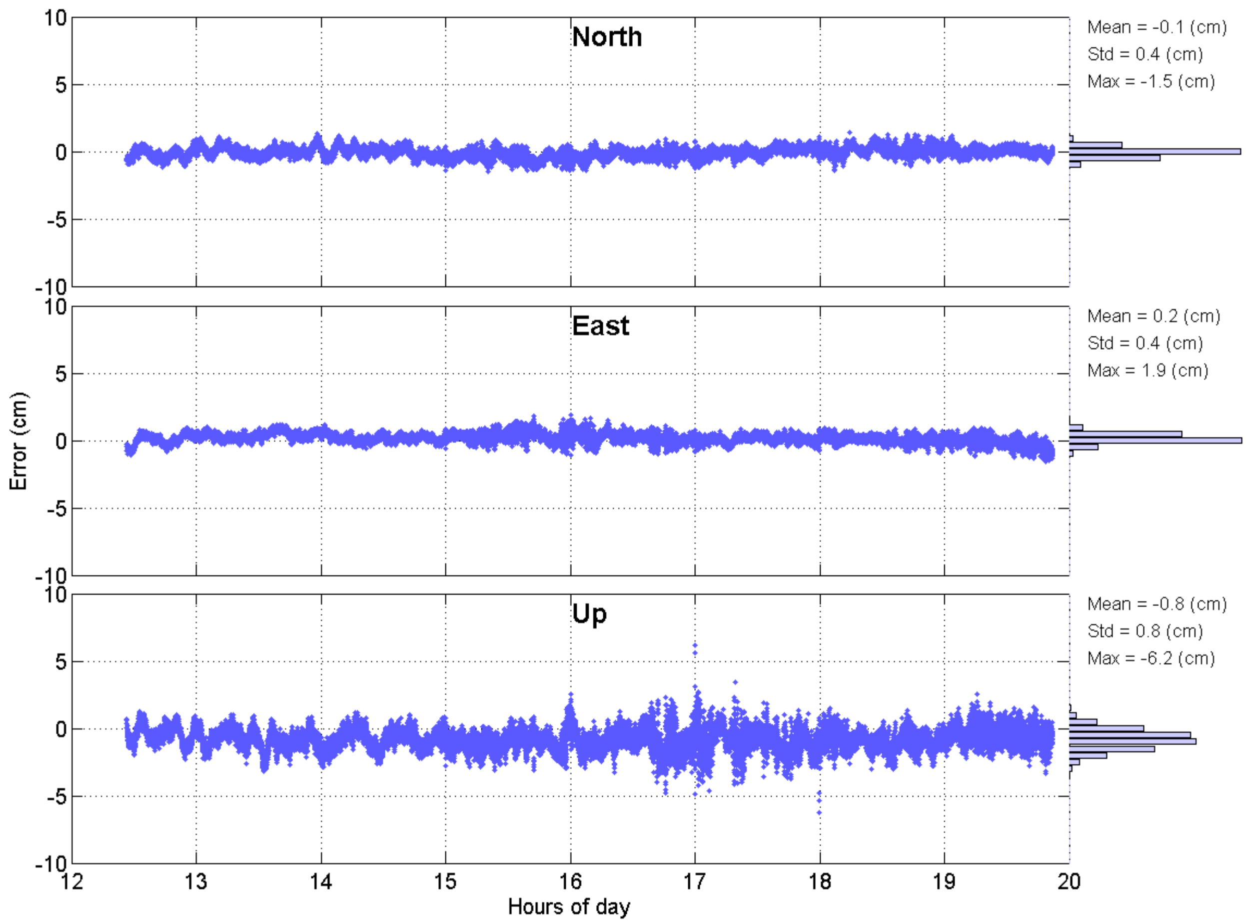

Figure 3-1. Example of "Good" quality network RTK solution

In contrast to Figure 3-1, Figure 3-2 displays a "not so good" solution showing larger variations of a few centimetres from the reference coordinates. The standard deviations in the north and east direction are 1.3 cm and 1 cm, respectively, and 2 cm in the height. The biases are 0.5 cm and 0.4 cm, respectively, for north and each component and 1.2 cm for the height. The precision is almost three times larger than the solution shown in Figure 3-2 in all directions with respect to Figure 3-1. A gap of 10 - 15 minutes can be seen between hours 14 – 16 of the data. This gap is not due to a discontinuation in the available solutions and is a result of removing outliers using the equipment provided coordinate variances. Furthermore, similar sinusoidal behaviour is present in the "not so good" solution as with the "good solution," and it seems to be more extreme than that of the results shown previously.

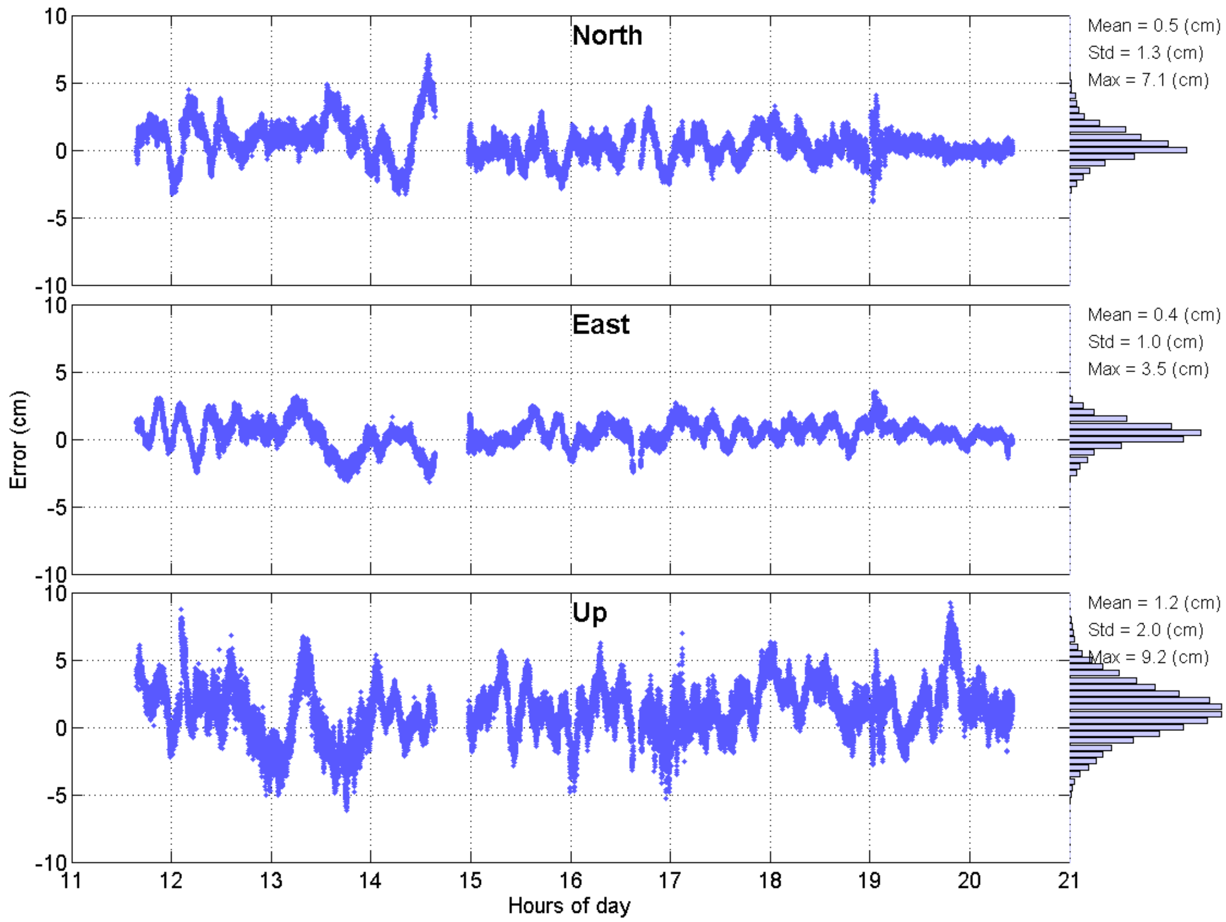

Figure 3-2. Example of "Not so good" quality network RTK solution

Figure 3-3 shows the existence of biases in the network RTK solutions. The time series in each component have non-zero means, which show unexpected behaviour of the solutions for service providers. The solutions are very precise in the horizontal component, as illustrated by the relevant histograms and the standard deviation values. The standard deviations for north and east components are 0.9 and 0.6 cm, respectively. However, large overall biases of 1.5 and 3.1 cm in the north and east component, respectively, paint a picture of a precise but "not so accurate" solution. Also, the same sinusoidal behaviour is seen, but with a higher frequency than shown in the previously results which is investigated further in Figure 3-4.

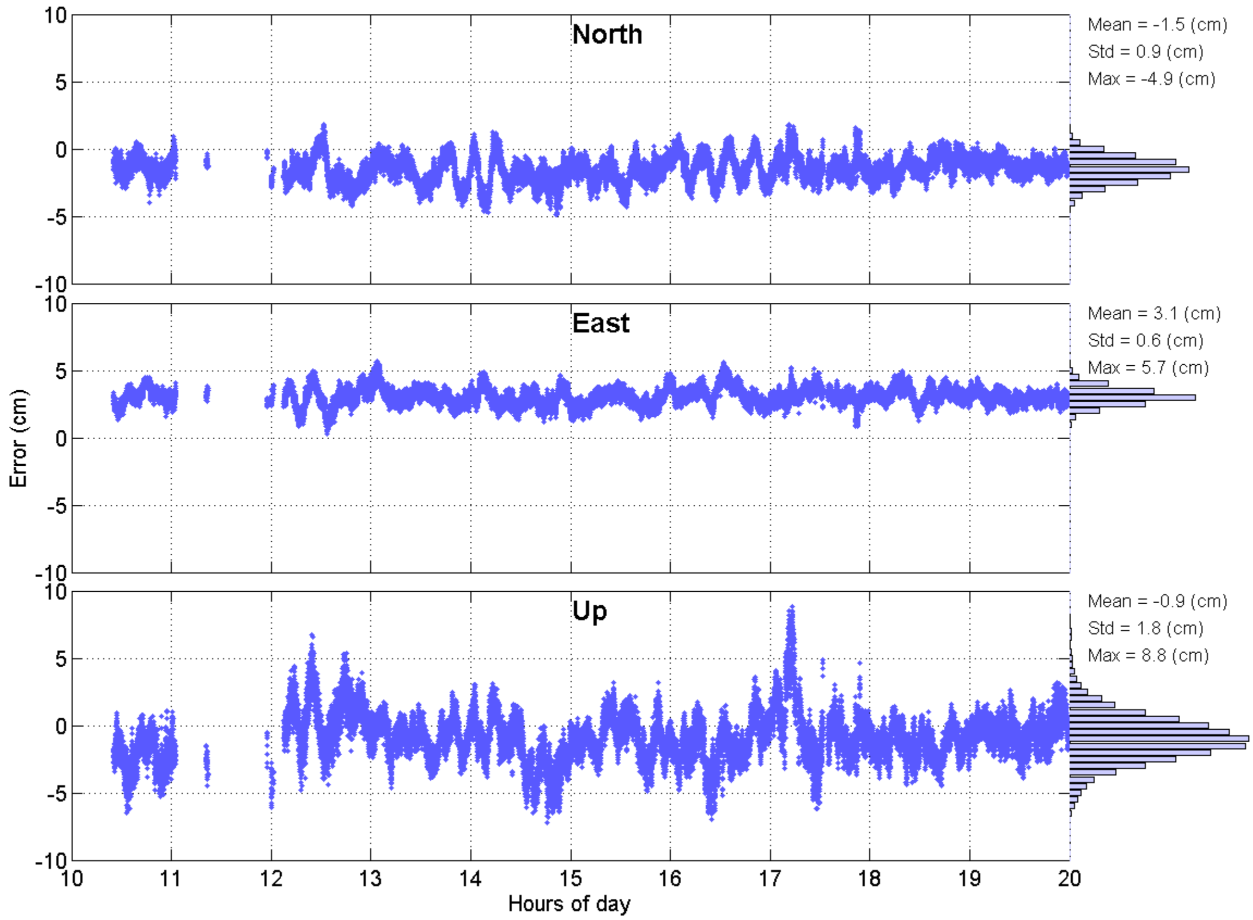

Figure 3-3. Biases in network RTK solution

Figure 3-4 demonstrates low frequency network RTK position solution behaviour. The solutions show a shorter period (~15 minute) oscillation through most of each time series, as compared to a ~20 minute period in Figure 3-3. Most of the solutions collected as part of this study are affected by this pattern; however, characteristics differ from location to location and based on the service provider. This sinusoidal affect is an excellent example why the user should be collecting more than one set of observations, offset by minutes or hours, to determine a more accurate solution using network RTK. For example, in Figure 3-4, if hours 14 to 14.5 are considered, the solution varies from -5 cm in northing to +5 cm within a 15 minute window. This means that if a user were to collect just a single position fix, or if the results were to be averaged using 5 minute windows, the solutions would differ significantly. The issue is that due to the real-time error estimation in the solution and the interpolation and filtering of network RTK, each epoch becomes part of a larger pattern that may affect the solution greatly. This should give sufficient evidence to take more than one set of observation for each survey and to also separate the observation trials by a few hours (possibly in different times of day) to avoid relying on observations that are not completely independent.

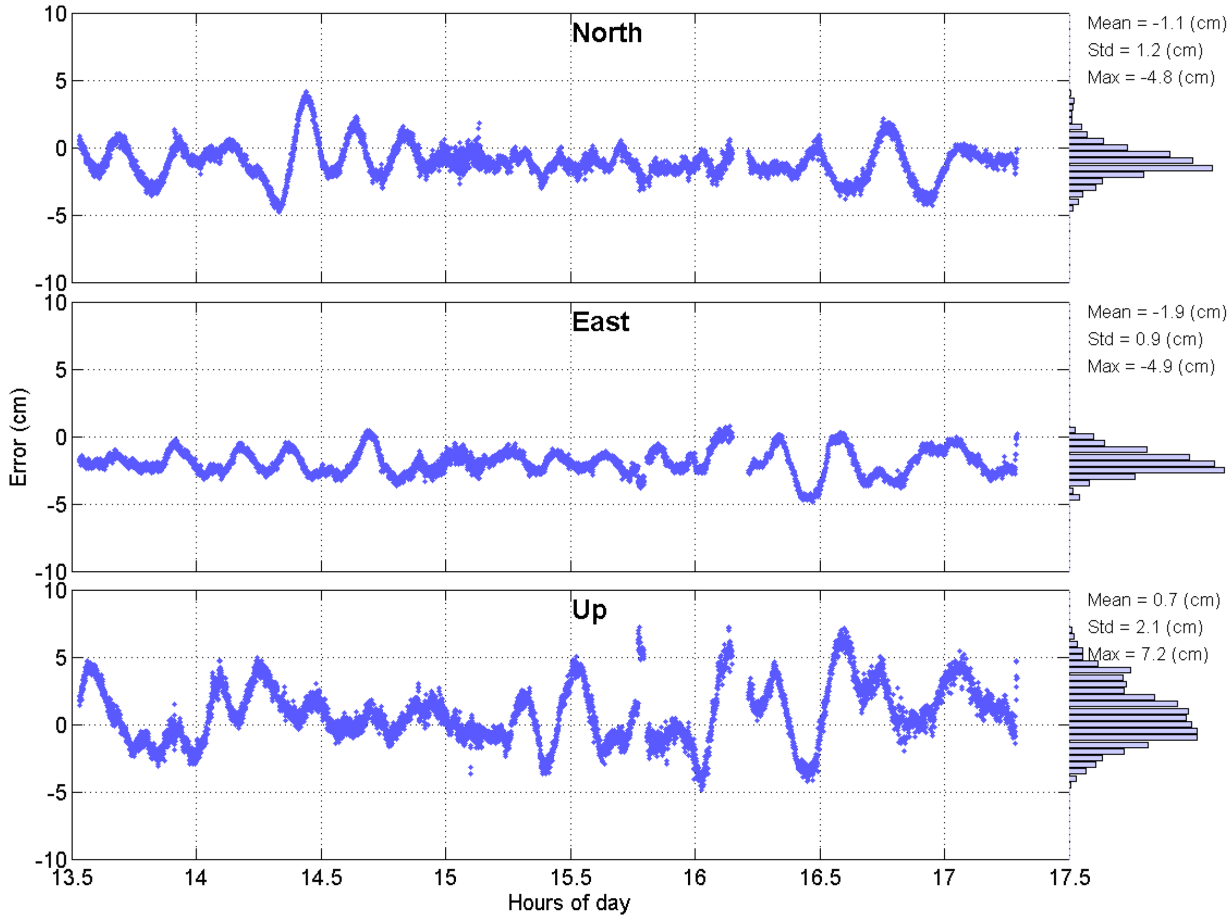

Figure 3-4. Sinusoidal behaviour in network RTK solution

3.2 Availability

Availability is one of the issues that need to be addressed when evaluating the performance of network RTK. This section of the results will display the availability percentages of each service provider at various test locations. Results are subject to a variety of issues that affect the user when using network RTK. Cellular coverage and access latency are the most prominent causes of data gaps. Another major issue is processing lag. Epoch skips and data lags may exist due to older hardware and software. Bluetooth issues are also troublesome. When using a data-collector and recording solutions at 1 Hz, Bluetooth connections tend to disconnect even at metre-level distances. However, it is important to consider that occupying a point for up to ten hours while collecting ambiguity-fixed network RTK solutions at a rate of 1 Hz is not typical for the average user. Though, this unorthodox method of testing is necessary to push the system constraints, and to observe and characterize the availability of the services.

3.2.1 Winter Campaign

The winter availability results can be seen in Figure 3-5 to Figure 3-7 for the service providers at different test locations around Ontario. Typically, for a fully operational network RTK service, an availability of 97% to 99% should be observed (Aponte et al., 2009).

Though, as Figure 3-5 illustrates, that is not the case for most locations for this particular service provider (Company 'A'). The average availability for this service provider is 86% ±11% (1σ). This is well below the expected levels for network RTK services. During the course of the field work, the equipment was checked every 30 minutes. Some of the missing data here may be due to losing Internet connection and the inability of the user equipment to automatically reconnect to the Internet, therefore requiring manual restarts. This issue presents a major short coming of network RTK equipment and service availability for long hours of data collection. So, the major limiting factor of network RTK availability is the two-way communications between the receiver and network server. Reliable network latency and cellular coverage is needed to be considered and remedied to be able to render network RTK as a 100% available service. Also, visibility affects availabilty. However, due to the locations of these test sites this was not a major issue. It can be seen from Figure 3-5 for sites in Ottawa ('ott'), Windsor ('win') and London ('lon') show an availability of almost 99%. Availability percentages of 99% suggests that this network and equipment is capable of providing this level of availability which validates the point made above that the network availability (cellular coverage, network latency and equipment problems) is, normally, the major issue.

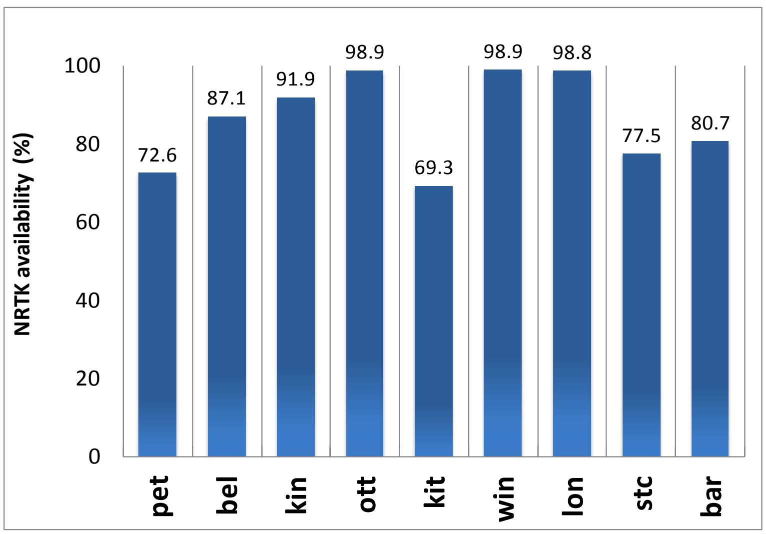

Figure 3-5. Availability percentage in winter campaign for Company 'A'

Results for Company 'B' can be seen in Figure 3-6. The average availability in the winter campaign is 42% ± 7% (1σ). This is less than half of what the availability for a robust network RTK system should be. There are no data available for test site Belleville ('bel') due to a hardware corruption issue. An unstable Bluetooth connection is the cause of some of the equipment disconnecting from the cellular modem and interrupt the Internet connection (mainly in sites 'pet' and 'kit'). Also, the lack of robustness of the network RTK software could cause lags in the estimation of the error corrections, which can lead to skipped epochs in solutions. The majority of the data gaps are due to regular skipping of records, for example every other second or every 5 seconds. In the upcoming §3.2.2 it can be seen that a slight change in hardware and software can increase the availability of the network RTK solutions. Solution availability is also affected by the user location within the network. Further details of epoch skipping due to network lag or reduced software robustness are shown in §3.2.3.

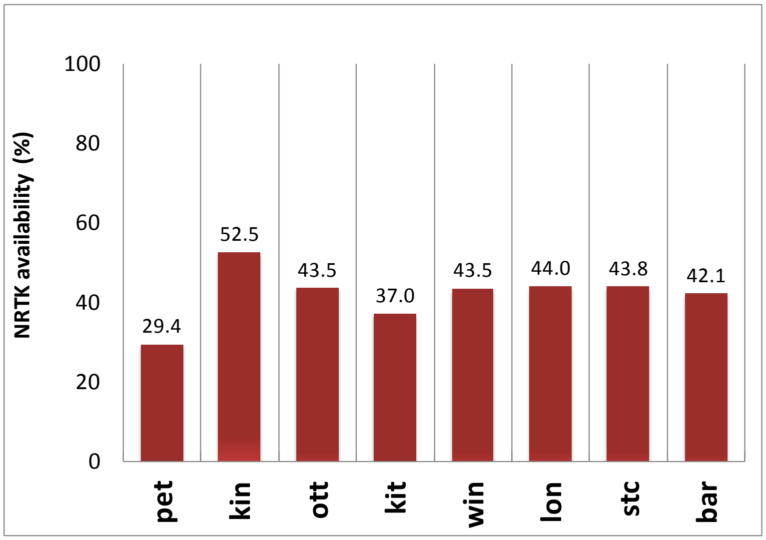

Figure 3-6. Availability percentage in winter campaign for Company 'B'

This can be seen in Figure 3-7, where availability is within acceptable levels at all sites except at Kingston ('kin'), which is located at the edge of this network. The average availability for Company 'C' is 98.5 ± 2% (1σ). This section shows that there is no uniform network RTK performance when it comes to solution availability from the service providers. Figures above show that percentages of available solution can change with location and service provider. Also, data gaps due to cellular connections and equipment malfunction over long periods of data collection (e.g., many hours) can cause lower availability. Furthermore, remote locations will be adversely by sparse wireless network coverage, as opposed to densely populated areas that tend to have significantly better coverage. The results seen above represent data availability percentage for extended periods of observation (many hours) and may not represent what the average user will encounter during their much shorter periods of observation.

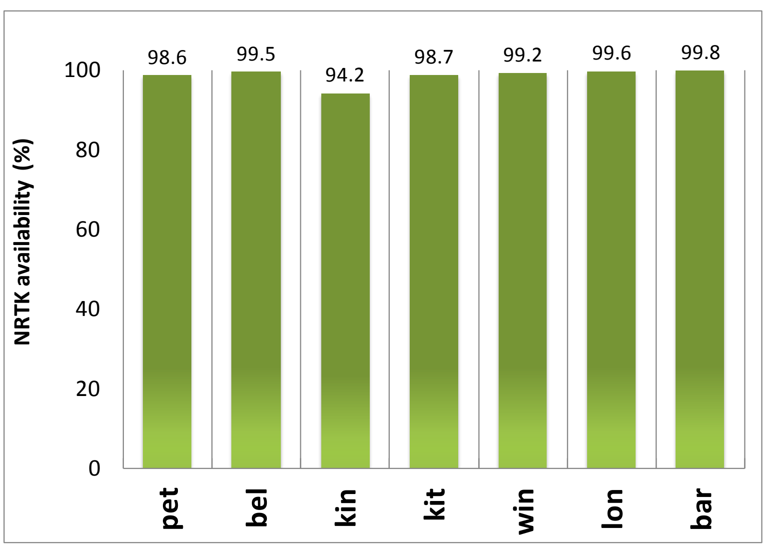

Figure 3-7. Availability percentage in winter campaign for Company 'C'

3.2.2 Summer Campaign

Figure 3-8 to Figure 3-10 show the availability percentages of solutions from the test sites revisited in the summer. Figure 3-8 shows significantly better results for Company 'A' than the winter results. The average availability in the summer is 88% ± 9% (1σ). This is closer to what the ideal case should be (>97%), but still leaves room for improvement. The improvement seen here may be due to slight changes in hardware and software.

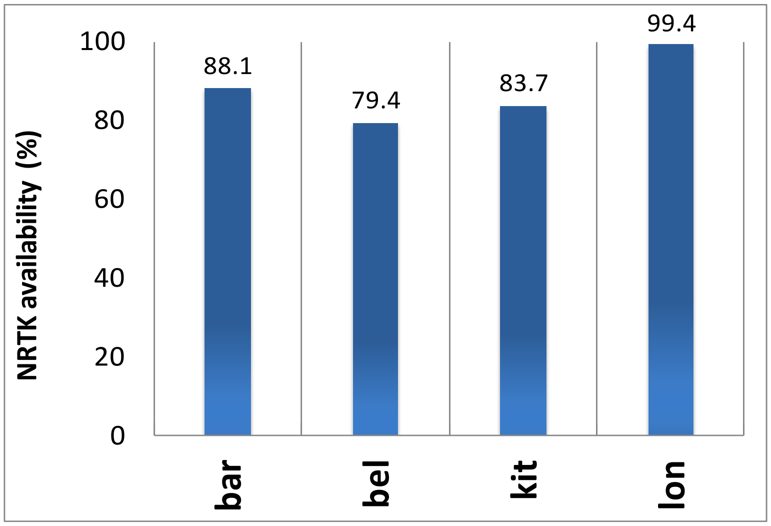

Figure 3-8. Availability percentage in summer campaign for Company 'A'

The results for Company 'B' in Figure 3-9 suggests that this particular service's availability was increased significantly to acceptable levels with a hardware upgrade. The average for the summer results is 90% ± 20% (1σ). This average would be higher and the standard deviation lower, if the Kitchener ('kit') site was ignored. The data shortage in this site was due to significant cellular issues and high connection latency.

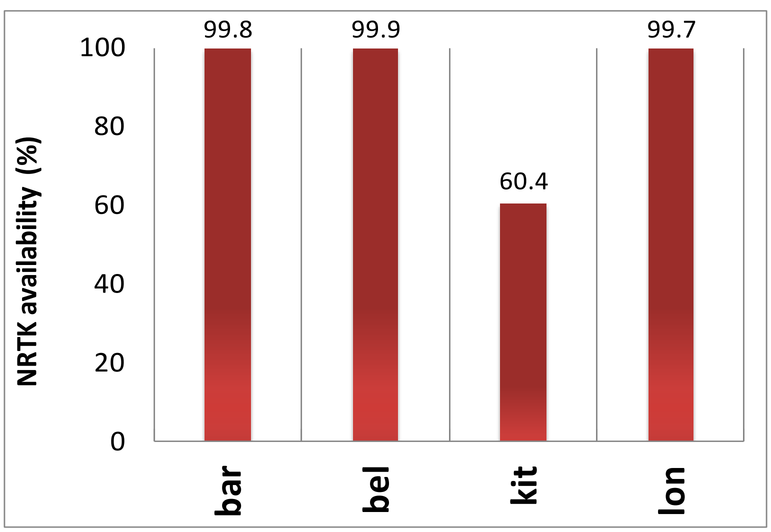

Figure 3-9. Availability percentage in summer campaign for Company 'B'

Figure 3-10 shows consistent results with the winter results for Company 'C'. The average for the service availability is 98% ± 1.4 (1σ), which is slightly above acceptable levels. However, for 'bar' Company 'C' is experiencing slightly below expected availability, which is not consistent with the winter results.

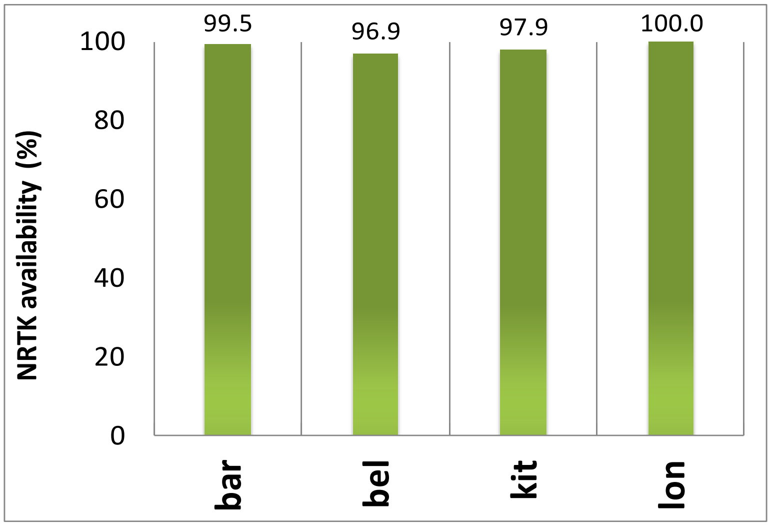

Figure 3-10. Availability percentage in summer campaign for Company 'C'

3.2.3 Data Gap Analysis

This section will show some of the data gaps that exist within the records collected. Table 3-1 shows the results for Company 'A,' indicating that the majority of data gaps are 1 second gaps. Also, a few 2, 3, 4 and 5 second data gaps were also observed. The majority of gaps larger than 5 seconds are actually a minute up to isolated cases of 10s of minutes in duration. This result, as mentioned, is most likely due to weaknesses in the robustness of the hardware and software used during the fieldwork, and could also be caused by any delay in the cellular network connection. However, these magnitudes of data gaps should not affect the user experience significantly, as the average user will not collect this amount of data for control and engineering surveys. Missing records can affect the availability of the solution significantly. For these results from almost 60 hours of data more than an hour is missing due to 1 to 5 second data gaps.

Table 3-1. Data gaps in winter campaign for Company 'A' (1 Hz data rate)

Site	1 sec skips	2 sec	3 sec	4 sec	5 sec	Epochs missing	>5 sec	Epochs available
pet	374	2	3	0	8	427	3	20521
bel	231	1	2	0	6	269	1	21858
kin	458	0	1	0	2	471	0	23509
ott	327	2	3	1	7	379	4	20735
kit	573	0	0	0	0	573	0	30886
win	654	2	0	0	4	678	0	27547
lon	510	49	18	4	20	778	5	21283
stc	403	11	7	2	6	484	4	23990
bar	415	9	12	1	16	553	3	29984
Overall	**3945(85%)**	**76 (3%)**	**46 (3%)**	**8 (1%)**	**69 (7%)**	**4612 (100%)**	**20**	**220313**

Table 3-2 shows the data gap analysis results for Company 'B,' and as the availability results suggested significant data gaps exist. The first noticeable issue is that there are more data missing from 1 to 5 second gaps than epochs available. Available epochs make up about 44% (typical availability results) of the total epochs that should be available, assuming 100% availability. Also, the majority of the data gaps are 2 second gaps (59% of missing data). With 1 to 5 second gaps, it can be expected that the availability of the data should almost double, and place well above 80%. However, other major issues such as long periods of disconnects played a significant role in the low availability.

Table 3-2. Data gaps in winter campaign for Company 'B' (1 Hz data rate)

Site	1 sec gaps	2 sec	3 sec	4 sec	5 sec	Epochs missing	>5 sec	Epochs available
pet	3205	2521	206	18	16	9017	4	7919
kin	3475	1330	1	0	4	6158	0	7104
ott	3983	3414	117	0	3	11177	2	9715
kit	4751	4734	536	0	1	15832	0	11960
win	5120	4870	623	2	4	16757	0	12897
lon	4334	4595	306	2	5	14475	0	11381
stc	4933	4564	591	0	2	15844	0	12366
bar	4215	4643	376	5	4	14669	2	11433
Overall	**34016 (32%)**	**30671 (59%)**	**2756 (8%)**	**27**	**39**	**103929 (100%)**	**8**	**84775**

Table 3-3 shows the excellent results for Company 'C'. Throughout the field campaign only five 1 second gaps were observed. Also, the majority of the gaps are 5 second gaps. Only two major interruptions occurred - both at 'bel'. The overall solution availability, as seen in the previous section and in Table 3-3, is above 98%, which puts the results in typical network RTK levels.

Results from each service provider are different, as with most results from this study. From various external studies, it can be seen that network RTK services are largely outperforming the services in Ontario in terms of availability. Only Company 'C's results seem to be demonstrating acceptable data availability for network RTK.

Table 3-3. Data gaps in winter campaign for Company 'C' (1 Hz data rate)

Site	1 sec gaps	2 sec	3 sec	4 sec	5 sec	Epochs missing	>5 sec	Epochs available
pet	1	0	0	0	11	56	0	28377
bel	3	0	0	0	11	58	2	29756
kin	0	0	0	0	32	160	0	30815
kit	0	0	0	0	6	30	0	28897
win	0	0	0	0	7	35	0	26627
lon	0	0	0	0	4	20	0	28421
bar	1	0	0	1	11	60	0	32742
Overall	**5 (1%)**	**0**	**0**	**1**	**82 (98%)**	**419 (100%)**	**2**	**205635**

3.3 Time-To-First-Fix

Figure 3-11 to Figure 3-13 show the average time-to-first-fix (TTFF) for each test site and their standard deviations recorded during the winter campaign. TTFF is heavily affected by the quality of the cellular coverage at any location. Figure 3-11 shows the average values and standard deviations of Company 'A' TTFF results. The majority of the results are under 25 seconds, with the one major exception of site 'kin'. Figure 3-12 shows the average and standard deviations of TTFF for Company 'B'. Between Figure 3-11 and Figure 3-12 it can be seen that the results in various locations are very different. For example at 'kin' Company 'B' has fast and consistent TTFF results, as opposed to the very large and inconsistent results from Company 'A', while the reverse effect can be seen for the Peterborough ('pet') test site. This may be due to the fact that companies are using different wireless carriers.

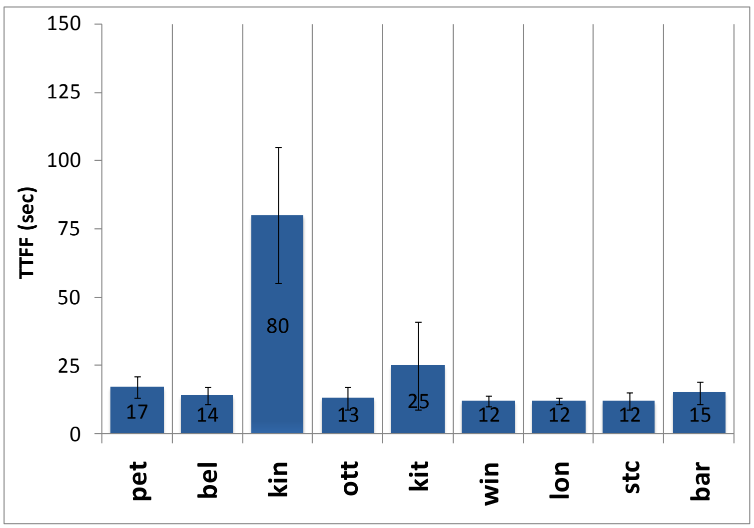

Figure 3-11. TTFF in winter campaign for Company 'A'

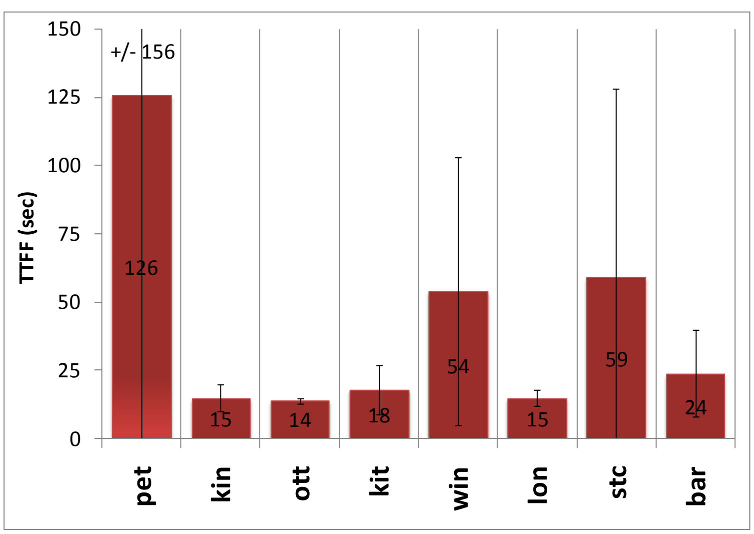

Figure 3-12. TTFF in winter campaign for Company 'B'

Company ‘C’, as it can be seen from Figure 3-13, illustrates similar results to Company ‘A’, which includes poor TTFF results at ‘kin’. Interestingly, the mean and standard deviation of TTFF for ‘kin’ is almost identical to the results shown in Figure 3-11. Generally, for most locations around Ontario approximately 15 to 30 seconds can normally be expected for the equipment to produce a network RTK position fix from a cold start. At some locations, for some service providers, there are occasions when the value can be as large as one to two minutes.

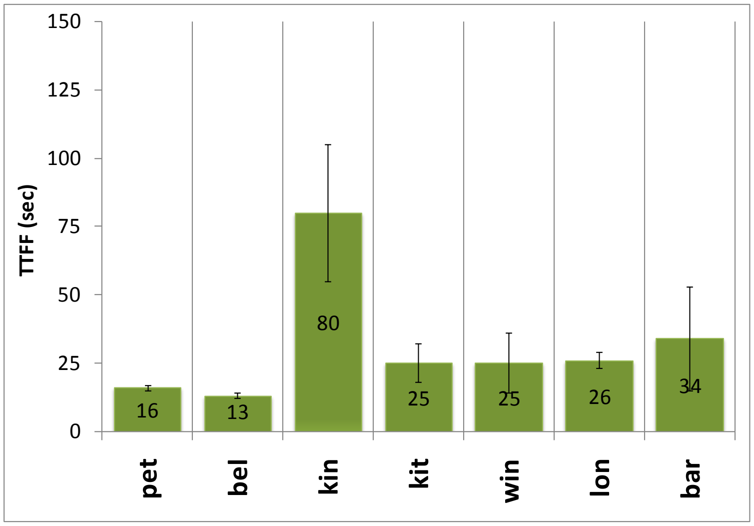

Figure 3-13. TTFF in winter campaign for Company ‘C’

3.4 Precision

The precision of the network RTK data gives the user an indication of the repeatability of the network RTK solutions over the short-term, where short-term is defined in terms of hours. In the next few sections, figures illustrating precision for both winter and summer campaigns are presented. The precision calculated here is the standard deviation (about the mean) of each time series, for each test site, from each service provider, computed initially in northing and easting components. The values have been appropriately scaled to illustrate the 2σ (95%) confidence level. In order to transform the 1σ (68%) horizontal precision into the 95% horizontal precision a scale factor of 2.45 for two-dimensional data is used (GSD, 1996; Harre, 2001).

3.4.1 Winter Campaign

Figure 3-14 to Figure 3-16 show all of the site precisions for the three service providers. The precisions are calculated with approximately eight hours of network RTK data for each service provider in the horizontal component. Figure 3-14 shows the horizontal network RTK precision (95%) for Company ‘A’ at each test site. As can be seen the results vary between 1.4 to 3.7 cm with a mean precision of 2.3 ± .8 cm over all test sites. There are some common trends that are shown in Figure 3-14 and Figure 3-15. For example, both results suggest that sites ‘pet’ and ‘kin’ are worse than ‘ott’, ‘kit’ and ‘lon’. This may be due to network geometry similarities between both service providers. However, at the site ‘bar’, a difference can be observed. The precision for Company ‘B’ at this site is almost half of that obtained with Company ‘A’: 4.3 cm versus 2.3 cm. The possible cause for this difference is the proximity of the closest reference station for Company ‘B’ compared to Company ‘A’.

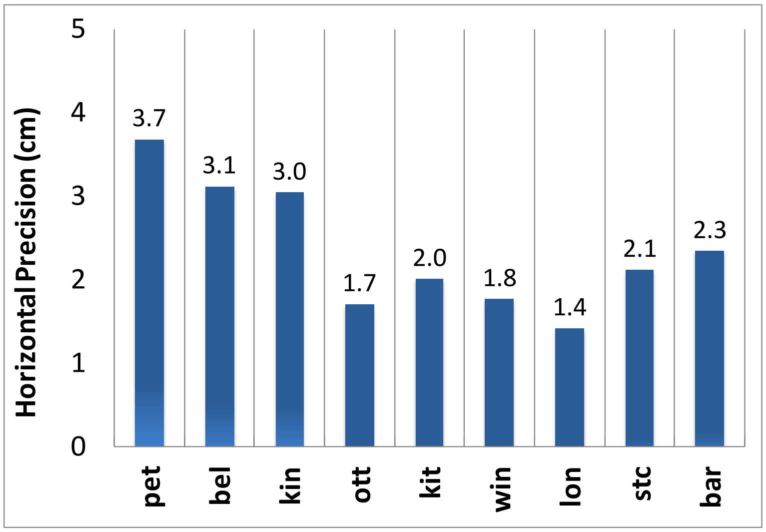

Figure 3-14. Horizontal precision (95%) in winter campaign for Company ‘A’

Figure 3-15 shows the horizontal network RTK precision (95%) for Company ‘B’. The overall precision from all test sites is 3.0 ± 1.1 cm, which slightly shows worse results than the other service providers. Interestingly, ‘lon’ sites shows consistent high levels of precision for all service providers and some of the best results for Company ‘B’. This may be due to the surrounding environment at this site, with great visibility and no significant source of multipath nearby. Also, consistent with the precision of Company ‘A’ and Company ‘C’ at test site ‘pet’ similar level of precision is demonstrated.

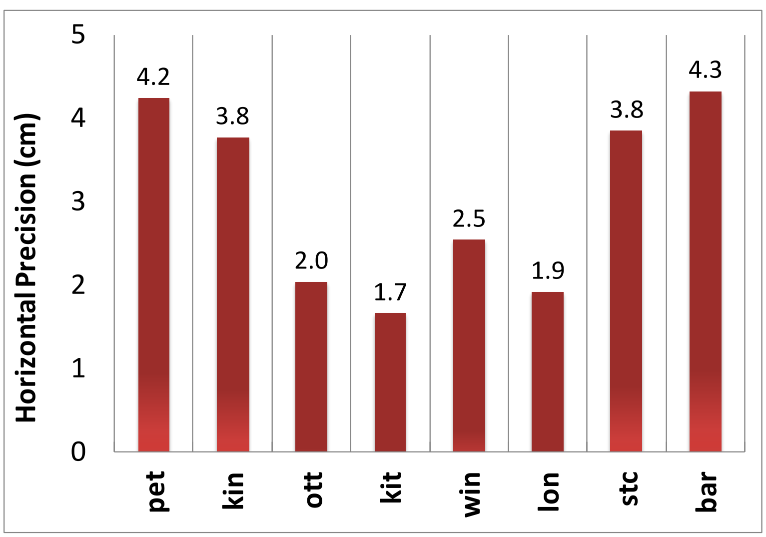

Figure 3-15. Horizontal precision (95%) in winter campaign for Company ‘B’

Figure 3-16 shows the horizontal network RTK precision (95%) at the test sites with overall precision of 2.4 ± 0.9 cm. Missing sites, as mentioned before, are due to solution unavailability resulting from service provider network maintenance. The precision for Company ‘C’ is at similar levels as the other service providers. However, ‘kin’ is seen here as having a lower precision than the rest of the results for Company ‘C’. This result is in fact the case for all networks at that particular location, which was at the edge of each company’s coverage during the time of the surveys.

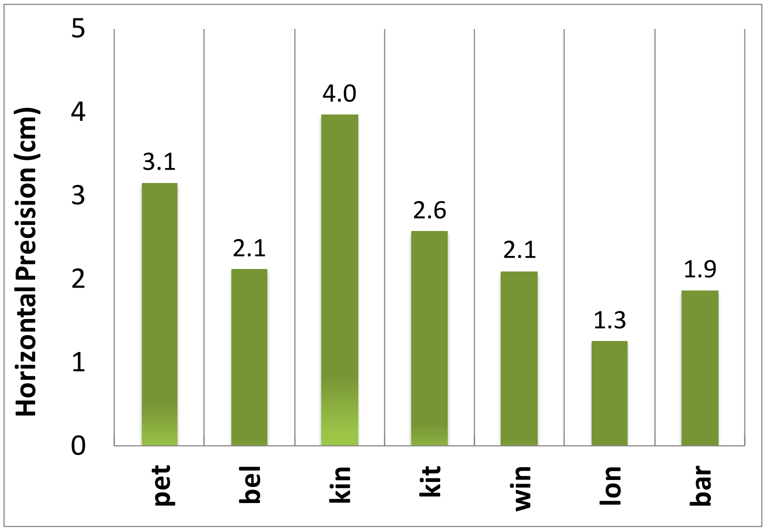

Figure 3-16. Horizontal precision (95%) in winter campaign for Company ‘C’

As can be seen, all three service providers offer very similar precision levels (on average 2 – 3 cm) in almost all locations around southern Ontario. This suggests that in terms of network RTK methods and network architecture there is no significant difference between various methods of network RTK put forward by the service providers. Also, the results indicate horizontal precision (95%) below 5 cm in all locations, which will be discussed with respect to the MTO specifications later in this report.

3.4.2 Repeatability –Winter vs. Summer

Figure 3-17 to Figure 3-19 display the precision of network RTK solutions for the revisited sites in the summer campaign and showing a comparison with the winter precision values. Figure 3-17 shows significantly worse results in the summer than the winter. This is possibly due to the collection of smaller number of data points in the summer campaign compared to the winter campaign (25% less data was collected in the summer), which could cause the standard deviation of the solutions to be larger. However, company ‘B’ in Figure 3-18, shows an improvement over the winter precision for the site ‘bar’ while every other result from company ‘B’ results tend to follow this pattern.

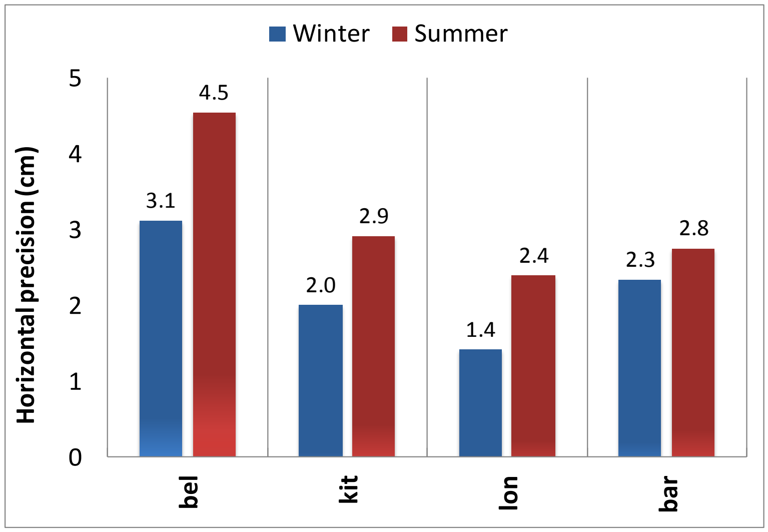

Figure 3-17. Comparison of winter and summer campaign precision for Company 'A'

The lack of availability from the winter for data from 'bel' has caused a gap in Figure 3-18 and no comparison between the summer and winter can be done at this location. Test site 'bar' does not exhibit the pattern of worsening precision from winter to summer. However, for 'kit' and 'lon' this behaviour is consistent with the results from Company 'A'.

Figure 3-19 displays the comparisons for Company 'C'. These results also consist of significantly higher values for 95% horizontal precision in the summer. These results also contradict the availability discussed previously. With availability, the overall quality of the results is improving from winter to summer with slight hardware and software upgrades.

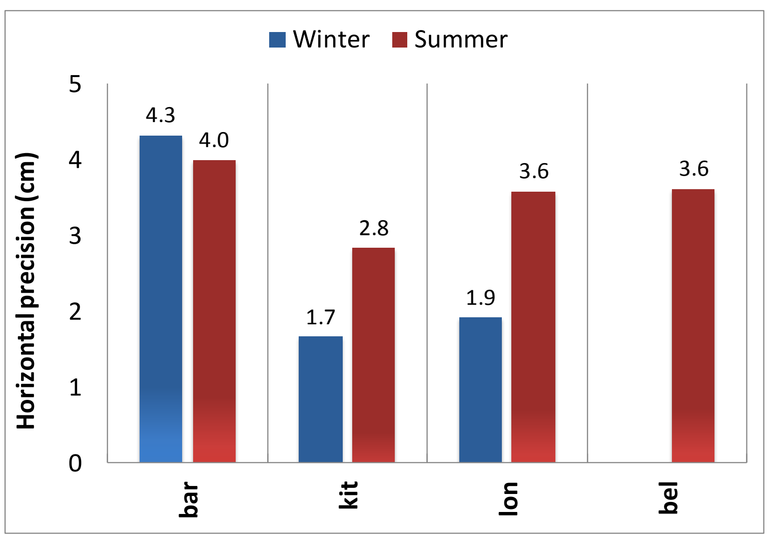

Figure 3-18. Comparison of winter and summer campaign precision for Company 'B'

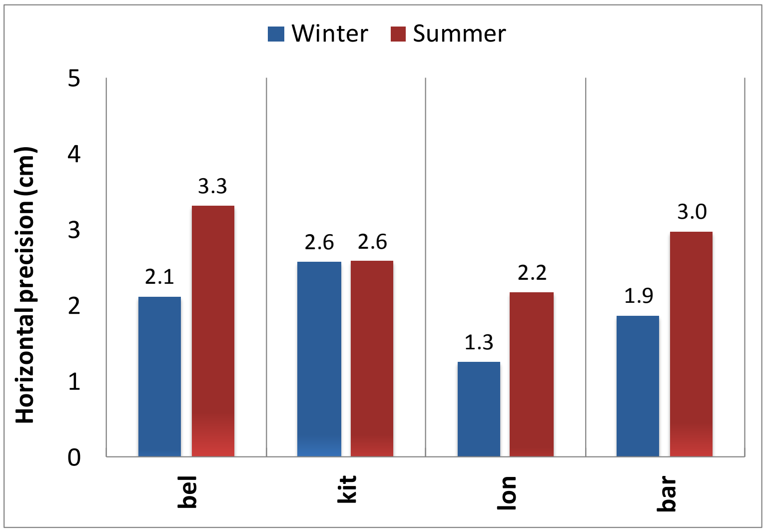

Figure 3-19. Comparison of winter and summer campaign precision for Company 'C'

3.4.3 Overall Precision

In order to get a clearer view of how precise the solutions of network RTK in Ontario can be, a plot of records of ambiguity fixed network RTK solutions collected from all companies in the winter campaign are shown in Figure 3-20. Looking at Figure 3-20, with over 510,000 fixed network RTK solutions, a horizontal precision of 2.6 cm is obtained. Note that this level of precision may not be achievable unless a significant amount of data is collected.

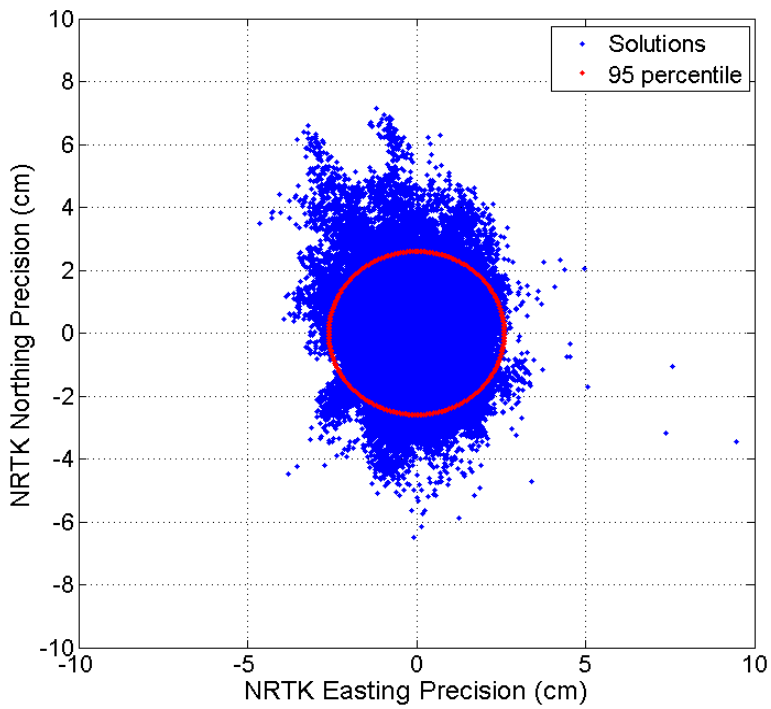

Figure 3-20. Overall precision of all data points collected in winter campaign

To confirm the level of precision that can be seen in Figure 3-20, the summer overall precision results are also plotted. Figure 3-21 shows a plot of over 250,000 fixed network RTK solutions collected over the summer campaign. In comparison with the winter, the horizontal 95% is actually 2.3 cm, which is smaller than the previous site-by-site comparison showing the summer precision value to be significantly larger than the winter in almost all locations revisited. This discrepancy in the results is mainly due to scaling of the precision of the summer results using a scaling factor of 2.45 standard deviations to achieve 95% confidence level as opposed to using the actual 95th percentile using a much larger sample pool for the overall precision. This also reveals that the 2.45 scaling factor provides a more pessimistic confidence interval (~98%) in comparison to the actual results.

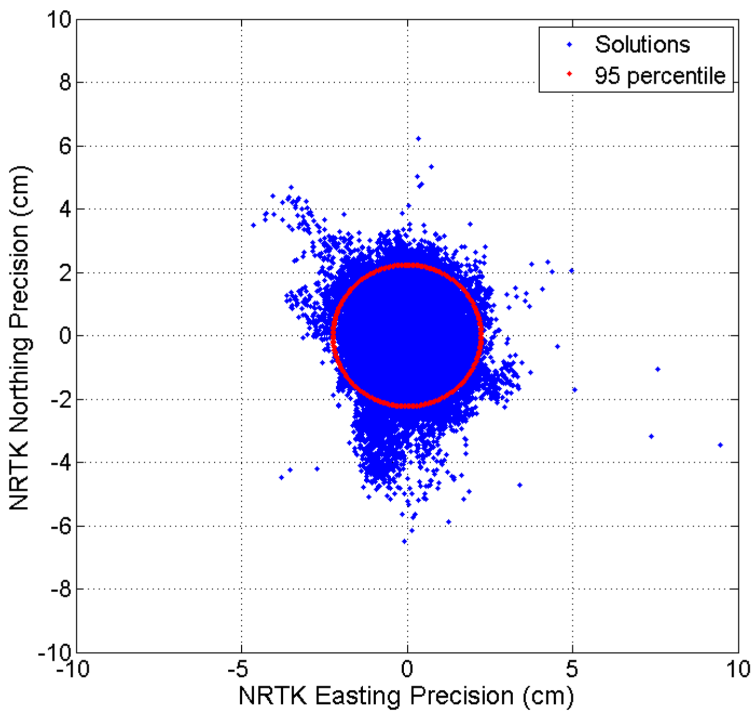

Figure 3-21. Overall precision of all data points collected in summer campaign

3.5 Accuracy

In this section, the observed mean error and rms[3] of the network RTK solutions will be detailed. The reference coordinates used and their determination are described in §2.5. Mean errors that are repeatable in network RTK are mainly caused by the quality of integration of the networks with the official datum, which in Ontario is NAD83 CSRS. Network RTK performance should be very consistent in the horizontal and indeed it is the height performance that contains the most variability (Rubinov et al., 2011). In this section, the

[3]Root mean square (rms) is a statistical measure of the quality of the solution, defining accuracy comprised of variance and bias.

horizontal quality of network RTK will be investigated to check its consistency and accuracy performance in southern Ontario.

3.5.1 Winter Campaign

Typical network RTK accuracies should range from 1 - 3 cm horizontally (Edwards et al., 2008; Rubinov et al. 2011). Though, with various other effects taken into consideration such as distance from the closest reference station, multipath environment and user's location within the network, this accuracy range can be larger. However, as the average user may not take all of these effects into consideration, when using network RTK, they may be irrelevant. Furthermore, private network operators continuously advertise complete coverage within their network, which suggests that network RTK's typical accuracy can be expected anywhere within their networks and since the main objectives of this study is to evaluate the horizontal accuracy of network RTK services as a whole, the details of the abovementioned effects will not be discussed in detail. Instead focus will be placed on significant accuracy issues and network distortions within each service provider's network. Figure 3-22 to Figure 3-26 display the mean error of the solutions for each service provider.

Figure 3-22 shows the mean errors at each test location, determined from the Company 'A' network RTK position time series compared against each site's reference coordinates. In terms of the components of the mean error, it is clear that the northing and easting both show systematic behaviour. In most cases, typical network RTK accuracy can be seen with the exceptions of 'bel', where the horizontal accuracy exceeds 3 cm in the horizontal. The systematic behaviour in the direction of the biases may be due to distortions in the integration of the network in the official datum. Also, long-term repeatability comparisons are made later in this section to show that the biases seen in the results are not products of short-term systematic behaviour, and are, in fact, due to distortions in the networks.

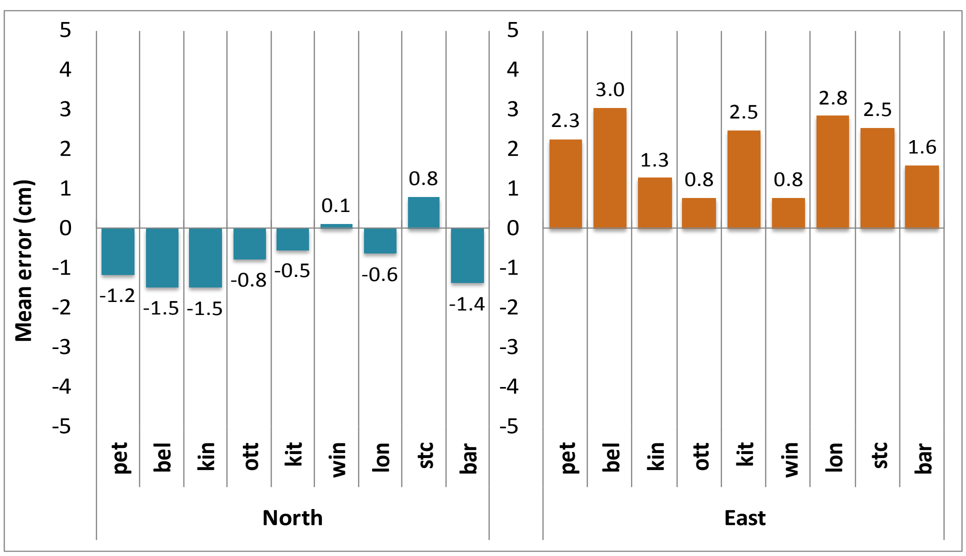

Figure 3-22. Mean error in winter campaign for Company 'A'

In Figure 3-23 the biases and their directions are shown for the Company 'A' results. For the most part, the biases are directed towards the southeast and the majority of the biases have magnitudes of 1 - 2.5 cm. This illustrates that Company 'A' network has a linear distortion of up to 3 cm horizontally. With closer alignment with a higher order network (e.g., CSRS network) these biases could be reduced.

Figure 3-24 shows the results of the mean error for Company 'B' at the test sites. As mentioned previously, the data for the winter visit to 'bel' are not available due to hardware corruption. The level of accuracy seen from these results is slightly worse than shown Figure 3-22. However, the horizontal accuracy is still within expected levels of typical network RTK accuracy, though closer to the upper boundary. Sites 'ott' and 'bar' with almost 4 cm biases in the horizontal are outside the expectations of network RTK-defined accuracies. Similar to the previous results, there is systematic behaviour that seems to suggest network misalignment with respect to the Ontario datum. This fact is displayed further in Figure 3-25.

Figure 3-23. Horizontal biases in winter campaign for Company 'A'

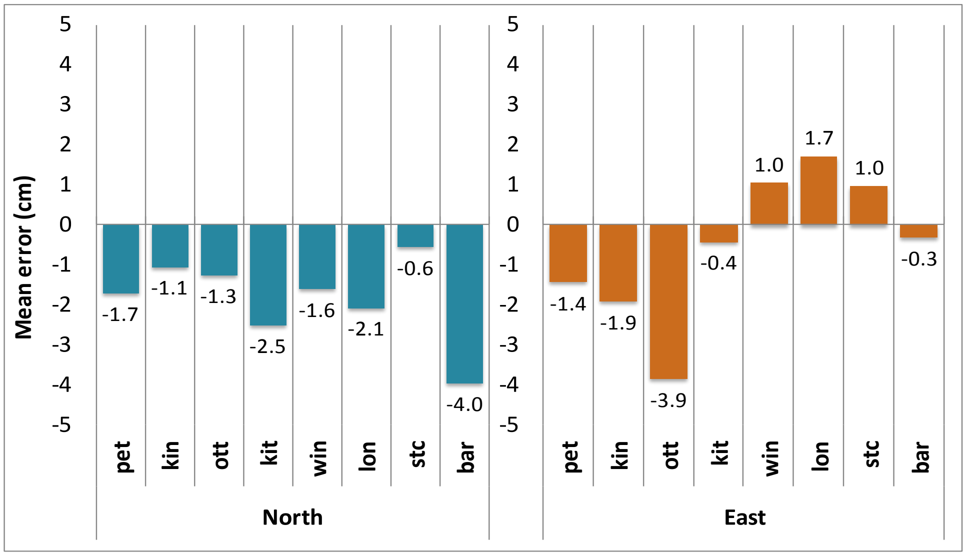

Figure 3-24. Mean error in winter campaign for Company 'B'

The interesting phenomena that can be seen in Figure 3-25 is the network distortion in a completely different pattern than Company 'A'. These distortions describe a more rotational pattern about a pivot point near the city of Toronto. This Figure shows how well this network is "tied" into the Ontario's official NAD83 CSRS datum.

Figure 3-25. Horizontal biases in winter campaign for Company 'B'

Figure 3-26 shows the mean biases existent in the solutions of Company 'C' at the test sites. As mentioned before, 'ott' and 'stc' are not available for this particular service provider due to issues with service availability. The biases shown in Figure 3-26 are all within typical network RTK accuracy. Test site 'win' shows the largest bias with a magnitude of 1.7 cm (horizontally). Figure 3-27 illustrates that there is no significant network alignment within the Company 'C' solutions as compared to the reference coordinates. For the most part, the biases tend to behave randomly and almost all are at or below 1 cm in the horizontal. Indeed, the biases are too small and random to conclude any significant network misalignments. Although the missing data lacks the ability to show the network's behaviour around areas close to Ottawa and St. Catharines. Also, the lack of significant misalignment can be verified in the upcoming §3.5.2, where the comparison of winter and summer results shows very small but repeatable biases (for the most part) in the solutions.

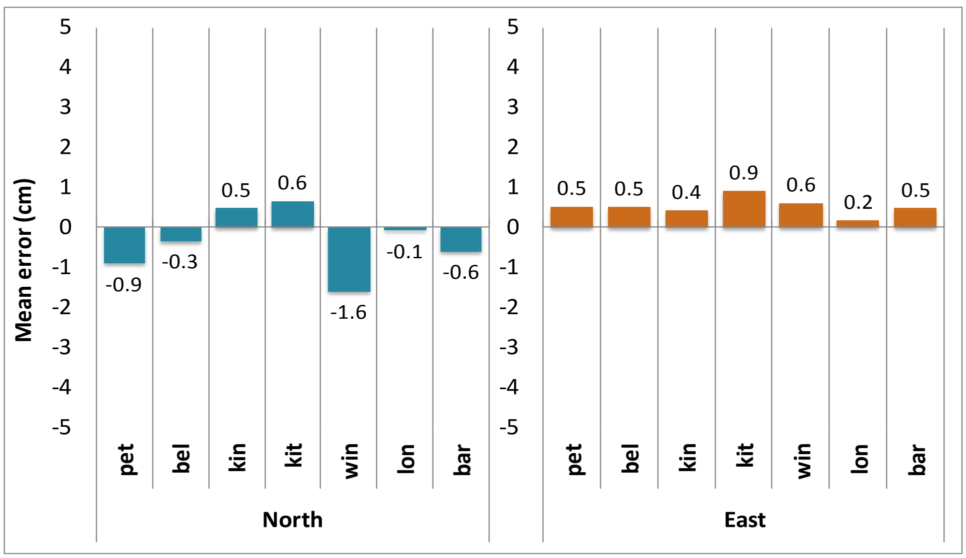

Figure 3-26. Mean error in winter campaign for Company 'C'

Figure 3-27. Horizontal biases in winter campaign for company 'C'

The rms can also be looked at show the level of accuracy of the networks under examination. The combination of short-term precision and solution bias display a better picture of the performance of each network. Figure 3-28 shows the rms at the test sites for Company 'A'. These results are typically affected by the mean biases present in each solution at each location. Test site 'bel' has not only the largest bias, but also the largest rms value, and 'win', with the smallest bias, has the smallest rms. This is mainly due to the similar levels of precision within the same network.

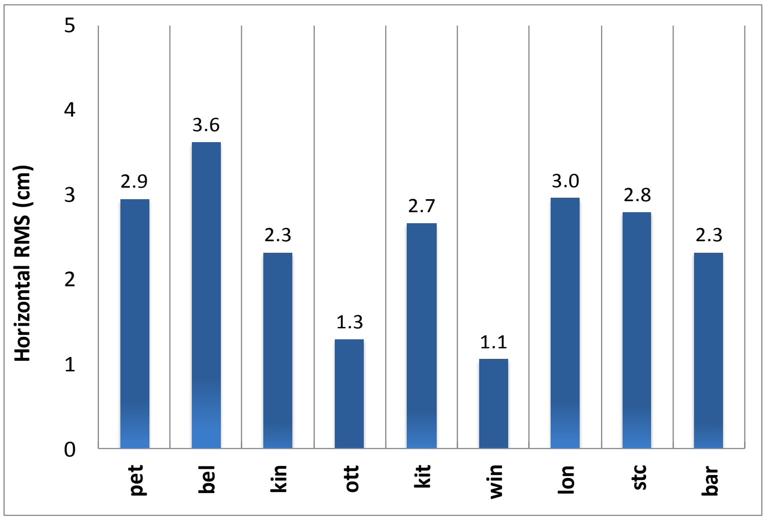

Figure 3-28. Horizontal rms in winter campaign for Company 'A'

Figure 3-29 shows the rms at the test sites for Company 'B'. The rms is larger than the one shown in Figure 3-28. Also, similar to the effect of biases on Company 'A' results, 'ott' and 'bar' with the largest mean biases are causing the largest rms values.

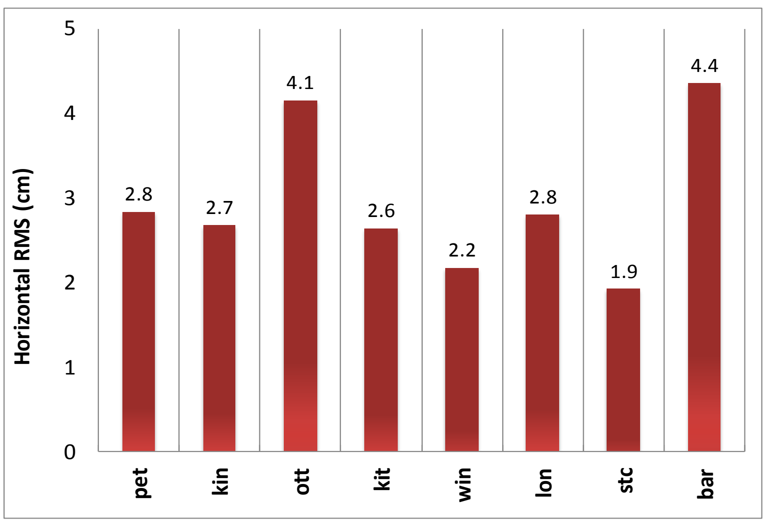

Figure 3-29. Horizontal rms in winter campaign for Company 'B'

Figure 3-30 shows the rms at the test sites for Company 'C'. Test site 'lon' has the lowest rms of all the results shown at ~0.5 cm. Though, the results are still showing a large rms at 'win' due to larger mean errors in the solutions with respect to other test locations.

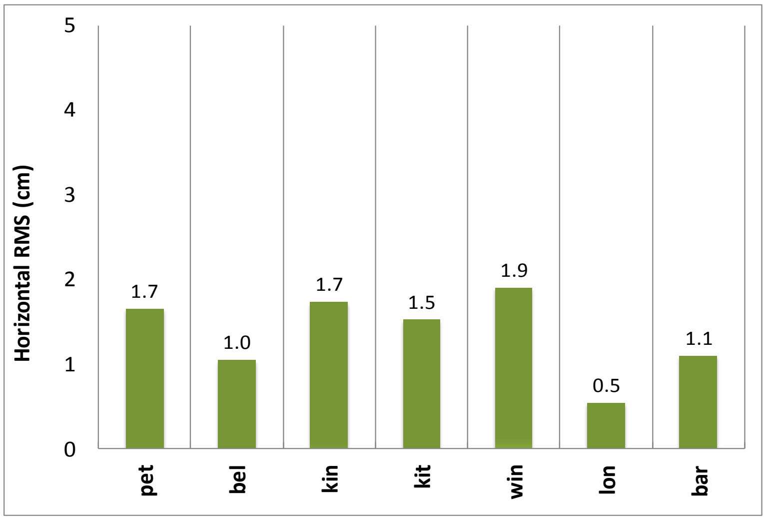

Figure 3-30. Horizontal rms in winter campaign for Company 'C'

3.5.2 Repeatability – Winter vs. Summer

In this section the results of the summer campaign will be compared to the winter. The main goal is to examine and separate any long-term systematic behaviour in the networks from the short-term errors that can affect the solutions. Also, the long-term repeatability of the solutions needs to be evaluated in order to be able to deem the network RTK services as "repeatable" methods of measurement. This evaluation involves looking at the accuracy of the solutions collected over 6 months to a year apart. In this case the winter and summer results are being compared.

Figure 3-31 compares the mean errors from the winter campaign with respect to the summer for Company 'A'. The biases, though in some cases large, display a repeatable pattern. The magnitude of the biases over time may change from a few millimetres up to a centimetre. An anomaly can immediately be seen in the northing of 'bel' with a difference of ~2 cm.

The systematic tendencies of these biases reinforce the assumptions made earlier in this section; accuracy of solutions of each service provider is mainly influenced by network reference station misalignment, and essentially the degree of integration of each network into the local high-accuracy datum. From the results seen in this section, the degree of influence by immediate sources of error (geometry, visibility, multipath, etc.) can be categorized as random errors affecting the short-term quality of the solutions. And the larger sources of error, such as network distortions, can be categorized as systematic errors that affect the long-term repeatability of the solutions.Figure 3-32 compares the mean errors from the winter campaign with respect to the summer for Company 'B'. Site 'bel' has no winter equivalent results from the winter to be compared with. The behaviour displayed is even more systematic than shown in Figure 3-31.

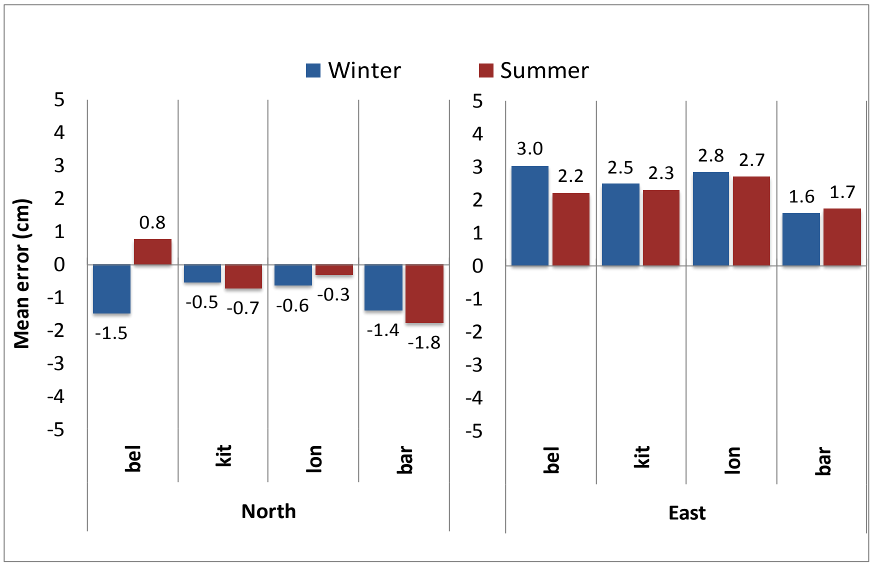

Figure 3-31. Long-term repeatability for Company 'A'

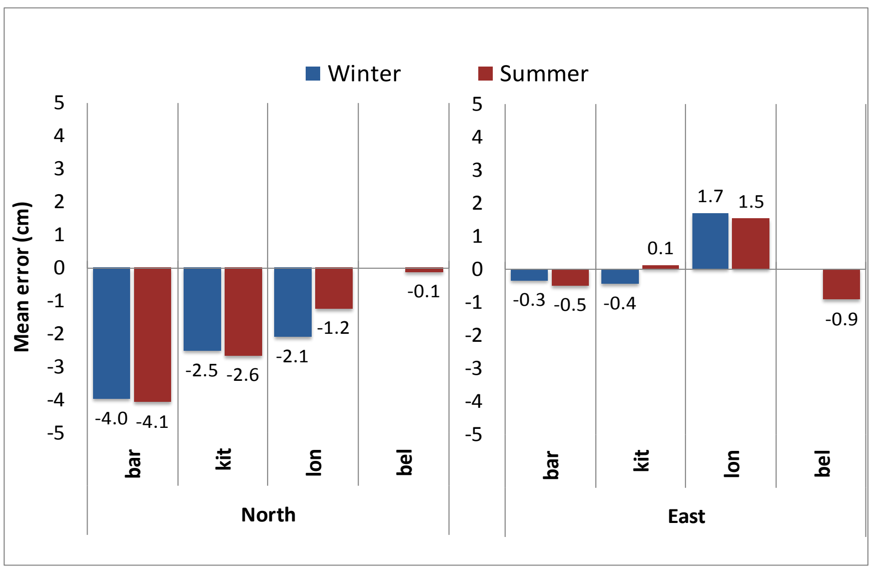

Figure 3-32. Long-term repeatability for Company 'B'

Figure 3-33 compares the mean errors from the winter campaign with respect to the summer for Company 'C'. It is interesting that even with sub-centimetre-sized biases, over large sets of data, the biases tend to repeat themselves between seven-month campaigns. Site 'bar' displays this phenomenon to the millimetre. This means that network RTK has developed to the state that, for large data sets, it can potentially remove most other sources of error from the solutions, leaving only the need for proper coordination of the network reference stations. Of course, this averaging would not have a major effect on smaller and shorter data sets as the GPS measurement noise and errors in the network RTK corrections would dominate solution accuracy.

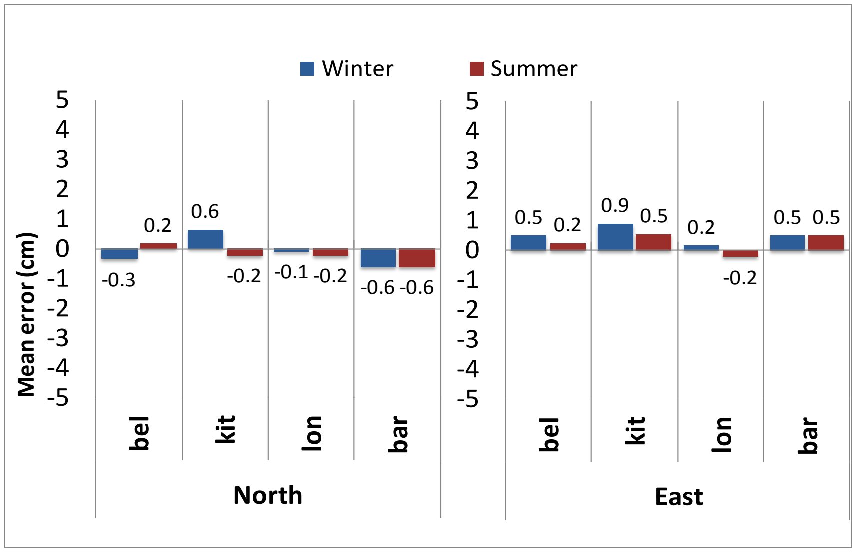

Figure 3-33. Long-term repeatability for Company 'C'

3.6 Solution Integrity

The solution integrity analysis consists of comparing actual errors in the network RTK solution with the coordinate quality values that are provided to the user by the service providers' equipment. These coordinate quality values (or CQ) vary from one service provider to another. The plot seen in Figure 3-34 shows the actual network RTK determined horizontal error (blue) in comparison with the 1σ, 2σ and 3σ values (red, yellow and green, respectively) determined from the quality covariances for a period of two hours for Company 'C' at site 'lon' in the winter. The network RTK horizontal solution error is predominantly within the boundaries of the standard deviation values. This is an example plot of the solution integrity: internal solution estimated error versus calculated actual error. More such plots for various service providers at each test location can be found in the report appendices. CQ values tend to follow the shape of the actual solution errors; they are usually within the 1σ level. However, the expanded portion of the plot shows the solution error being almost entirely outside the 1σ and for a small period time close to the 2σ boundaries.

The results from Figure 3-34 in comparison to the actual errors are actually overestimated for the most part. The 1σ values actually contain ~85% of the actual data points, which contains ~17% more results than the 68% of the normal distribution. In this section of the report, the focus will be on showing correlation plots that can compare the distribution of estimated error by the equipment with respect to the actual errors in the solution. The results shown here for each company represent typical levels of quality and are not 'worst' or 'best' case scenarios.

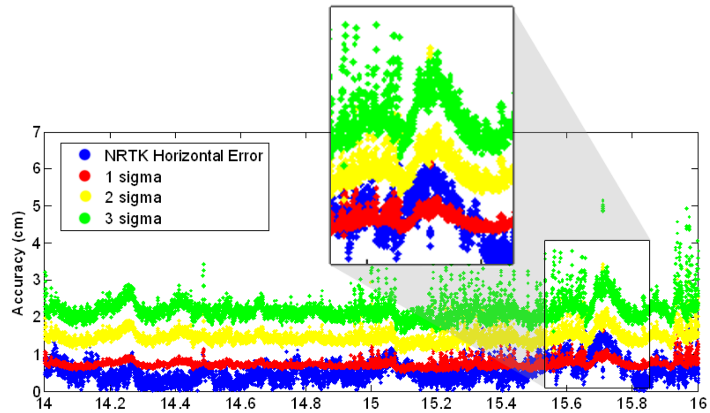

Figure 3-34. Company 'C' network RTK errors versus 1, 2 and 3 sigma for 'lon'

Each epoch of data is accompanied by its corresponding horizontal estimated rms provided by the equipment. The values are plotted against each other for Company 'C' for site 'kit' in Figure 3-35. The horizontal rms values for these plots have been scaled appropriately to the 95% confidence interval. The green line represents one-to-one correlation. Any data point on the left side will be deemed to be and overestimation of the error and the right side would represent underestimation of the actual error in the solutions. Approximately 94% of the equipment-provided uncertainty values are larger than the actual errors. Figure 3-35, as the statistics indicate, shows that for the most part this solution set has overestimated rms values, since the large bulk of the data points are on or to the left of the highly correlated line. Correlation plots from other service providers can be viewed to demonstrate of typical behaviour in terms of solution integrity for each network.

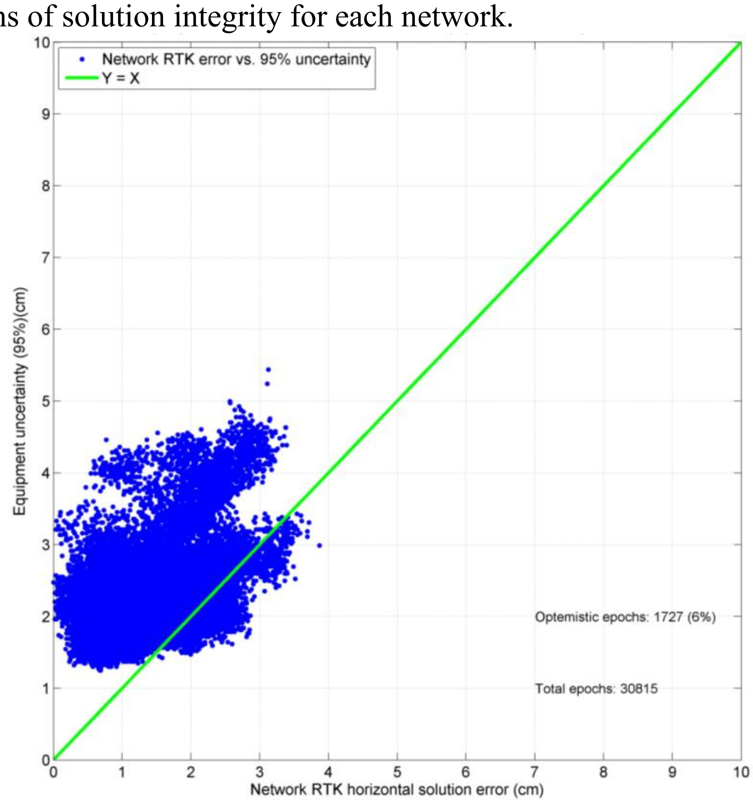

Figure 3-35. Solution integrity for Company 'C' at 'kit'

Figure 3-36 shows the correlation plot for Company 'B' at site 'win'. Approximately 8% of the equipment-provided uncertainty values are larger than the actual errors. This result is very similar to that in the previous Figure. However, due to lack of solution availability, the number of epochs presented is less than half. Discreet lines can be seen due to millimetre rounding in output by the equipment. Also, vertical lines appear above the 2 - 4 cm horizontal error that is typical for Company 'B' results. The vertical shape shown is in every solution integrity result for Company 'B' and is usually focused around a specific interval of absolute error. It is not clear why this pattern in the estimated error exists however it may be very well due to issues in the error estimation process. The majority of the epochs recorded do not show a significant amount of error underestimation, which is to be expected.

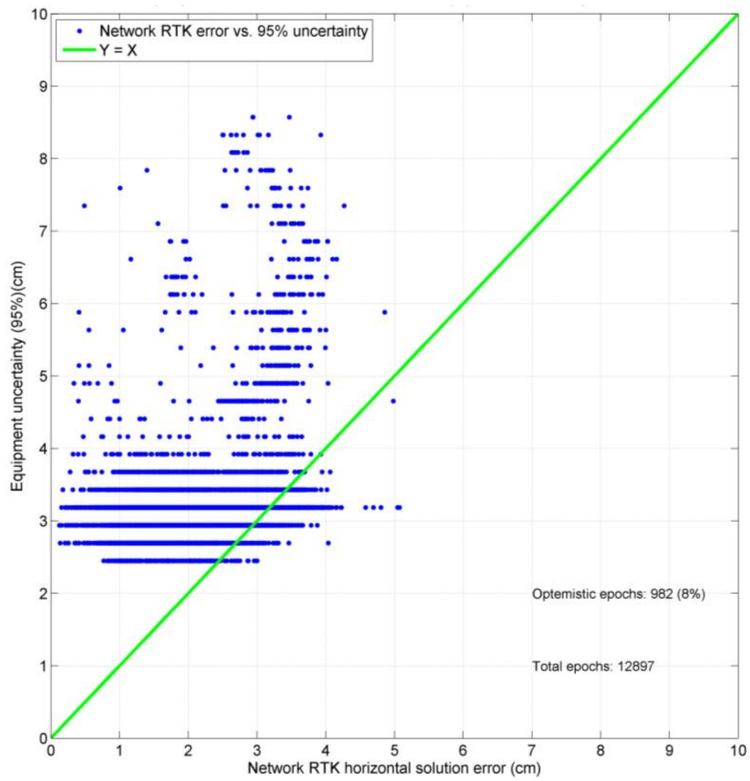

Figure 3-36. Solution integrity for Company 'B' at 'win'

Figure 3-37 shows correlation plot for Company 'A' at site 'kin'. Typically, a significant percentage (>7%) of the equipment estimated errors are underestimations. In isolated cases, close to all of the epochs collected are to the right of estimated error at 99% confidence. Also, the same discreet lines can be seen that are due to millimetre rounding of the QC output.

From the results presented in this section, it can be concluded that like most other analyses there is no unified pattern shown in the behaviour of various providers in Ontario. Each service provider's estimated error shows individual characteristics which indicates that a standard process for error estimation and reporting is not used. Without following a standard procedure for error estimation it is very difficult to rely on the provided rms values as the only source of quality control of the solutions. Also, proper scaling of the estimated errors (at

95% uncertainty) need to be performed and reported to the user to avoid any confusion in terms of confidence levels of the solutions provided. The errors computed will take into consideration the estimated parameters when calculating the position of the user; however, these estimated values do not consider sources of errors, which in certain conditions may dominate the measurement noise. Hence, the user needs to be very careful when using the equipment coordinate quality indications, as under certain conditions these values will be extremely optimistic and unrealistic.

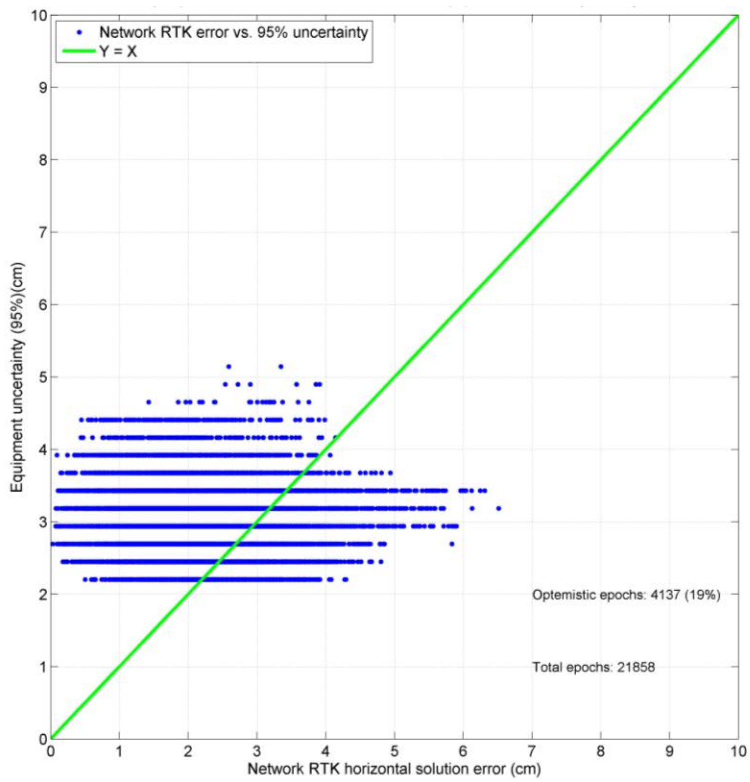

Figure 3-37. Solution integrity for Company 'A' at 'kin'

3.7 Moving Average Filtering

This section shows the quality of the filtered solutions with network RTK coordinates computed from moving averages of 5 seconds, 30 seconds, 60 seconds and 300 seconds of network RTK position fixes, for each test site. These periods were selected to examine the effect of moving average filtering on the time series in terms of precision and maximum error. The main goal here is to use the averaging time bins as a filter to compute an acceptable duration for a static network RTK survey to fit MTO's specified precision and accuracy. The largest window was selected as 300 seconds, as with longer periods of observation the viability and efficiency of utilizing network RTK tends to lose its luster and also the average user may not deem network RTK a significant upgrade over the older methods of relative positioning. The accuracy of the solutions over periods of several hours will contain biases that cannot be removed by averaging windows of up to 5 minutes. The mean biases are completely unaffected by this type of short-term averaging. The precision of the solution on the other hand can be significantly improved, as each window will dampen the results of the individual points into one single solution.

3.7.1 Precision

The following Figures display the effect of moving average filtering on the 95% precision of the solution. As mentioned above, the results from this section should provide an understanding of the most efficient observation time to meet MTO's specifications for control surveys. Figure 3-38 shows the results for the precision of Company 'A' results at the winter test sites. The precision tends to improve with larger window sizes.The largest window size (300 seconds) provides the most significant improvement over the rest of the results. For example an improvement of 1 cm in horizontal precision can be seen for 'kin' with respect to the 5 second window size and 1.2 cm improvement over the original 1 sec solution set precision.

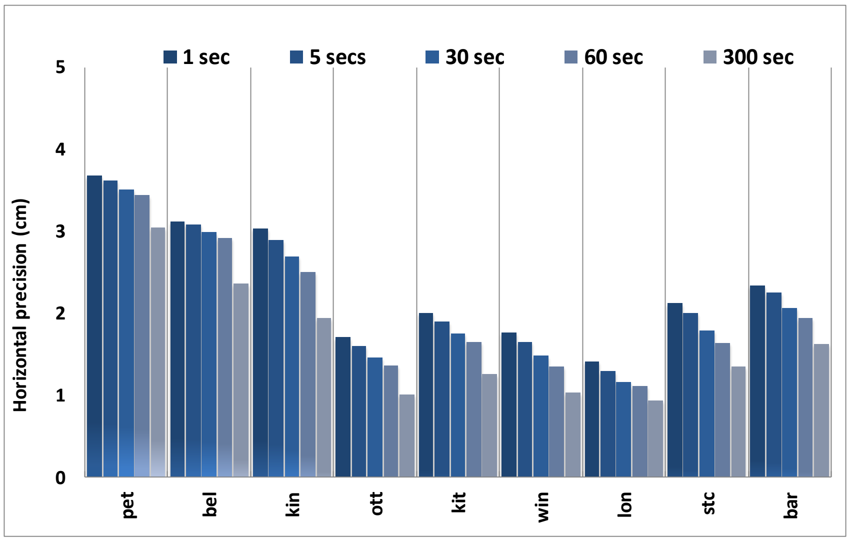

Figure 3-38. Moving average filtering vs. precision for Company 'A'

Figure 3-39 shows the moving average filtering results for Company 'B'. The 'stc' results show that the precision has improved 1.3 cm with 300 sec filtering. However, Company 'B' shows smaller improvements overall with moving average filtering with respect to Company 'A' results. This may be due to the fact that the Company 'B' solution time series have a lower sinusoidal period much larger than 5 minutes, and small window sizes of a few minutes cannot have a major impact on improving the precision.

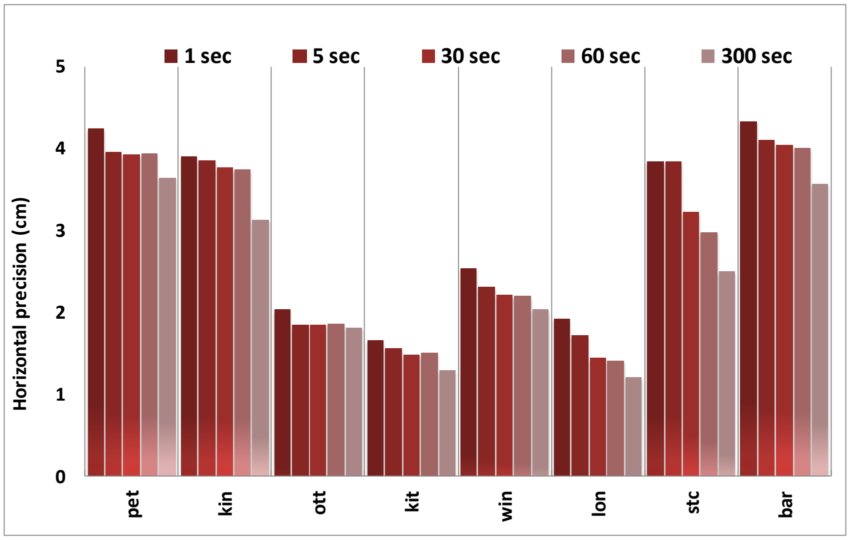

Figure 3-39. Moving average filtering vs. precision for Company 'B'

Figure 3-40 shows the effect of moving average filtering on Company 'C' precision. The most significant enhancement is at 'win' with a 1 cm improvement. The results are not at all systematic. In some cases the solution precision is affected significantly for the 5 minutes time window filter. If the solution set is well spread out over a small interval, it is expected that the precision will not change significantly with larger time bins.

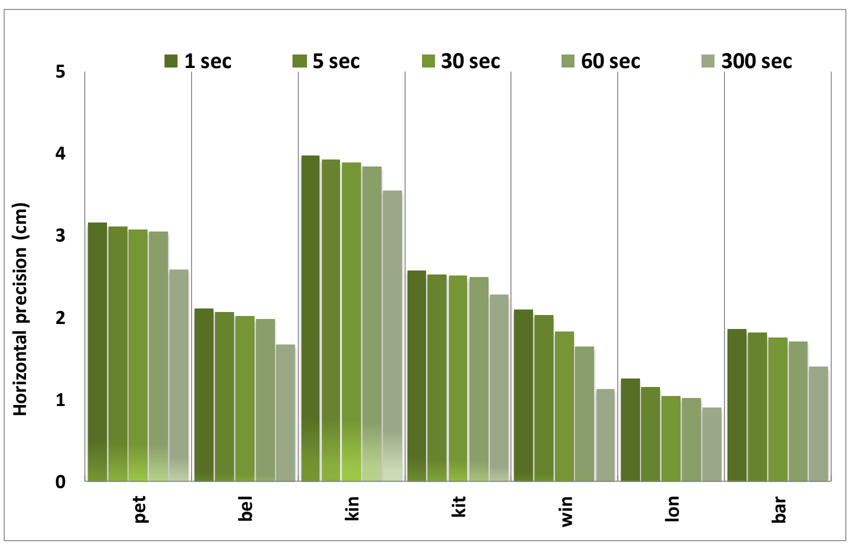

Figure 3-40. Moving average filtering vs. precision for Company 'C'

Significant precision changes here indicate that there may have been large isolated errors that have been dampened by the larger moving average window sizes. Table 3-4 shows a table of the improvements over the original 1 Hz data set in terms of precision for each of the service providers. As it can be seen from Table 3-4, the improvement of 300 sec averaging is superior to the all other time bin sizes, on average doubling the results of the next largest time bin (60 seconds), and increasing precision by more than 25% over the original solution precision. An improvement of 6 mm in 95% precision over the original solution is significant and cannot be ignored.

Table 3-4. Statistics for improvement of precision with various time bin sizes

Time bins	Company 'A' (cm)	Company 'B'	Company 'C'	Overall
5 sec	0.1	0.2	0.1	0.1
30 sec	0.3	0.3	0.1	0.2
60 sec	0.4	0.4	0.2	0.3
300 sec	0.7	0.7	0.5	0.6

3.7.2 Maximum Error

This section displays the effect of moving average filtering on the maximum error of each solution set. Figure 3-41 shows the change in magnitude of maximum horizontal error with various window sizes of moving average filtering for Company 'A'. The maximum error is more affected by the moving average filtering than precision. In some cases, improvements over 5 cm in the horizontal maximum error can be observed. This result is of great importance to the average user, given their limited period of observation. The results indicate that with up to 300 seconds of observations, the maximum error can be reduced significantly. For example, site 'bel' is shows an improvement of 5.8 cm with a 300 seconds time bin as opposed to a single 1 Hz position fix.

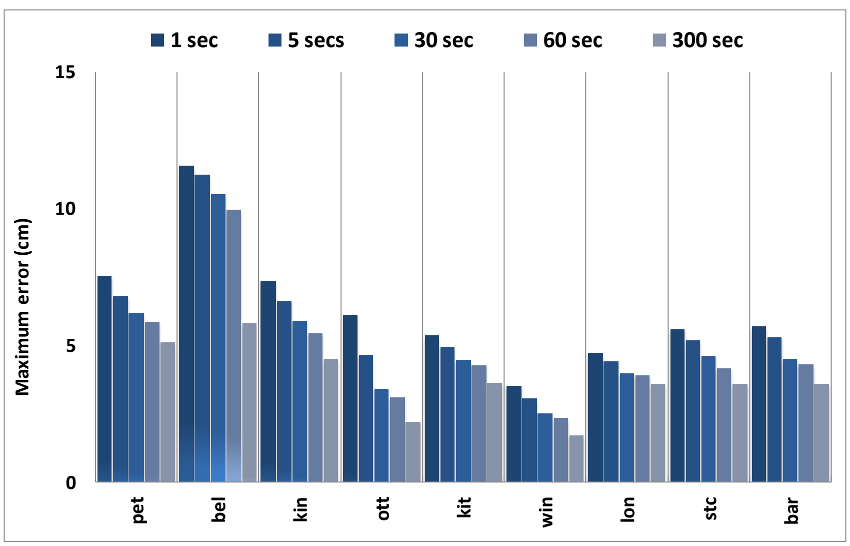

Figure 3-41. Moving average filtering vs. maximum error for Company 'A'

Figure 3-42 displays the improvement of maximum error with moving average filtering for Company 'B'. A very large reduction in the maximum error can be seen for the 'stc' site. The largest error has a magnitude of 78 cm in the horizontal, which was not filtered properly by the equipments' quality control mechanisms. With 300 seconds of averaging, a significant improvement can be seen that reduces this error to 4.1 cm in the horizontal. Similar behaviour is noted for sites 'lon' and 'bar' that demonstrates the effectiveness of averaging through larger windows of observations on reducing the magnitude of maximum horizontal errors.

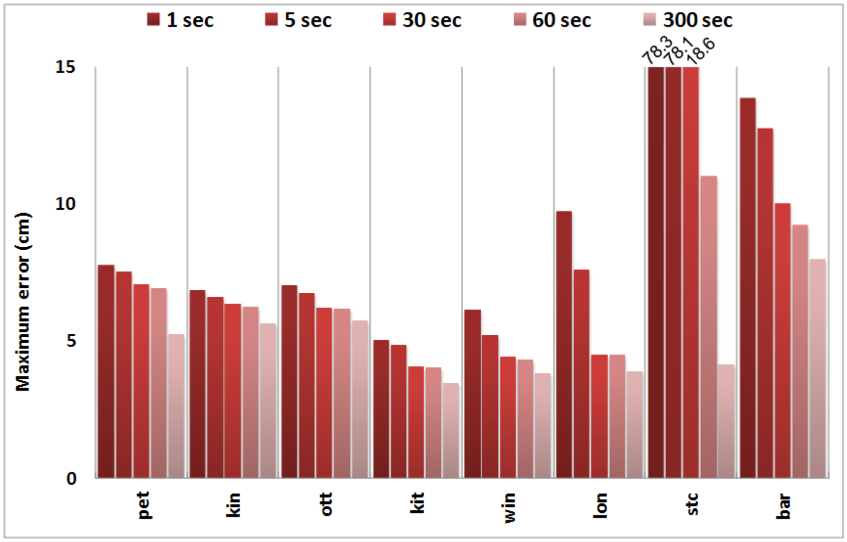

Figure 3-42. Moving average filtering vs. maximum error for Company 'B'

For Company 'C', Figure 3-43 shows smaller improvements for maximum error in comparison to the other service providers. This is mainly due to the significantly lower maximum error in the horizontal. However, notable improvements are still made for various sites such as 'bel' and 'kin'. A reduction of 2.8 cm in the horizontal maximum error can be seen for both sites 'bel and 'kin'.

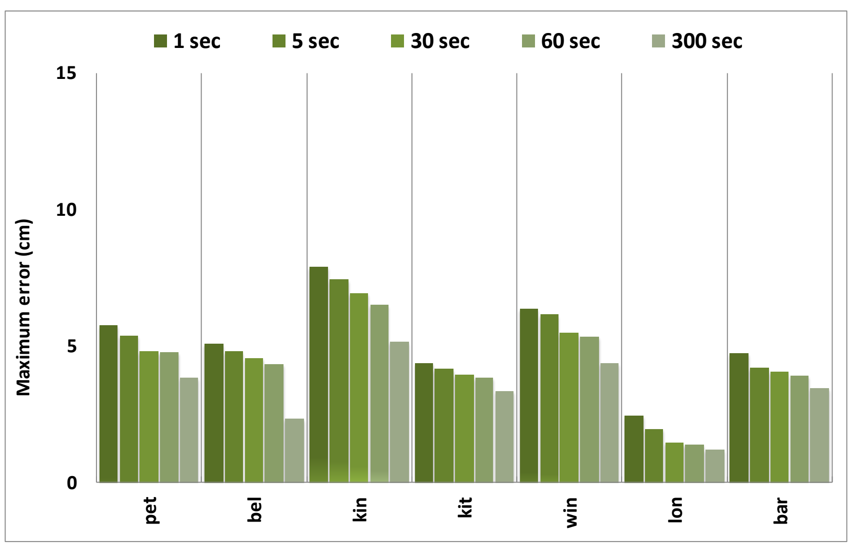

Figure 3-43. Moving average filtering vs. maximum error for Company 'C'

Table 3-5 shows the improvement of the network RTK solution in terms of maximum errors for all three service providers. The maximum is significantly reduced by moving average filtering as can be seen from Table 3-5. Only 300 seconds of averaging of the solutions is able to reduce the magnitude of the maximum error by close to 40%. Of course, each network behaves differently when it comes to maximum error.

Table 3-5. Statistics for improvement of maximum error with various time bin sizes

Time bins	Company 'A' (cm)	Company 'B'	Company 'C'	Overall
5 sec	0.6	0.7	0.4	0.6
30 sec	1.3	9.2	0.8	3.8
60 sec	1.6	10.3	0.9	4.3
300 sec	2.6	11.8	1.9	5.4

The same effect, as precision, can be seen here with Figure 3-40 to Figure 3-43; the moving average filtering dampens those very large maximum errors existent in each data set. In some extreme cases, the maximum error is reduced from decimetre level to a few centimetres (for Company 'B' in site 'stc'). This type of behaviour suggests, as outlined in the previous section, the existence of isolated large errors that affect the precision of the solution significantly and can be overcome by just using a larger pool of measurements. However, the averages of the 30, 60 and 300 seconds results are heavily skewed by the large maximum present in the Company 'B' solution at 'stc' (~80 cm horizontal maximum error).

3.8 Control Survey Results

The control survey results are shown in Figure 3-44. This is mixture of the results of over 180 trials of static network RTK solutions collected with 1, 2 and 5 minutes observation periods. Figure 3-44 shows a histogram of horizontal position errors (at the 95% confidence level) from these static trials. Statistical tests have shown that there is significant advantage in terms of absolute error to collect 5 minutes of measurements over the 1 minute observation window. However, this observation period will obviously have no effect on any sizeable systematic biases that may exist in a network since a large number of solutions from each of the observation periods lie over the solution bias and the rest of the points are spread out over a larger range. Though the goal of this analysis is to simulate an actual control survey performed under standard conditions and 5 minutes or more of data collection provides a more ideal solution.

Table 3-6 shows the rms of horizontal network RTK position error for all points in the control survey. On average, the rms values of 1 and 2 minutes observation periods show no change and the 5 minutes observation period shows a 4 mm improvement. We can see the same trend in the Figure 3-44 histogram, where the 1 and 2 minutes results do not display an improvement. Also, in some instances the solution gets worse from the 1 to 2 minutes observation window. This can be seen in the results from points 4, 6 and 7. For points 2 and 3, 5 minute observation periods show worse results with respect to the smaller observation windows. This is most likely due to mixing of the results from all companies for different observation periods. However, all horizontal rms values are below 3.5 cm, which appears to fit third order accuracy specifications (5 cm).

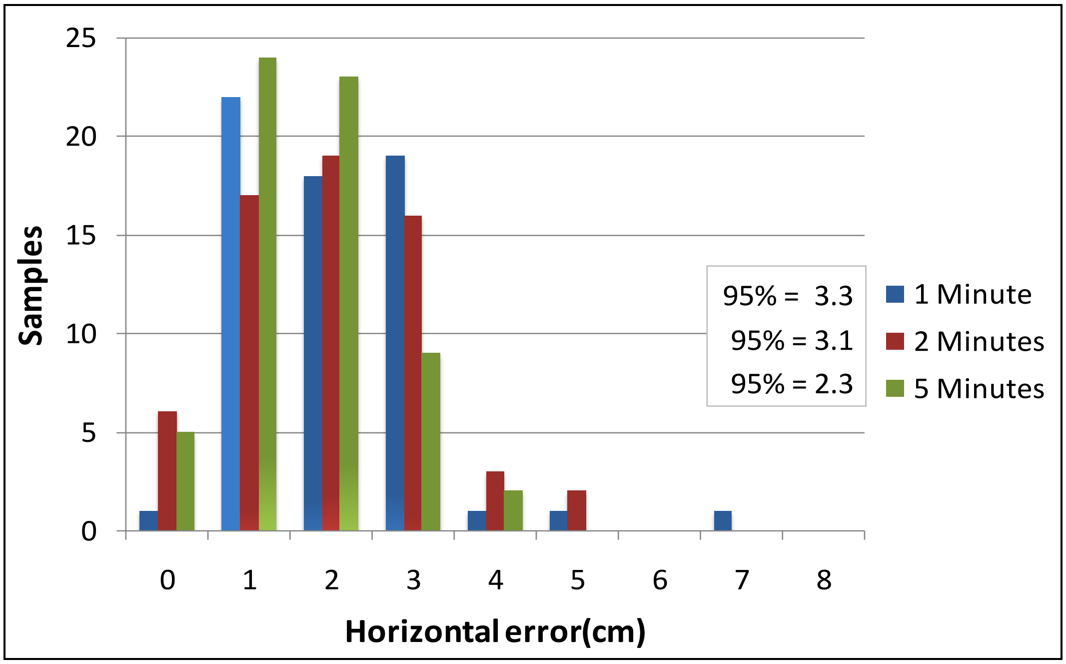

Figure 3-44. Control survey histogram for 1, 2 and 5 minutes periods of observation

Table 3-6. rms of horizontal network RTK position error for points in the control survey

Point	1 Minute RMS (cm)	2 Minutes RMS	5 Minutes RMS
1	2.50	2.16	1.79
2	2.33	2.22	2.42
3	2.07	1.96	2.34
4	1.87	2.45	2.00
5	3.28	1.97	1.90
6	1.54	2.41	1.75
7	2.29	2.90	1.45
Overall	**2.32**	**2.32**	**1.98**

Figure 3-45 shows solution integrity results of the control survey: a comparison of the equipment's uncertainty estimates scaled to the 3σ level with the computed actual horizontal errors. As in the section on solution integrity, the solution uncertainty for each company shows its own characteristics when compared with computed actual rms error. For example, Company 'B' results show almost entirely underestimated errors of sub-centimetres, while the actual errors are mostly above 1 cm. Both Companies 'A' and 'B' seem to be split between the highly correlated line, with some overestimation, as well as underestimation.

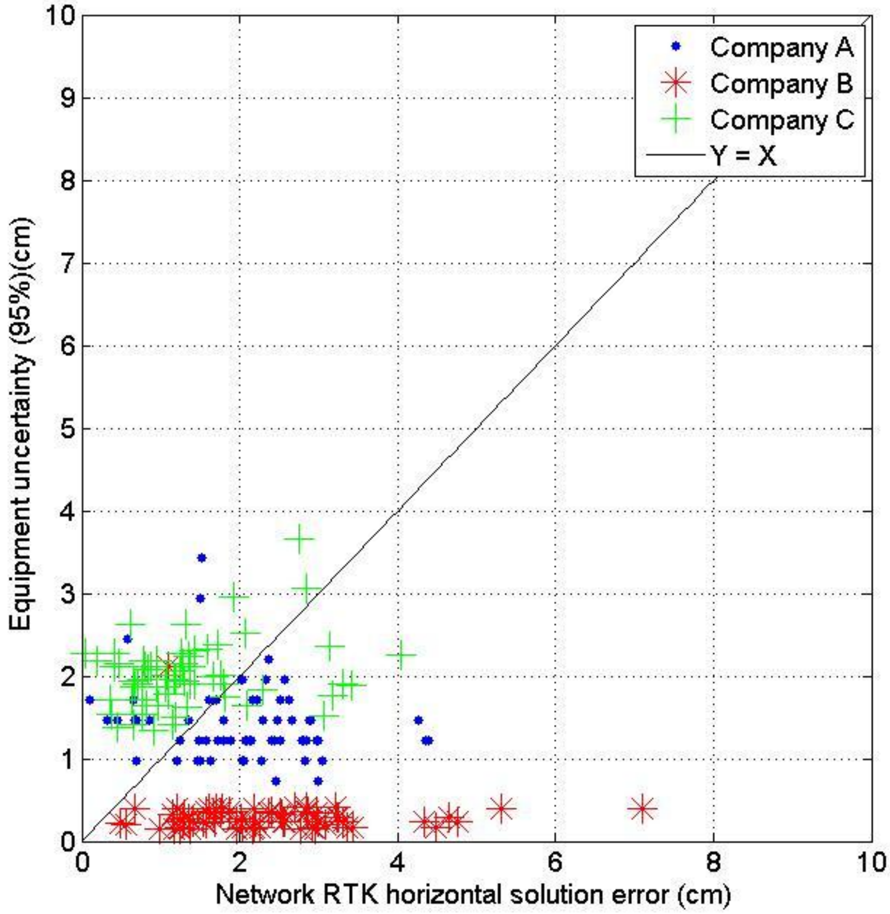

Figure 3-45. Solution integrity of control survey results

In order to thoroughly define a procedure for using network RTK in control surveying, a simulation was performed on the solutions collected the control survey procedure. As mentioned in §2.1.2, a traverse was performed using existing MTO third-order monuments. Each point was surveyed with three trials each with a unique static network RTK solution. As part of the simulation, the open loop misclosure of the traverse was computed in comparison with the MTO coordinates. The results of these tests are shown in Table 3-7.

First, for each point in the control survey, solutions from the 5 minute observation trials 1, 2 and 3 are averaged using each pair of observations at each point. Each set of baselines is computed using the averaged solutions, and using the law of error propagation and each solution's corresponding internal variances (σ_x, σ_y and σ_z), baseline variances are computed for each averaged solution. Each set of baselines is then put through statistical testing (using the Z-test). The statistical testing contains the null hypothesis that each set of baselines, which is deduced from pairs of trials is the same. The accepted set of baselines is then used to compute the misclosure of the control survey. The misclosure was calculated by comparing the relative baselines from point 1 to 7 of the control survey; using the averaged network RTK solutions with the baseline computed from MTO coordinates from point 1 to point 7.

Table 3-7 should be examined to better understand each relative baseline between consecutive points and the misclosure of the point 1 to 7 loop. The misclosure of this particular test survey with respect to the MTO coordinates is approximately 1.7 cm in the horizontal which is well within the MTO specifications that are discussed in the next section. The length of this traverse is almost 6.5 km.

Table 3-7. Relative baselines and misclosure of control survey

Baselines	**δX (m)**	**δY**	**δZ**
1 – 2	374.861	146.096	96.561
2 – 3	548.956	228.601	130.680
3 – 4	456.681	184.905	102.295
4 – 5	452.943	181.891	101.197
5 – 6	448.606	181.612	101.373
6 - 7	3692.186	1492.510	813.523
Misclosure	**North (m)**	**East**	**Up**
Loop 1 - 7	0.010	-0.013	0.010

4 Field Practice Recommendations

This section focuses on recommendations and suggested common practices that should be followed in order to utilize the network RTK technology in MTO control surveys.

4.1 Precision and Accuracy

The guidelines for using the static GPS and RTK methods is given in the MTO "Ontario Specification for GPS Control Surveys" document (MTO, 2006). Network RTK provides relative positioning somewhat similar to traditional RTK, though the solution is presented as an "absolute" solution, making so-called "traceability" of the solution difficult, if not impossible. The network RTK service as a turn-key product functions as a black-box, which makes the use of precise positioning equipments and solutions simple. This structure creates a problem of transparency of the underlying issues, such as the biases that plague the "true" accuracy of the system. In fact, systematic biases, depending on the network at various locations around southern Ontario, severely undermine the absolute accuracy of network RTK services as a whole. These biases are closely related to the methods used by service providers in the integration of their network to the NAD83 (CSRS) framework in Ontario.

Therefore, a service provider needs to conform to the official datum and epoch, NAD83 CSRS 1997.0, and perform free network adjustments with no fixing of any network reference stations with respect to the official CSRS network that consist of Canadian Active Control Stations (CACS) and the Canadian Base Network (CBN). Furthermore, a service provider may need to provide their users with access to the methodology and procedures followed in their network adjustment or with a contour map of the network distortions with respect to the official datum. Such information can ensure that the network RTK service conform with the official datum. A precise network RTK solution biased away from the "true" position by a few of centimetres is of little use in practice. Hence, both precision and accuracy need to be evaluated about the quality of network RTK solutions. On one hand, it is expected that a network RTK service delivers near-unbiased solutions within the network in all locations. On the other hand, it is necessary to devise a standard on how to adjust the GPS network and update the coordinates from time to time.

According to the MTO specifications, both precision and accuracy are used as separate entities when defining the quality of the surveys performed. However, when defining the actual required accuracy of the solutions, accuracy is treated to be equivalent to precision if solutions are deemed not to have any significant biases. In practice, two accuracy criteria are specified, which are "network accuracy" and "local accuracy". The former refers to the "absolute" accuracy at the 95% confidence level of the position of a control point with respect to the reference system (NAD83 CSRS). The latter refers to the accuracy of a control point with respect to adjacent points at the 95% confidence level (MTO, 2004; GSD, 1996). We therefore consider these terms analogous to absolute and relative precision in the absence of biases. Quality control of a control survey using network RTK technology should be executed using MTO local accuracy criteria with respect to the project datum. However, the utilization of network RTK technology in establishment of a project control network is a rather unorthodox procedure, due to the current manner in which the solution is provided. Network RTK solutions are computed with respect to either the GPS network, or a number of the GPS reference stations within the network, which is undoubtedly dependent on how the network RTK solution is generated. At the current time, this procedure is invisible to a user, hence the terminology: lack of traceability.

The reference stations within an RTK network are “tied” to an existing official authorized control network through the coordinates used for these stations. For control surveying with respect to the existing authorized control network that consist of MTO control points or CACS and/or CBN points, each solution needs to be converted into relative baselines between points to check the solution quality. The variances provided to a user from a network RTK service should represent the network accuracy of that particular solution. This may not be the case, as it is not clear if the accompanying variances together with the estimated coordinates are determined with respect to the RTK network or represent just a local accuracy with respect to one or a few of reference stations from a service provider. Furthermore, commercial and ambiguous terms such as “hrms” or “vrms” cloud the actual quality of the solutions provided by the networks under study without clear indication of the meaning of these terms and the parameters used to compute them, or even the confidence interval at which they are presented to the user. A network RTK service may need to clearly and implicitly provide the users with a full 3×3 covariance matrix (north, east, height or x, y, z) of the estimated position with respect to their network. All coordinate variances may also be scaled appropriately to conform to the 95% confidence interval as stated in MTO specifications (and desired by many other users).

Solution traceability is another issue that needs to be properly addressed. Although it may be more difficult for some methods of network RTK (such as VRS) than for others, service providers should offer their users more information to allow for the retracing of computation steps and identifying of any possible problems. With every epoch of the solution, not only the main reference station used, but all the information used in the computation (such as other stations, all vectors and corrections) of the solution should be provided to the user. In case of VRS, the vector from the virtual reference station to the user’s position should be available to the user for each individual solution.

As can be seen throughout this report, most of the solutions indicate precisions of ~2.5 cm at the 95% confidence level. However, the results reveal significant horizontal biases up to 4 cm throughout southern Ontario. In some locations, the solutions are able to meet third order accuracy specifications (5 cm upper boundary). Not all of the three services deliver the same positioning accuracy, even at the same locations. For example, Company ‘A’ has a horizontal rms of 2.8 cm in St. Catharines and 1.3 cm in Ottawa, whilst Company ‘B’ has an rms of 1.9 cm in St. Catharines and 4.1 cm in Ottawa. Each company shows its strength in their solution in particular locations and its weakness in others. Non-uniform levels of absolute accuracy create a complex situation when it comes to setting procedures and specifications. The evaluation of the “overall” mixed results makes sense only if the solutions are very similar in terms of precision and accuracy in most locations. This fact strongly suggests that the near-worst case scenarios should be taken into consideration to guarantee that the network RTK performance meets the specifications for third order or lower for control surveying.

4.2 Practical Considerations

When one establishes a control network using network RTK technology and does so to improve precision, accuracy and efficiency of the survey, there are some common factors that need to be addressed based on the results of this analyses, as well as the issues and problems that were encountered during the course of both winter and summer campaigns.

Network Geometry

In order to use network RTK technology, it is important for the user to closely examine the network geometry around the work area, to ensure that the work area is enclosed by the reference stations, as network geometry is one of the most important factors affecting network RTK solution quality. Good planning aids solution quality, and also increases productivity when using network RTK. Long distances from the main reference station to the user location could affect the quality of solutions, even leading to loss of fixed solutions or not being able to obtain fixed solutions at all. A few occurrences of this nature were encountered during the campaigns. In general, the issue of distance from the primary reference station was not a principal concern of the study, and no quantitative value can be given as the maximum distance from the primary reference station. However, another study has shown that for centimetre accuracy solutions, the length of baselines needed to be shorter than 30 - 40 km (Grejner-Brzezinska et al., 2005). This is not a critical issue in southern Ontario with the existing network RTK services. But there are locations within each network where the user needs to take extra care such as Kingston and south of St. Catharines closer to the U.S. border.

Datum

The commonly-used official datum in Ontario is NAD83 CSRS epoch 1997.0. The differences between epochs (i.e., 1997 and 2002) within the same datum can be more than 2 cm horizontally in southern Ontario. This difference can account for a significant amount of the error budget for third order accuracy. It is imperative that the officially-specified datum and epoch be used when using network RTK. A user should ensure that the datum used by the service provider conforms to that of the project. If this is not the case, transformations may be needed to be performed. The Geodetic Survey Division of Natural Resources Canada can provide a variety of tools to aid with transformation of coordinates from widely used datums to NAD83 CSRS. Among them, TRNOBS (GSD, 2011) is the utility that converts various epochs of ITRF into NAD83 (CSRS) and vice versa. A good practice would be for commercial services to the current official standard, and not leave the responsibility to the user community.

Quality Control

Network RTK equipment typically includes visual aids for the quality of the solution. The user is recommended to pay attention to these aids to determine whether a solution is ambiguity fixed. Also, it is recommended to wait for a period of at least 30 seconds after a cellular modem connection has been made before collecting observations. This can ensure that the equipment is able to receive all possible corrections and does not report “false quick fixes”. It is recommended to turn on all internal quality controls. Horizontal quality control should be set to a value no larger than 5 cm. The threshold for the internal coordinate quality can be set to a value lower than 5 cm. Otherwise, this may cause a significant number of observations to be rejected and extend observation time undermining the efficiency of the survey depending on the location. In other words, the coordinate quality threshold should not be significantly lower than the accuracy of the survey (5 cm in horizontal for third order accuracy). Also, most receivers give the user the option of a GDOP quality control indicator, with the maximum tolerable GDOP value of 3 in this case (Edwards et al., 2008).

Window of Observation

As was shown earlier, the benefit of having a large observation window on precision and maximum error is significant. It is recommended that at least 5 minutes of network RTK observation should be made for each occupation. Based on the results from the moving averages analysis, the best solutions in terms of precision and maximum error were delivered from the large windows, which provided significant improvement over short observation windows. For the sake of time efficiency in a survey when using network RTK, the 5 minute observation time is preferable. Furthermore, it is recommended that points be reoccupied at least once (preferably twice) after a time delay of at least a few hours to take advantage of changing satellite geometry. This procedure will reduce the effects of network RTK solution drift (as seen from the campaign position error time series), and issues caused by human error, such as: incorrect set up, incorrect antenna heights, wrong point occupied and other such errors that could possibly jeopardize the quality of the survey.

Visibility

For areas where there are visibility issues with GPS constellations, the other GNSS satellite constellations (assuming GNSS enabled receiver) will suffer from the same problem. Therefore terrestrial measurement techniques may have to be applied. For areas with little visibility, such as over hangs or close to bridges, it is recommended to utilize traditional terrestrial observations instead of using network RTK.

Raw GPS Observations

A network RTK service provider should ensure that their users are provided with the ability to record raw GPS observations concurrently with network RTK observations. This option empowers a user to be able to post-process the data and identify potential issue that may have adversely affected the real-time solution. This recommendation will not only improve traceability, but also aid in addressing any legal inquiries made of the survey.

4.3 Project Control Set-up

In terms of procedures to establish project control, a set of guidelines for setting up a horizontal project control network for static GPS and traditional RTK surveying methods was provided in § 5.3.1 by MTO (2006). There are no guidelines for the use of network RTK technology, as no commercial network RTK service was available in Ontario at that time. The network RTK solution is considered as an “absolute” positioning method. However, in case of control network establishment, it is crucial to use the system as a relative positioning system when it comes to quality control. Accordingly, proper steps are taken to convert the absolute coordinates obtained from network RTK to be used for control network setup, in order to ensure the quality of network RTK solution. The procedures are described in more detail below.

4.3.1 Preparation

When establishing a control network it is important to collect all available information about existing control monuments and undertake field *reconnaissance*. The latter is an essential component in the planning stage, as the working area may have changed significantly. In reality, due to continuous construction, a large number of monuments have been removed or disturbed in southern Ontario. In areas where no existing higher order control points can be found, at least two or more new control points should be first established through connection to other available control points outside the working area. The issue with using network RTK for this procedure is that the lower accuracy results may undermine the quality of the newly established primary control points within the network. So, it is recommended to use more accurate methods of surveying (i.e., static baseline GPS or total station) to establish new control points.

MTO recommends that only “third order” or higher accuracy class be used in its projects (MTO, 2006). The primary horizontal control network consists of the control points with higher accuracy than the expected accuracy of the new points. For example if the requirement for the project network is to be an accuracy class of ≤5 cm or “third order”, the existing monuments used should at least be of class of ≤2 cm or “second order”.

Sectioning

Sectioning of the network can be performed as recommended by MTO for the single baseline RTK observation. MTO recommends the maximum distance for the site calibration sections to be 5 km, to minimize the error in the calibration of the coordinates and also to reduce communication problems between base and rover. The communication issue does not exist with network RTK in areas where there is sufficient cellular coverage. Although the official datum in Ontario is NAD83 CSRS epoch 1997.0, some companies use variations of this datum, i.e., a different epoch of the same datum. Hence, this difference must be taken into consideration for precise applications such as control survey. Surely, a site calibration as for traditional RTK may be required while applying the network RTK technology in case of a discrepancy between the project datum and the provided official coordinates of the existing control points.

Calibration

The purpose of a calibration is to estimate the transformation parameters, normally a seven parameter Helmert conformal transformation between datum ***A*** and datum ***B***. For an arbitrary common point, the transformation is expressed as in Equation 1:

$$\begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} = \begin{bmatrix} D_X \\ D_Y \\ D_Z \end{bmatrix} + (1+s) \begin{bmatrix} 1 & -r_Y & r_Z \\ r_Y & 1 & -r_X \\ -r_Z & r_X & 1 \end{bmatrix} \begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} \quad \text{Equation 1}$$

wherein D_X, D_Y and D_Z are three translations, $\boldsymbol{s}$ is the scaling factor, and r_x, r_y and r_z are the three rotational parameters. Three small angular rotations are expected as there exist no significant rotations between two geodetic datums in practice. At least three common points are required to solve this seven parameters system. The estimated parameters from a calibration are used to transform the network RTK solutions into the official datum used by the primary control monuments, so that a consistent datum is maintained in the entire network. This approach is more preferable locally than the transformation based the official datum transformation parameters, as there may contain certain biases in the existing local control points. Note that for more straightforward transformations, the scale and even the rotations can be removed from Equation 1.

Network RTK Solution Quality

Each primary control monument should be occupied for a minimum of 5 minutes, which allows continuously collecting at least 300 epochs of network RTK solution at a 1 Hz data rate. A double run observation should be introduced in two different time frames (hours apart) in order to take advantage of the geometry change of the satellite constellation for two independent solution sets.

Two network RTK solution sets should be compared with each other and also with the official coordinates of the primary control monument to ensure the quality of network RTK solution in the area. Any deviations from the official coordinates should be analyzed for possible outliers. For example, if the network is to be a third order accuracy network, any outliers that are larger than 5 cm horizontally should be removed from individual epoch solutions. If the number of removed outliers is greater than 5% of the total available records, other primary monuments' results should be checked for any systematic behaviour. If systematic trends are shown in the network RTK solutions, one may conclude that the results are consistently worse than the expected network accuracy in various primary control monuments within the section at the 5% significance level of Type I Error. The biased results may indicate a problem with network geometry or the surrounding environment. Thus, these network RTK solutions should not be used for the area enclosed within the primary control points under test before one clearly identifies the biases and can efficiently compensate for them, or other methods should be employed within that section. If the results from each primary control monument within the section is acceptable with respect the accuracy boundaries of the network at the 95% confidence level, new points can be surveyed.

4.3.2 Fieldwork: Traversing

The observation of a traverse starts from a primary control monument and all the traverse sections should be visited one by one at both of the end points. After each observation period the receiver should be at least disconnected from the Internet and left to lose fixed network RTK solution, which should simulate a cold start for any successive observation either at the same traverse point or at a different traverse point until all points in the traverse sections are occupied. As shown in Figure 4-1, one starts at the beginning of the traverse with the existing monument and visiting each new monument to perform the individual observations at least 5 minutes for each observation period. Once the end point (or the adjacent existing monument) is reached, a whole run is completed. A second run is required for the entire traverse in a different time frame. A double run observation makes two sets of results for each traverse section available and provides users with good opportunity to minimize issues of equipment set up such as centering mistakes or antenna height blunders together with good opportunity to monitor the solution consistency. Maintaining a fixed rover rod antenna height, if possible, is also similarly helpful.

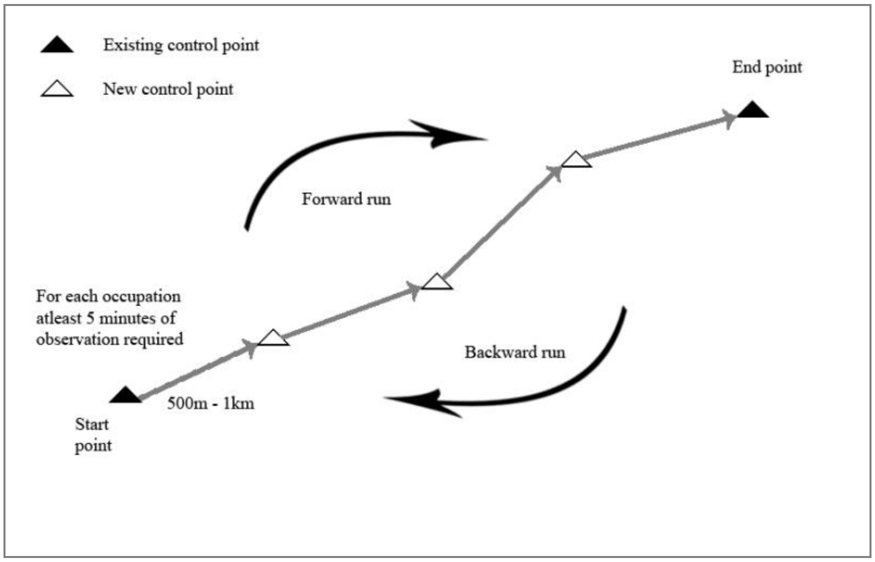

Figure 4-1. Forward and backward traversing

4.3.3 Quality Control

The double run differences on each section allow evaluation of solution quality. This quality control can be performed in three different ways: coordinate inspection; double run differences of a baseline; and the misclosures of the traverse based on the law of error propagation. Coordinate inspection involves comparing the coordinates obtained from multiple observation periods at an identical point. Each set of differences should be examined and the differences between the absolute coordinates should not exceed half of the MTO specified accuracy of the control network or 2.5 cm horizontally for third order surveys. If significant differences are found among the results, one more observation corresponding to the specific traverse sections may be introduced to confirm the results. The double run differences on each section can also be analyzed in order to determine if an average can be taken as the final traverse baseline or another observation is introduced in order to obtain two consistent solutions. The traverse closure errors in components, as either a closed loop or an annexed traverse, can be computed and further statistically analyzed. In the case the misclosures are acceptable, they will be distributed to each of the baseline measurements. Otherwise, a further investigation or a repeating field observation is needed. At the end, the coordinates will be calculated for all of the new points.

Figure 4-2 shows the procedure of how to check the loop misclosures for a traverse between two primary control points, and the equation that should be used (comparison of BSC with respect to all other baselines combined) as well. Each of the baselines is derived differently; for example BS1 is the results of differencing the averaged network RTK solution from the forward run over the starting point and point 1, and BS2 is the result of differencing the solution over the backward run over point 2 and point 3. This alternating procedure will mix results from both runs and can help pin-point blunders and large errors in the solutions. The loop error in the horizontal for each section should not exceed the defined value from Equation 2 determined for the entire distance of the traverse. For example, a traversed area of 1 km should not have a misclosure larger than 10 cm in the horizontal. If the error is larger than the accuracy specified, then each individual baseline needs to be examined and they should conform to the relationship shown in Equation 2, where R is in cm and d is the spatial distance between the points in kilometres.

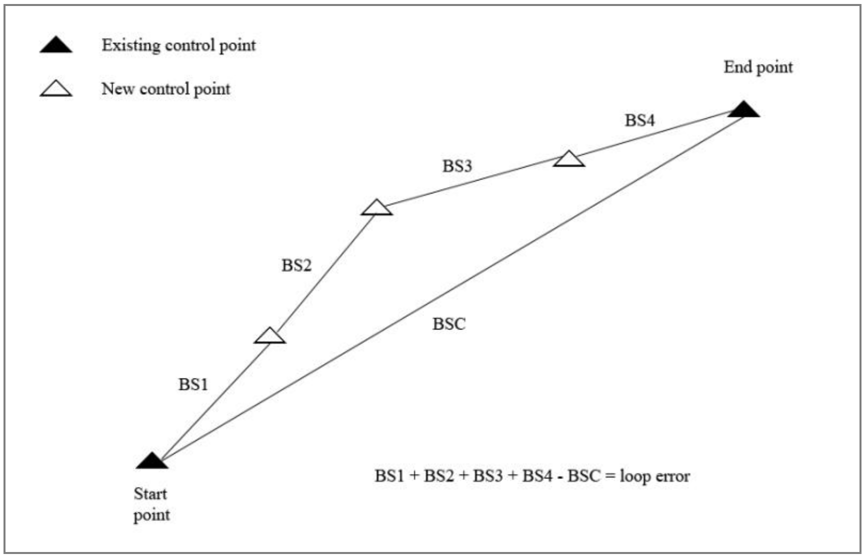

Figure 4-2. Quality control procedure

$R \leq 2.5 \; for \; d \leq 0.25 \; km \qquad and \qquad R \leq 10d \; for \; d > 0.25 \; km$ Equation 2

Each occupied point should be associated with a horizontal uncertainty value (rms) that is provided by the equipment along with each solution. The variances of each individual solution at each surveyed point can be redistributed into the averaged set of coordinates using law of error propagation by simply taking the square root of the 1σ variances of each forward and backward run results. These uncertainty values can be used to determine the horizontal error.

However, from the solution integrity analysis in the report it was shown that the uncertainty values provided by the equipment may be unstable and tend to be over and underestimation of the actual error in the solution. It is not recommended to rely only on the error propagation method to check the error in each section of the control survey. Therefore other methods described should be used in parallel to ensure that the performed survey meets MTO specifications.

Upon completion of the quality testing procedure on the results of the survey, the forward and backward run can be averaged to represent the final coordinates of each new point established in the control survey.

5 Summary

The main goal of this study was to evaluate the quality of network RTK services in southern Ontario and to determine whether it is a feasible replacement for current methods of surveying, such as static relative GPS positioning; also, through the results of the evaluation, to devise guidelines for users to be able to meet MTO control surveying specifications. Hundreds of hours of data were collected while visiting nine test sites in southern Ontario. Fieldwork was completed in two campaigns in December 2010 and July 2011. Equipment and networks from the three service providers in southern Ontario were used at each test site, close to 8 hours of data were collected in the winter and 6 hours of data in the summer, which included network RTK and raw GPS observations. Also, a separate set of tests were performed in July 2011 to simulate the utilization of network RTK in a control survey.

The data collected were used to analyze the quality of network RTK services in terms of six performance metrics: availability, time-to-first-fix (TTFF), precision, accuracy, integrity and long-term repeatability. The availability results show that service performance can vary significantly, but solution availability of 82% to 97% can be expected. This large range is attributed to differing equipment and field locations. TTFF of 30 seconds, on average, can be expected with extreme cases of 100 seconds or more before obtaining an ambiguity-fixed, network RTK solution. Generally, TTFF performance is affected by the latency of the cellular connection at the user's location. The results indicate precision of ~2.5 cm (95%) or lower in the horizontal. The results also show biases that can be up to 4 cm in the horizontal. In terms of accuracy, each service provider's solution had these biases, to varying amounts, at sites across southern Ontario. These biases result in rms ranging from 2 to 5 cm. In terms of long-term repeatability, biases in the solutions are mostly repeatable; however, precision levels vary by a few millimeters in the 95% over period of seven months, although still within typical network RTK levels (1-3 cm). Moving average filtering was used to determine the ideal period of time that is needed to meet MTO's specifications, by showing the effects of moving averages on various window sizes on maximum error and precision. Moving average filtering for 5 minutes time bins showed a precision improvement of 25% and maximum error reduction of 40% of over the original 1 Hz data sets. Note that short-term averaging does not reduce long-term biases. Overall, the results of the analyses have not been uniform and each network possesses individual characteristics, which could be address by regulatory guidelines for performance and quality of the services provided.

The dominant issue that was encountered during the course of this study was the lack of a unified set guidelines or procedures for the private networks to be integrated into Ontario's official datum, NAD83 CSRS, which may account for the noticeable centimetre-level biases that are present in the solutions. This issue can be discussed in further detail, possibly through subsequent studies. Large network biases in some of the solutions undermine the capability of network RTK as a whole. Future studies can be performed to set procedures for integrating networks presently operating in Ontario into the NAD83 CSRS reference and to reduce the magnitude of solution biases that currently reside in the network RTK services in Ontario. Another issue is the fact that not all locations within these networks were assessed. With sufficient testing, "blind spots" can be found (as a few were found in this study), where all prerequisites of network RTK are met and yet no solution could be provided to the user.

From the results of the analyses and the control survey simulation, network RTK services can meet MTO specifications for third-order horizontal (5 cm, 95% uncertainty) or lower control surveys. A set of practical considerations and procedures have been devised in this report for the use of network RTK that are essentially based on the issues and outcomes of the survey campaigns performed for this study as well as baseline RTK guidelines. Control surveys should be divided into sections and primary control points should be identified. More than one set of observations needs to be taken at each control point and the observation window should exceed 5 minutes with 1 Hz data rate. Different observations windows for each point should be separated by a period of at least several hours, if possible, to take advantage of the change in satellite geometry. The quality of the network RTK solution should be checked in the area by collecting observations over the primary control points and checking the 95% precision of the solution against the published coordinates. Due to the network RTK solutions being provided to the user as absolute coordinates, relative baselines between new control points need to be deduced and used to check the quality of the solutions utilizing loop misclosures, statistical testing and error propagation. Misclosures are formed using relative baselines computed from network RTK solutions. The misclosure should be within the specified overall accuracy of the control survey. Statistical testing is required to check the quality of the network RTK solutions utilizing the provided variances by the equipment. Error propagation is employed to determine the corresponding variances when averaging or computing the baselines from more than one network RTK observation. Depending on the results of the quality control procedure, more observations may be needed. After such quality control, the coordinates of each new control point can be obtained by taking the weighted average of the solutions.

Comparing network RTK in southern Ontario with similar places such as Great Britain or Australia, in terms of both accuracy and availability, the services provided in Ontario are sub-par. In most places, network RTK installations have been an extension of the state (or province) owned and operated reference stations, contracted to private companies and regulated by the government or some sort of regulatory association. This is not the case in Ontario as there are only a few CACS in place and they are owned and operated by the federal government. These stations are hundreds of kilometres apart in some case. Generally, the results have shown that network RTK can be used for MTO third order control surveying or lower; however, there are significant improvements that can be made to the existing systems to make them comparable to the high-performance network RTK services.

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