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Publication Title	**On the Certification of Network RTK Services for MTO Surveys**

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Abstract	Network RTK (Real-Time Kinematic) has become a standard method of precise, e.g., few centimetre- level, satellite-based positioning for urban land surveying applications. As such, MTO has been exploring this technology's use for various types of MTO highway surveys. This report proposes approaches for the government certification of such network RTK services for use by MTO and potentially the broader community. Eleven recommendations have been made regarding: the integration of service providers' reference stations into the provincial network; monitoring of service providers' existing and new reference stations; and network RTK certification options for Ontario.
Key Words	Global Positioning System; Network Real-Time Kinematic; surveys; certification
Distribution	Unrestricted technical audience.

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Executive Summary

Network RTK (Real-Time Kinematic) has become a standard method of precise, e.g., few centimetre- level, satellite-based positioning for urban land surveying applications. As such, MTO has been exploring this technology's use for various types of MTO highway surveys. The goal of the current report is follow-on research from an MTO 2010 HIIFP project authored by York University to propose approaches for the government certification of such network RTK services for use by MTO and potentially the broader community.

Eleven recommendations have been made regarding: the integration of service providers' reference stations into the provincial network; monitoring of service providers' existing and new reference stations; and network RTK certification options for Ontario:

- Given the complex nature of reference station integration into the Canadian datum, have GSD continue with its processing of NRTK reference station data voluntarily supplied by companies.
- For new sites the weighted average of one week of daily PPP-determined coordinates can be used for the initial reference station coordinates.
- Another reference station coordination approach would be for service providers to process long baselines with high-quality commercial GNSS software, and then using an adjustment software tool, such as RTKNetworkAnalysis developed for this report, perform the network adjustment using the estimated baselines as measurements.
- Static PPP processing can be used to monitor network RTK reference station and integrate new stations.
- Service providers can also process new station data with commercial GPS software capable of deriving high-quality long baseline solutions as prescribed and adjust these baselines with adjustment software such as RTKNetworkAnalysis, or wait for proposed routine, e.g., daily or weekly, GSD station coordinate processing result.
- An adjustment software tool, such as RTKNetworkAnalysis (developed for this report), should be used to perform the network adjustment using the estimated baselines as measurements for, e.g., free network adjustments and coordination of new stations with respect to fixed stations.
- Standardized, consistent, unified and harmonized (integrated) network services in the form of coordinate datums and datum transformations should be achieved and publicized to the user community.
- Some form of RTK network certification or operational guidelines should be established in Ontario, in order that the user community can access a standardized and consistent reference frame throughout the province.
- Develop in partnership with industry a reference station design and installation guidelines for existing and new network RTK CORS based on a subset of the

presented digest of existing standards.

- Develop in partnership with industry network RTK maintenance and expansion guidelines based on a subset of the presented existing standards.
- Develop in partnership with industry network RTK operator and user guidelines based on any or all of the user coordinate verification options described.

Aside from these eleven recommendations based on the accumulated research, measurement processing and software development, this report contains 49 figures, 33 tables, and 54 references.

Table of Contents

List of Figures

List of Tables

1 Introduction

Network RTK (Real-Time Kinematic) has become a standard method of precise, e.g., few centimetre-level, satellite-based positioning for urban land surveying applications. As such, MTO has been exploring this technology's use for various types of MTO highway surveys. The focus of an MTO 2010 HIIFP project authored by York University (Bisnath et al., 2012) was to investigate the performance of private network RTK services in southern and eastern Ontario for use in MTO control and engineering surveys. The report concluded that these services could provide the necessary performance for certain classes of MTO surveys with certain restrictions. The goal of the current report is follow-on research to propose approaches for the government certification of such network RTK services for use by MTO and potentially the broader community.

1.1 Background

Over the past two decades, the U.S. Global Positioning System (GPS) has become ubiquitous in outdoor positioning and navigation. Other Global Navigation Satellite Systems (GNSSs), such as the Russian 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 other scientific and engineering applications; two such very precise applications are land surveying and engineering 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. For example, MTO uses relative GPS for precise control and engineering surveys. Relative GPS positioning approach requires that two sets of GPS equipment be set up – at either ends of a baseline to be determined. In case, one end of the baseline has known coordinates, and with the GPS-determined vector, the unknown coordinates of the other end of the baseline can be calculated. If one end of the baseline is associated with its approximate coordinates at the required accuracy, the baseline vector can still accurately be determined as measurements in a control network.

Relative GPS has been augmented in different ways to improve its operational capabilities. One such change is known as network RTK (real-time kinematic), which is based on (single-baseline) RTK (Vollath et al., 2002b, 2002c; Wanninger, 2000, 2003, 2008; Wübbena et al., 2001; etc.). RTK is a relative GPS positioning procedure which (without going into unnecessary detail for this introduction) produces few centimetre-level positioning accuracy after seconds to tens of seconds of data collection in real time. This RTK performance is limited to <10-15 km baselines, as longer distances cause increased measurement errors, which cannot be successfully managed by processing software. Network RTK was developed to effectively pool the measurements from a set of RTK reference (or base) receiver stations (which are receiver / antenna assemblies at known locations) to produce RTK-like performance over a larger area (Aponte et al., 2009; Bäumker, 2003; Grejner-Brzezinska et al., 2005; Hu et al., 2003; Retscher, 2002; Vollath et al., 2002a; Wanninger, 2002; etc.). A positive consequence is that reference stations can be spaced many 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 – though a radio receiver (typically in the form of a cellular modem) is needed for the network RTK corrections. These corrections can be generated by means of a number of different approaches, including the virtual reference station (VRS) approach.

The focus of academic research and industrial development has been oriented to practical use of this innovative technology from the very beginning. During the last decade, various countries and regions worldwide have developed network RTK service (AdV, 2004; Engfeldt, 2005; Higgins, 2001; Kanzaki et al., 2005; Marel, 1998; Pietikäinen, 2004; Rizos, 2002; etc.). Currently, one of the most active research and industrial development objectives is to standardize the practical use of this technology in April 2012 Page 2 of 7 order to ensure its accuracy and reliability in engineering surveying (Euler et al., 2004; Park et al., 2010; RTCM, 2005; Takac et al., 2008; etc.). Over the past decade, a number of commercial network RTK services have been established in southern and eastern Ontario. With a single RTK GPS unit (receiver and antenna), cellular modem, and subscription-based corrections, the service providers claim that few-cm horizontal and vertical positioning is attainable within their networks.

1.2 Objectives

The goal of this follow-on research is to propose approaches for the government certification of such network RTK services through the following specific objectives:

a) Integration of service providers' reference stations into the provincial network.
b) Continuous monitoring of service providers' reference stations.
c) Certification of these network RTK systems.

These three objectives can be detailed as follows:

a) *Integration of service providers' reference stations into the provincial network.*

Results from the 2010 York University study indicate that for some networks, up to a few centimetre biases exist in user coordinates, which were inferred to be systematic rotation and translation biases in reference station coordinates. The federal government (Natural Resources Canada – NRCan) has recently agreed to a Canada-wide coordination of all current network RTK reference stations within their national network.

i) This project work will begin by reviewing the methods and results of this federal coordination for stations in Ontario; datums and epochs will be considered, along with processing methodology and output coordinates and covariances.

ii) With support from the service providers (for raw station GPS data), the on-line NRCan Precise Point Positioning (PPP) GPS data processing software will be used to estimate reference station coordinates, if the station belongs to the existing control network, in order to compare with the previous federal solutions. It is hypothesized that by processing enough days of data with PPP, similar positioning resolution will be obtained.

iii) The baseline vector of a network RTK station, if it does not belong to the existing control network, will also be determined with respect to the nearest stations in the provincial network by using the Bernese GPS data processing software. The derived baselines can be used in an integrated network adjustment to determine the potential biases.

b) *Continuous monitoring of service providers' reference stations.*

Related and as important to common coordination of reference stations is the continuous monitoring of these reference stations and new reference stations added to networks.

i) From (a)(ii), PPP processing methodologies will be developed for monitoring of the coordinates of existing and new reference stations.

ii) From (a)(iii), baseline vector processing methodologies will be developed for monitoring of the coordinates of existing and new reference stations.

iii) A geodetic network analysis software tool will be designed and developed to input station coordinates (and covariances) and the baseline vectors (and covariances) as pseudo-observations in order to carry-out network analysis, such as computation of absolute and relative error ellipses and application of standard statistical tests for monitoring of network coordinates and addition of new reference stations to existing networks.

c) *Certification of these network RTK systems.*

The final portion of this research project will be to propose a process of certification of these network RTK systems. This research will:

i) Review the literature concerning government certification of network RTK services in other jurisdictions from around the world.

ii) Provide guidelines for reference station design and installation, following specifications from NRCan, IGS, NOAA NGS, UNAVCO, etc.

iii) Provide guidelines for the maintenance and expansion of networks in terms of station coordination based on (a) and (b).

iv) Develop user coordinate verification options.

v) Develop additional guidelines and / or specifications as suggested by MTO.

2 Integration of Reference Stations

Integration refers to the integration of service providers' reference stations into the provincial network, that is, the coordination of NRTK stations with respect to provincial standards. These coordinates are references to NAD83 (CSRS) in Canada, but as described in the "Guidelines for RTK/RTN GNSS Surveying in Canada" (Donahue et al., 2013), different provinces use different versions. In Ontario, Version 3.0.1 (1997.0) has been adopted but the move to Version 6 (2010.0) is imminent. Hence, for provincially sanctioned surveys, coordinates must be computed in this datum, whether for NRTK surveys the reference stations and therefore the user stations use such coordinates or system's native coordinates are accurately transformed to the required datum.

Results from the 2010 York University study (Bisnath et al., 2012) indicated that for some networks, up to few centimetre systematic biases existed in user coordinates, which were inferred to be systematic translation and/or rotation biases in reference station coordinates. In discussions with the service providers, a variety of approaches were used to coordinate existing and new stations using different processing modes (point, relative, and network), using different subsets of regional reference stations, and producing coordinates in different datums. Much of this information was not transparent to users.

In 2012, the federal government (the Geodetic Survey Division (GSD) of Natural Resources Canada (NRCan)) agreed to a Canada-wide coordination of all current network RTK reference stations within their national network processing and adjustment scheme. The results have lead to a more homogeneous and well-defined integration strategy.

The objective of this section is to provide recommendations for the integration of NRTK reference station coordinates within Ontario's desired datum. To research this objective the federal integration approach is reviewed, the use of Precise Point Positioning (PPP) is considered, relative network position processing is revisited, and all the approaches are compared.

2.1 Review of Federal Integration Methodology

GSD carried out an initial (re-)coordination processing campaign in 2012 with the cooperation of most of the NRTK service providers across the country, and has since continued to process reference station data. The descriptions provided here are derived from Craymer and Piraszewski (2012) and Craymer (2013).

2.1.1 Network Baseline GPS Data Processing

21 weeks of GPS data were processed by GSD from June 5th to October 29th, 2011 (GPS Weeks 1639-1659) using the Bernese GNSS software package. Some sites provided much less data, especially new ones, which were installed in these growing networks during the processing period. Data from six service providers, totalling 444 sites were used, including approximately 150 sites in Ontario. GSD had a number of metadata issues related to site names and inaccurate log file entries all of which had to be manually corrected.

The GPS data processing (keeping in mind that many of the station receivers also make GLONASS measurements) was performed using the Bernese GPS Software v5.0 (Bernese, 2013). This software is a complex academic processing package, which requires training and experience in order to operate at its limited, i.e., producing mm-level static, network, relative GPS position processing, and as such, has limited usage, mostly in government and academic institutions.

Given limitation in network relative positioning, each RTK network was processed as a separate sub-network. Daily solutions for each sub-network were computed, and these solutions combined into weekly sub-network solutions. While the need for sub-networks is a constraint, static relative network processing still provides the most accurate form of GNSS data processing.

The processing methodology used was the same as GSD uses for the continuous Canadian Active Control System (CACS) network and for the Canadian Base Network (CBN) campaign data. The adopted International GNSS Service (IGS) models and conventions were used, e.g., precession, nutation, ocean loading, solid Earth tides, etc. And the IGS08 reference, precise orbits and satellite and receiver antenna calibrations were used.

Daily coordinate estimate outliers were removed if they exceeded a few centimetres, and discontinuities were estimated if larger than 1 cm. The overall results were very consistent, with weekly solutions within a ± 1 cm envelope, only 6 discontinuities observed, and 4 outliers removed. Trends were observed in some time series; however, more data, e.g., one year, would be required for trend analysis.

2.1.2 Coordinate Adjustment

In order to integrate the determined coordinates into NAD83 (CSRS) Version 6, the unconstrained weekly sub-network solutions were combined and then either a minimal constraint adjustment was performed for analysis purposes or a weighted constraint adjustment was performed for the actual integration. In terms of the combination, the weekly solutions were transformed from IGS08 to NAD83 (CSRS) Version 6, and the GHOST adjustment software was used to perform a weighted least squares adjustment of the 21 weekly solutions.

The minimal constraint adjustment was performed to verify the internal fit of each sub-network. For the Ontario stations, NRCan station ALGO was held fixed. From the determined time series relative to the first week, residual outliers and discontinuities were examined. For the actual NAD83 (CSRS) Version 6 integration adjustment, the CACS Version 6 weighted constraints were used at NRCan stations ALGO, CHUR, DUBO, HLFX, NRC1, SCH2, and STJO for the Ontario NRTK reference stations.

The final epoch of the coordinates was the epoch of the adjustment, nominally the middle epoch of the data processed: 2011.6247, which was propagated to the respective provincially adopted NAD83 (CSRS) epochs using the NRCan-derived velocity model. The service providers who participated in the experiment appeared to be pleased with the outcome and it appears that they have adopted the NRCan-derived reference station coordinates for their networks.

2.1.3 Effectiveness and Practicality of Method

Network adjusted, static relative positioning with days, weeks, months, or years of data is recognised as the most accurate form of GPS-based positioning over small and large aperture station networks. GSD can be considered the recognised leader in such processing in Canada, and is the creator and steward of the national geodetic reference system and reference frame. This GSD work also implies the generation of the national and continent-wide GPS-based station velocity fields. As such, GSD provides the most accurate means for NRTK reference station coordination.

It would be a somewhat unusual situation for private firms to construct NRTK infrastructure and supply positioning services to clients, but rely on the federal government to provide coordinates for the NRTK reference stations integrated into the national reference frame. However, given the significant effort, and more importantly, expertise (as will be described throughout this report) that is required to successfully carry out such reference station integration, this ad hoc public private partnership appears practical and effective.

For traditional (non-satellite measurement-based) geodetic control networks, the official published coordinates may not be updated often due to the limited availability of new network adjustments and the high costs of updating the existing authoritative geospatial databases and user products. However, modern GNSS technology allows frequent updating of control networks, especially with CORS networks. Indeed, CORS function with the potential to continually estimating their individual positions and positional changes and their relative positions. However, it remains a challenge for authorities as to the optimal update cycle, as any new authorized update will affect downstream users, especially users with relative long-term and large-scale projects. The authors observe the very slow change on the technical specifications, for example, in Ontario, and in Canada at-large, and that for some jurisdictions, the provision of some coordinates with respect to a particular datum are specified by legislation. Therefore due to GNSS technology, there is a significant disconnect between geodesists, who are happy to produce constantly changing coordinates given physically reality and improvements in defining horizontal and vertical datums, and data users, who want understandable and stable coordinates in which to define boundaries, construct infrastructure, etc.

Specifically, with GNSS RTK networks, commercial services providers are responsible for any changes in the coordinates of their reference GNSS stations. However, their clients may go unaware of any such changes. Ideally, a service provider would want to get the initial coordinates of new reference stations "right" at the initial operations phase, then future coordinate changes due to tectonic plate motion, glacial isotatic adjustment, etc. would be factored in to time stamped coordinates with associated velocities with respect to a specific datum.

The issues of what practical scheme to use for updating reference station coordinates and how frequently, and the impact on NRTK user coordinates from epoch-dependant reference station coordinate updating are substantial issues.

2.1.4 Recommendations

<u>RECOMMENDATION 1: Given the complex nature of reference station integration into the Canadian datum, have GSD continue with its processing of NRTK reference station data voluntarily supplied by companies. These few hundred pan-Canadian stations add density to GSD's on going North American velocity field estimation, even though the CORS are not necessarily of the highest monument stability. The frequency of data processing and coordinate updating will have to be decided by all parties, as well as the level of formality of the GSD processing and companies' usage of determined coordinates.</u>

2.2 Integration by means of PPP processing

The Precise Point Positioning (PPP) (Zumberge et al., 1997; Kouba and Héroux, 2001) GNSS data processing technique is considered as an alternative method of reference station integration / coordination, as it provides a very computationally efficient station-by-station data processing approach versus the computationally demanding relative positioning (i.e., baseline and network adjustment) approach performed by the Bernese software as used by GSD. It is hypothesized that by processing enough days of data with PPP, similar positioning resolution will be obtained as with the relative positioning approach. With support from the service providers, who provided raw reference station GPS data, the York-PPP software (Seepersad, 2012), which is based on the on-line NRCan PPP-CSRS software was used to estimate reference station coordinates of stations belonging to the existing control network, in order to compare with the previous discussed GSD solutions. If, in fact, comparable solutions could be produced, then PPP processing would provide another option for station integration.

2.2.1 PPP GPS Data Processing

GPS data from three NRTK companies (148 stations) observed during DOY 156 to 302 in 2011 were processed using the York-PPP software. The data were processed on a Windows 7 desktop with Intel® Core™ i7-3770 Processor for a total processing time of 4 days. York-PPP was developed based on the processing engine used by the on-line CSRS-PPP service (NRCan, 2010). The sites chosen were a subset of the stations located in southern Ontario. The distribution of the sites is illustrated in Figure 1. Dual-frequency receivers tracking either the C/A or P(Y) pseudorange on L1 were used. Settings used for the evaluation include the ionosphere-free combination of L1 and L2 data, 2 m and 15 mm a priori standard deviations for pseudorange and carrier-phase observations, respectively, and a 10° elevation cut-off angle.

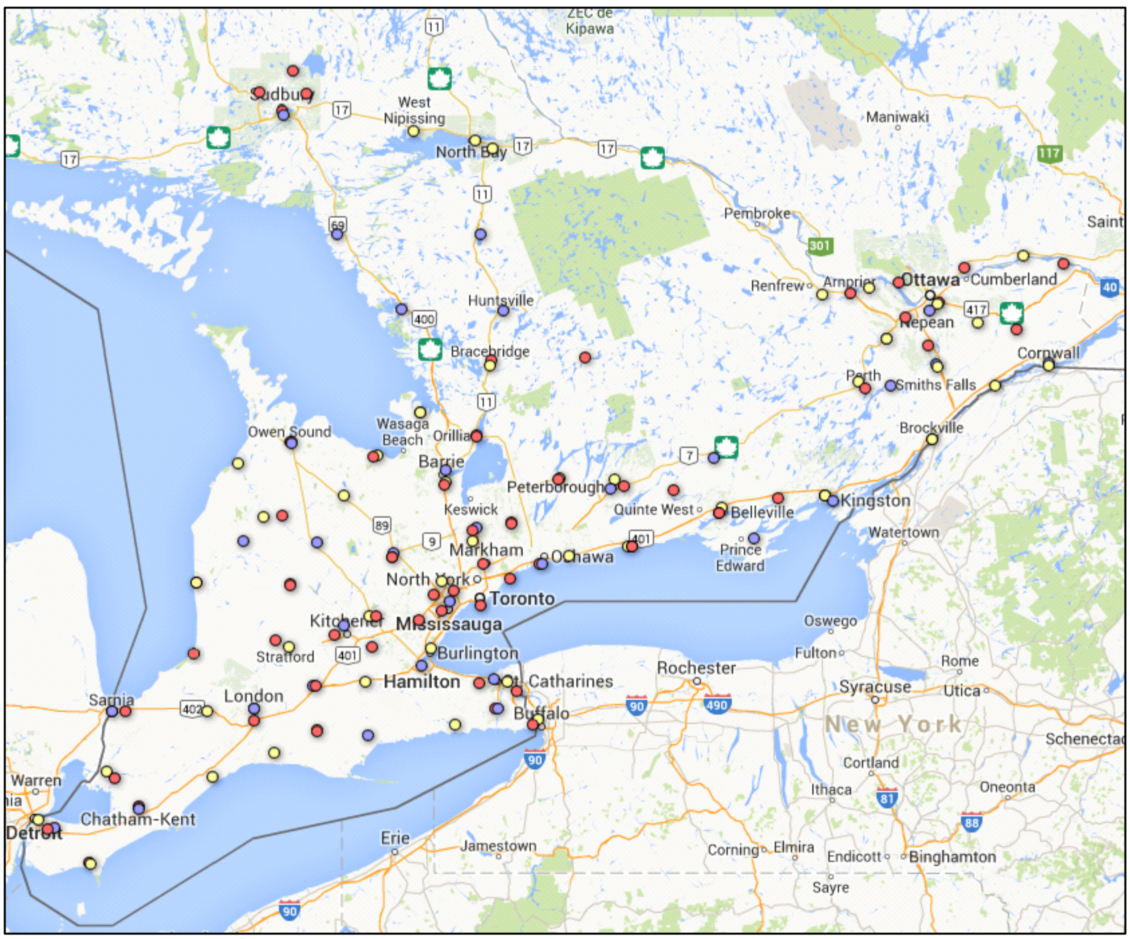


Figure 1: Geographic distribution of network RTK reference stations under study in Southern Ontario.

IGS final 5 minute orbit and 30 second clock products were used. The reference stations were analysed in static mode. Receiver clocks were estimated epoch-by-epoch. The zenith tropospheric delays were estimated every 60 minutes with a priori standard deviation of 2 cm/sqrt (hour). The station coordinates were estimated with an initial constraint of 1 km. The IGS relative antenna model file was used and ocean loading and solid Earth tides were obtained from Scherneck (2011) for each of the sites being processed.

2.2.2 Coordinate Adjustment

PPP-estimated coordinates do not require adjustment as is the case for relative positioning solutions, in the sense that PPP coordinates are determined by the frame in which the precise GPS orbits and clocks used in the processing are referred to. In the case of the processing performed in this report, Final IGS orbit and clock products were used, and the coordinates are therefore referenced to ITRF 2010.

If PPP coordinates are required with respect to another reference system or at a different epoch of a reference system, then a known coordinate transformation or known station velocity field correction is applied. Such transformations and corrections for modern North American systems are generally known to the few millimetre-level in terms of final station coordinates. Depending on the application, daily or weighted-average weekly PPP solutions are used.

2.2.3 Effectiveness and Practicality of Method

PPP is capable of producing sub-centimetre accuracy in the horizontal component and centimetre in the vertical. To quantify the accuracy of PPP, all estimated daily positions were compared with the NRCan weekly SINEX solution. Solution here refers to the estimated float PPP solution generated after processing the entire 24 hour dataset in static mode. Presented in Table 1 is an overview of the summary statistics for all three NRTK providers located in southern Ontario. The horizontal component has an rms of 3 and 5 mm in north and east, respectively, and in the up component, the solution has an rms of 12 mm. Removal of one NRTK provider from the data processing reduced the rms in the up component by 5 mm as highlighted in Table 2. The major deficiency in the individual solutions from this NRTK provider relates to systematic biases caused by erroneous antenna (and radome) information provided for ~85% of stations. RINEX observation files did not include the correct model types for the equipment, that is, they are not aligned with the conventional names given by the IGS (2013a).

Table 1: Final solution produced by York-PPP from 24 hour datasets from all three NRTK providers for DOY 156-302, processed in static mode. Units in mm.

Component	max	mean	std dev	rms
Northing	63	0	3	3
Easting	48	-1	5	5
Horizontal	79	1	6	6
Vertical	31	-5	11	12
3D	81	5	12	13

Table 2: Final solution produced by York-PPP from 24 hour datasets from two of three NRTK providers for DOY 156-302, processed in static mode. Units in mm.

Component	max	mean	std dev	rms
Northing	63	0	3	3
Easting	48	-1	4	4
Horizontal	79	1	5	5
Vertical	31	-1	7	7
3D	81	1	8	9

The distribution of the solutions in the north, east and up components are illustrated in Figure 2, Figure 3 and Figure 4, respectively, with histogram bin sizes of 2 mm. In the north component, 95% of the data range between ± 6 mm with an average bias of 0 mm and standard deviation of 3 mm. In the east component, 95% of the data range between ± 8 mm with an average bias of -1 mm and standard deviation of 4 mm. As expected, the bias and standard deviation in the east component is greater due to unresolved carrier-phase ambiguities. In the vertical component, 95% of the data range between ± 14 mm with an average bias of -1 mm and standard deviation of 7 mm. It is expected for the vertical component to be of a lesser accuracy than that of the horizontal component due to satellite geometry (inherent to all modes of GNSS data processing) and resolution limitations in the models used for atmospheric modelling and the solid Earth tides and ocean loading.

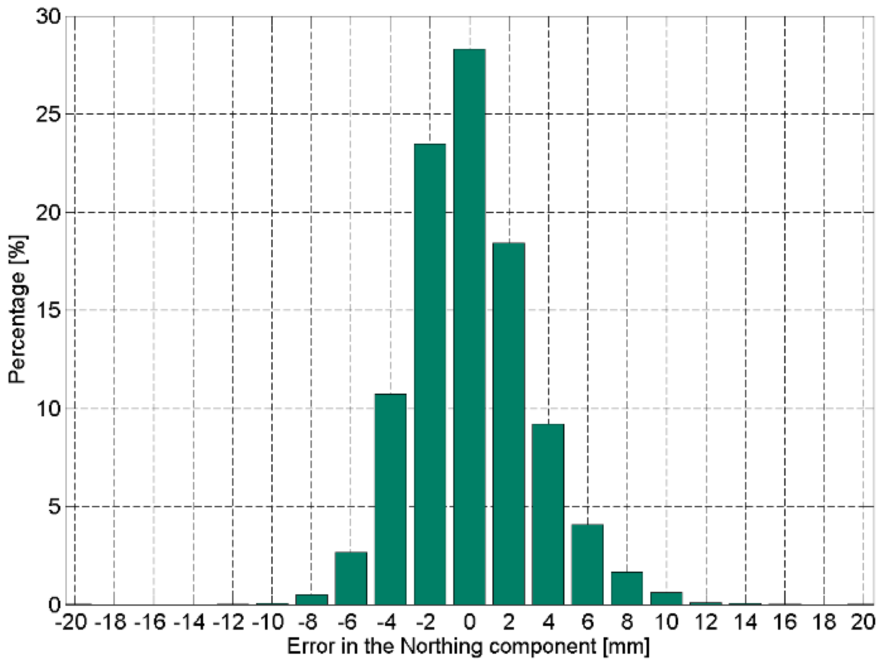


Figure 2: Histogram showing error in northing component with a mean of 0 mm and standard deviation of 3 mm.

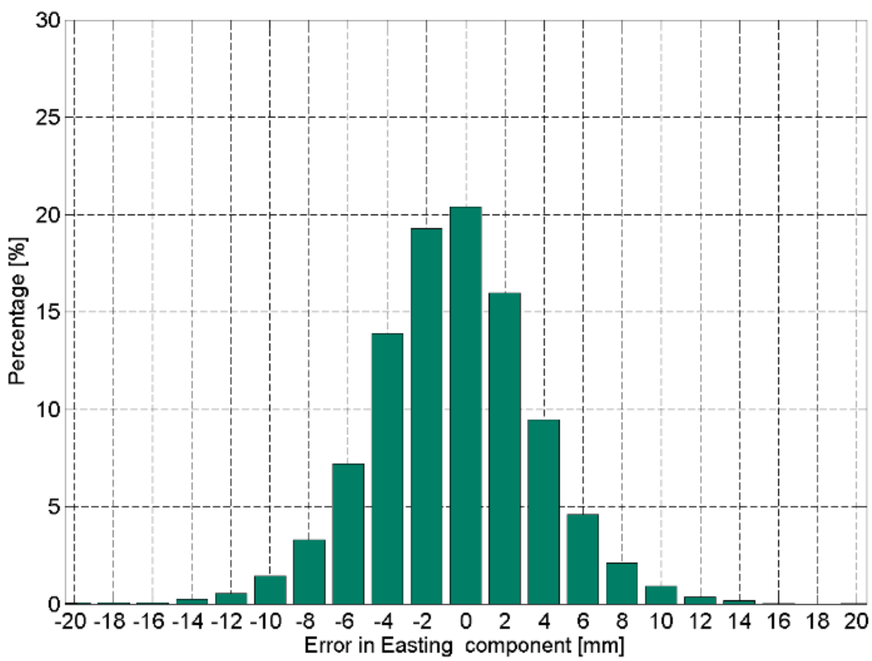


Figure 3: Histogram showing error in easting component with a mean of -1 mm and standard deviation of 4 mm.

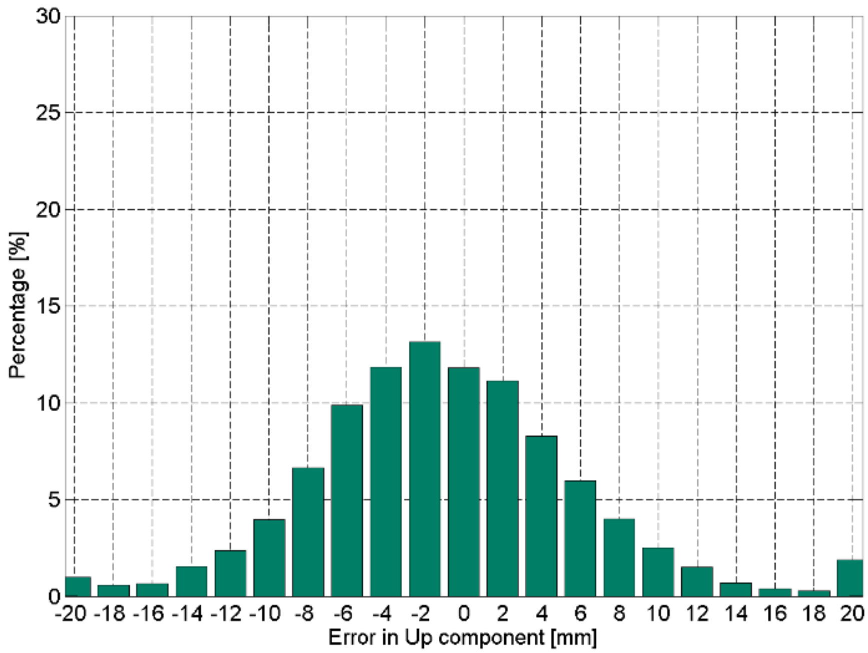


Figure 4: Histogram showing error in up component with a mean of -1 mm and standard deviation of 7 mm.

2.2.3.1 Comparison of averaging multiple daily solutions

Given that the daily PPP solutions are comparable to the weekly relative positioning results at the sub-centimetre-level, the logical next phase of analysis is to determine whether or not multiple day averaging of daily PPP solutions will reduce differences in this inter-comparison.

Presented in Figure 5 and Figure 6 are the comparisons between the average solution over multiple days from the York-PPP software compared to NRCan's weekly SINEX solution. Averaging was performed over 1, 3, 5 and 7 days, where 1 day represents the daily solution. The most significant reduction in the bias was noted in the horizontal component between the daily and 7 day average solution with a reduction of 1.2 mm. Similarly for the standard deviation, the most significant improvement was noted between the daily and 7 day average solution with a reduction of 1.4 mm in the up and 0.8 mm in the horizontal.

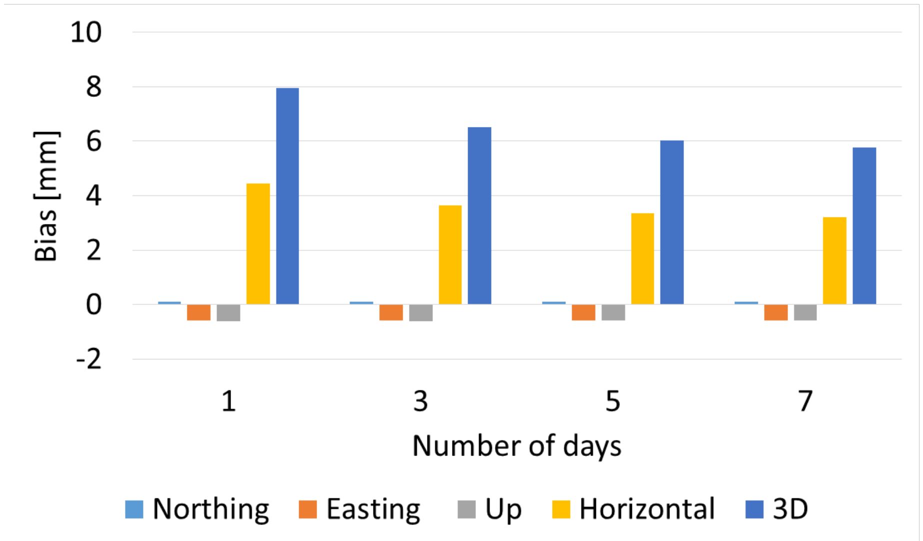


Figure 5: Comparison of the bias between York-PPP float solution and NRCan's weekly SINEX for the averages of multiple days.

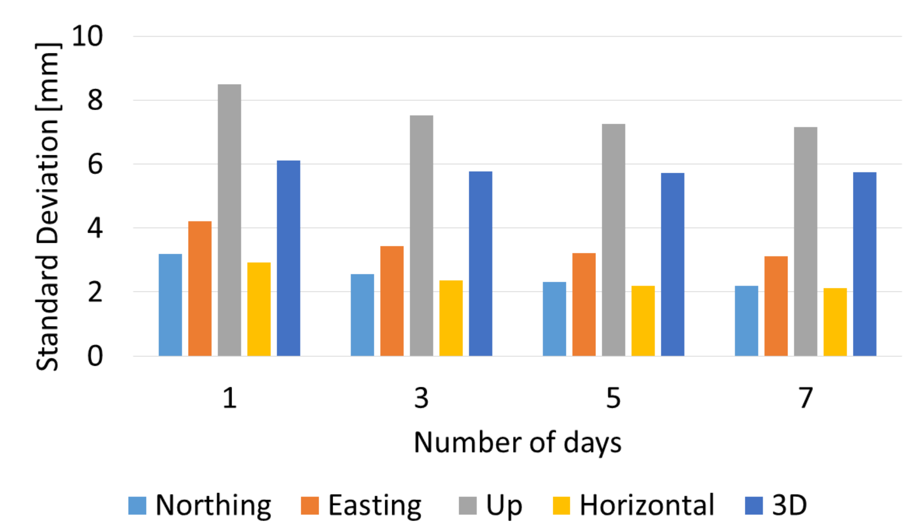


Figure 6: Comparison of the standard deviation between York-PPP float solution and NRCan's weekly SINEX for the averages of multiple days.

2.2.3.2 Convergence

PPP definitely presents advantages for many applications in terms of operational flexibility and cost-effectiveness. One of its major limitations is its relatively long initialization time as carrier-phase ambiguities converge to constant values and the solution reaches its optimal precision. PPP convergence depends on a number of factors such as the number and geometry of visible satellites, user environment and dynamics, observation quality and sampling rate (Bisnath and Gao, 2009). As these different factors interplay, the period of time required for the solution to reach a pre-defined precision level will vary (Seepersad, 2012).

For this NRTK reference station integration study, PPP convergence is of interest only with respect to how quickly PPP solutions can be produced compared to network baseline processing, e.g., as performed in Section 2.3. In static mode, the estimated parameters are constrained, allowing the ambiguities to be estimated within a shorter time period. Recommendations for the quantity of data to be logged are based on the time period 95% of the solutions took to achieve the specified threshold of 5 and 10 mm, respectively, for the horizontal and vertical components. A 5 mm horizontal threshold was set based on the current performance of the Bernese processing as presented in Section 2.3 and 10 mm on the current accuracy performance of PPP in the vertical. Figure 7 illustrates the estimated convergence period results. In the horizontal component, a linear trend is contrast to the quasi-linear trend in the vertical. 35% of the data processed had an initial error of 5 mm and 10 mm or less in the horizontal and vertical component, respectively. In the horizontal component, a minimum of 23 hours is recommended to meet a horizontal threshold of 5 mm and 20 hours for the vertical to meet a threshold of 10 mm. Therefore, in-line with the daily PPP analysis, PPP convergence for geodetic-quality positioning requires one day of static processing.

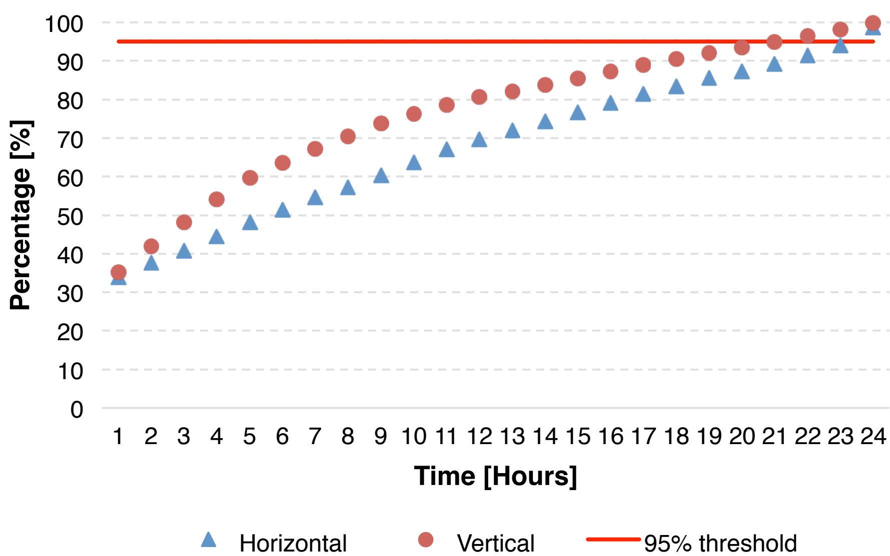


Figure 7: Cumulative histogram showing convergence period to 5 mm horizontal accuracy for static PPP.

2.2.3.3 Time series comparison

As a final component of the PPP processing analysis in the NRTK reference station integration portion of this study, a selection of individual daily time series will be assessed. The rms error for each station was calculated from all of the datasets processed. The selection of the time series presented is based on sites that had a 3D rms error at the 0, 50, 95 and 100th percentile and with at least 75% solution availability from DOY 156 - 302, 2011. Table 3 provides the summary coordinate determination statistics for each of the 4 sites with respect to NRCan's weekly SINEX solution coordinates. It can be seen that there is very little difference (a few millimetres) in the accuracy of the PPP horizontal components between these sites, and that the reduced 3D coordinate accuracy from the 0 to 100th percentile sites is driven by millimetre-level vertical differences between the PPP results and the relative positioning.

Table 3: Summary of the station rms error at percentiles 0, 50, 95 and 100. Units in mm.

Station	Percentile	Northing	Easting	Vertical	Horizontal	3D
A	0	3	3	5	4	6
B	50	3	4	6	5	8
C	95	4	3	5	9	10
D	100	3	4	12	5	13

For illustrative purposes Figure 8 provides Station A (0th percentile) daily coordinate difference time series, Figure 9 provides Station B (50th percentile) daily coordinate difference time series, Figure 10 provides Station C (95th percentile) daily coordinate difference time series, and Figure 11 provides Station D (100th percentile) daily coordinate difference time series. A number of interesting phenomena can be seeing in theses time series. Daily outliers, especially in the up component can be observed, even in the "best" results. Biases in the up component for the 95th and 100th percentile sites can be seen, but horizontal results are comparable to the 0th and 50th percentile sites. And of most consequence to the present study, small, but noticeable trends can be seen in the horizontal components of some of the sites. This last issue will be further investigated in Section 3 (reference station monitoring).

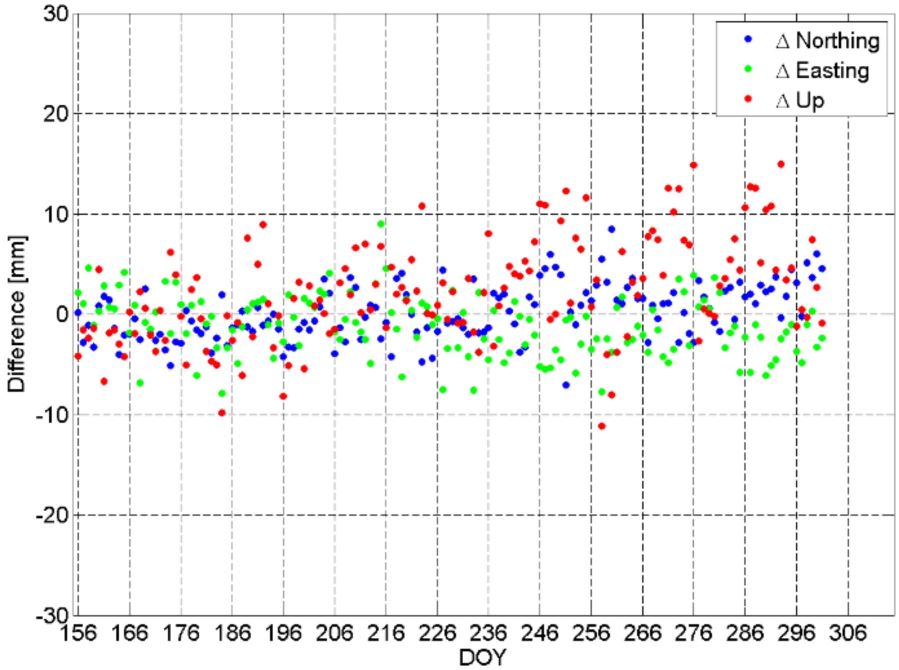


Figure 8: Station A (0th percentile) daily coordinate difference time series.

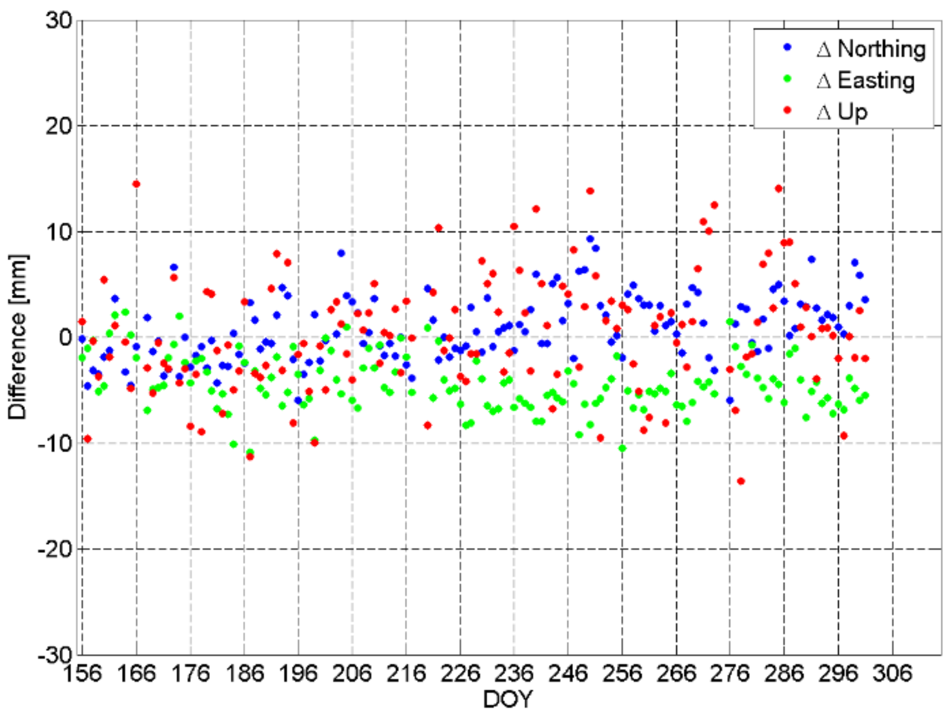


Figure 9: Station B (50th percentile) daily coordinate difference time series.

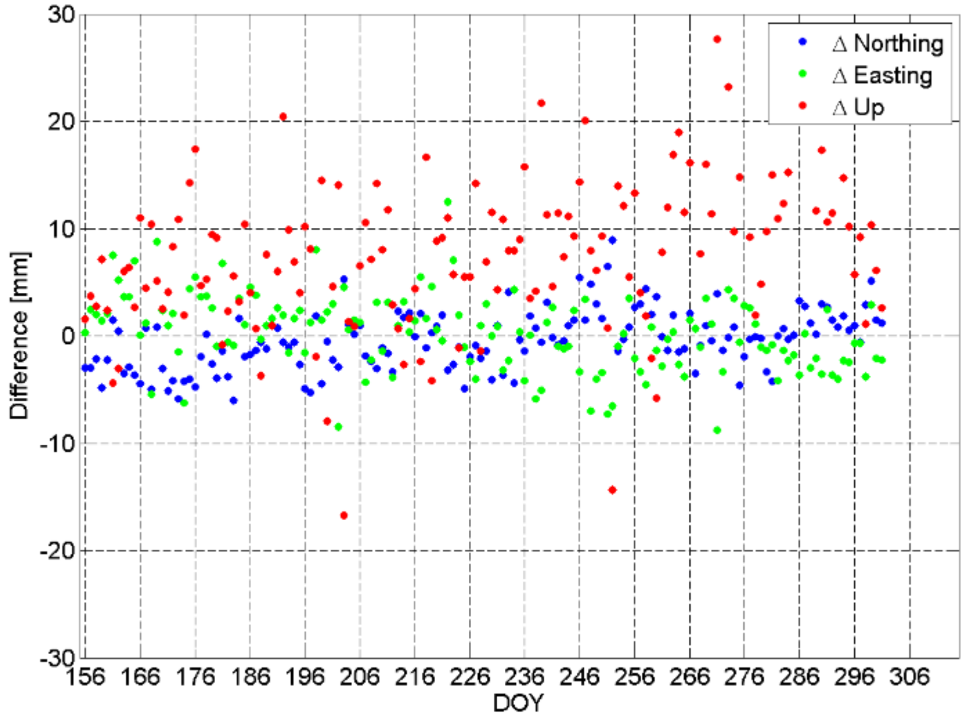


Figure 10: Station C (95th percentile) daily coordinate difference time series.

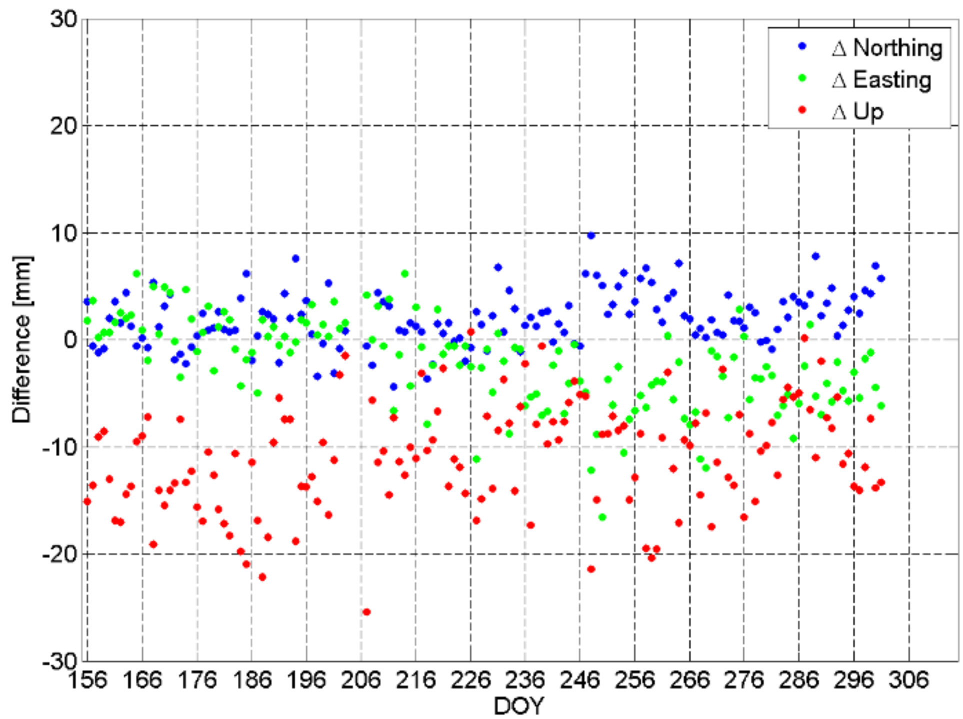


Figure 11: Station D (100th percentile) daily coordinate difference time series.

2.2.4 Recommendations

RECOMMENDATION 2: Given that daily static PPP processing of NRTK reference station measurements produce few millimetre-level horizontal coordinate differences with respect to relative positioning weekly averages, and that weekly averaging of daily PPP results further reduces these differences, it is recommended that for new sites, that the weighted average of one week of daily PPP-determined coordinates can be used for the initial reference station coordinates. To provide uniformity, all service providers can use the NRCan on-line PPP processor, CSRS-PPP.

2.3 Integration by Means of Network Baseline Processing

The main objective of this task is to integrate the RTK network stations into the existing reference stations or an existing control network, i.e., the Canadian Base Network (CBN) or the provincial control network.

The baseline vectors connected to a network RTK station, if the station does not belong to the existing control network, will also be determined with respect to the nearest stations in the provincial network by using the Bernese GPS data processing software. The derived baselines can be used in an integrated network adjustment to determine potential biases among the fixed stations, measurement outliers and then coordinates of these network RTK stations.

Two situations need to be considered in the network integration process:

1) The integration of the entire RTK GPS network into the CBN and the provincial network, and
2) The integration of new RTK GPS network stations into the existing RTK GPS networks.

In situation 1, a two-stage procedure is proposed to integrate the stations of a RTK GPS network into the provincial network:

Stage 1: Determine the maximum number of independent baselines one by one, which will be used as pseudo-measurements in a network adjustment.

Stage 2: Introduce the network adjustment using the baseline measurements, which normally consists of two steps: 1) The minimum constrained or free network adjustment with the available baselines as pseudo-measurements derived from the raw data at all of the stations; and 2) The generic parametric adjustment by fixing the stations which belong to the provincial network.

In situation 2, a similar procedure as for situation 1 can be applied. However, the choice has to be made as to whether only the coordinates of the new stations or the coordinates of all of the RTK GPS network stations are treated as unknown parameters.

Before the network integration process, three questions should be addressed:

1. What is the average separation among the stations in provincial network?
2. Will one need to set up GPS receivers to log the raw data for integration?
3. Should we focus on ACPs / CORS?

These questions will be answered in Section 2.3.1.

Certain software, e.g., the Bernese GNSS Software in this case, can process raw GPS data from multiple stations as a network directly day-by-day (or perhaps week-by-week). In this case, it is necessary to study how to appropriately combine the individual daily or weekly coordinates.

However, a general problem exists with an RTK GPS network: no redundant baseline measurements are available if the entire network is treated as a free network or an independent network only with one fixed station, where all baselines are derived from raw data acquired simultaneously over the same time duration. Even with stations from a provincial network fixed in step 2 above, one still cannot obtain enough redundant baseline measurements, because the number of fixed stations is normally much smaller than the number of RTK network stations. Only if one wants to densify the individual RTK network stations using the available provincial network stations as fixed control, may one have the possibility to perform error analysis. However, the resulting average baseline length using this approach may be relatively long.

How to construct a GPS baseline network to enable appropriate error analysis remains a challenge, which will be further studied in the near future. The proposed two-stage procedure as the general integration strategy will be described in detail in the following subsections.

2.3.1 Network Baseline GPS Data Processing

Data from GPS stations in the Canadian Active Control System (CACS) were used to integrate new stations into the existing provincial network. CACS was created to improve the precision and efficiency of GPS positioning in Canada and to provide easy access to the Canadian Spatial Reference System (CSRS). CACS consists of numerous ACP or CORS tracking stations, which are equipped with a high precision, dual-frequency GNSS receiver. These ACPs are distributed across Canada, and several local provincial ACPs were selected. The IGS08 reference frame and CACS IGS08 coordinates were used for the five ACPs used: ALGO, NRC1, PARY, GODR, PWEL and KNGS (see Figure 12).

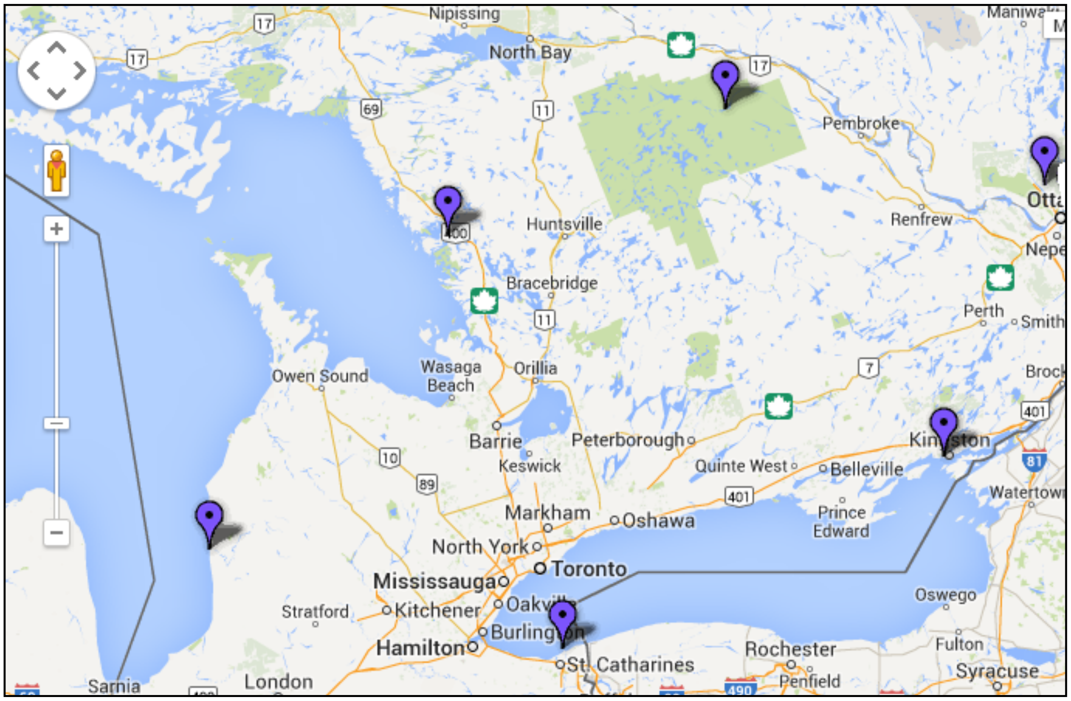


Figure 12: Six ACPs in southern Ontario used in this study.

The coordinates of the ACPs are based on the IGS08 coordinates system at epoch 2005 (2005.00). Their velocities are applied in X, Y, Z directions for their movement for the current sessions (current dates). For example, the published IGS coordinates for ALGO are calculated based on Table 4. These velocity corrections can be extrapolated to a given epoch. The computed coordinates of the station at that epoch are used as the reference coordinates.

Table 4: IGS08 position and velocity for ALGO at epoch 2005.0 (SOPAC, 2013).

X (m)	918129.374
Y (m)	-4346071.263
Z (m)	4561977.857
Latitude	45 57 20.99141 N
Longitude	078 04 16.92513 W
Ellipsoid height (m)	200.910
VX (m/yr)	-0.0158
VY (m/yr)	-0.0041
VZ (m/yr)	0.0042
Northward (m/yr)	0.0024
Eastward (m/yr)	-0.0163
Upward (m/yr)	0.0035

In this project, the basic network adjustment was performed for three service providers' RTK networks in southern Ontario: Leica, Topcon and Cansel. Table 5 provides metadata for these RTK networks. From Table 5, it can be seen that the observation data used from network stations were 24 hours long, day after day for 21 weeks (GPS weeks 1639-1659 in 2011).

Table 5: Names, number of stations, and observation periods for RTK networks studied.

Name of service provider	Number of stations	Time period of observation data	Number of weeks
Leica	56	24 hours	21 weeks
Topcon	35	24 hours	21 weeks
Cansel	53	24 hours	21 weeks

The basic procedure and concepts of GPS network baseline processing by using Bernese GPS software is described below. Before the introduction of GPS network baseline processing, the three questions in Section 2.3 will be revisited.

Two major factors which affect the performance of RTK networks are baseline lengths (distance between the reference stations) and network configuration (geometric distribution and number of reference stations). It is well known that the accuracy of RTK positioning is affected by distance-dependent errors, because their correlation decreases with the increase in baseline lengths. For optimum RTK network performance, the baseline lengths among reference stations should range from 20 km to 100 km. The average separation among ACPs of CACS in Ontario is beyond 100 km, and this suggests that the additional new RTK reference stations should be integrated to the existing provincial network in order to improve the accuracy. However, most of the RTK network stations are located among the existing control stations inside or within their geometric network, so that a densification network is constructed for the RTK network stations. Hence, the baseline lengths will be shorter than the baseline lengths among the existing control stations.

The network integration process will be performed through post-processing of GPS reference station data. This situation indicates that a user does not need to set up GPS receiver to log the raw data for integration purpose. The federal Active Control Points were selected to integrate these network RTK providers' reference stations to the existing network. Any external conflicts that may exist among these stations may introduce biases to these RTK networks. It is important to check the conflicts before the network integration process.

The two situations mentioned in the above section are similar. The only difference between them is whether only the coordinates of the new stations or the coordinates of all of the RTK GPS stations are treated as unknown parameters. In the first stage of the proposed procedure, the maximum number of independent baselines are determined that will be used as pseudo-measurements in the network adjustment. In the second stage, the network adjustment is introduced using all of the baseline measurements. At this stage, the minimum constraint or free network adjustment is first performed without fixing any or only one ACP, or a control station within the provincial control network. Then, a generic parametric adjustment is performed by fixing all of the control stations – either the ACPs or the stations that belong to the provincial control network.

The reason of performing a minimum constraint adjustment or a free network adjustment before the generic parametric adjustment is to produce a solution without introducing any external constraints due to the redundant initial data, i.e., the fixed control stations. The minimum constraint adjustment method also ensures no statistically significant internal conflict among the used baseline measurements. This solution can assist in detecting any possible measurement outliers. Any possible conflict among the existing control stations may be identified based on the solution from a minimum constraint or a free network adjustment.

Version 5.1 of the Bernese GNSS Software (Bernese, 2013) was used to process the raw GPS measurements in this project. The Bernese GNSS Software is a sophisticated tool, which has the highest quality standards of Global Navigation Satellite Systems (GNSS) data processing. It uses double-difference as basic observables but only the single-differences are stored in output files. Usually, only the phase single-differences are used for further computations. The derived baseline vectors of network RTK stations can be used in an integrated network adjustment. Since a network consists of multiple options of maximum independent baselines, the baseline selection and formation strategies will be determined first.

The current "session" represents a 24 hour period for the selected date. In order to determine the maximum number of independent baselines, a baseline selection algorithm known as the maximum path method is used, which introduces the "maximum flag" concept to select a group of the appropriate baselines to form a network. Assume there are m receivers in the current session, which means there are m zero-difference measurements to each satellite and $m-1$ maximum independent baselines available at each epoch. The algorithm starts to order all possible baselines according to a user-defined criterion such as baseline lengths or the number of the available single-difference observables. Then, all the active receivers in the current session will receive the initial flag 0. The optimum set of baselines will be selected. These two receivers of that baseline will receive flag 1, and the variable "maximum flag" will be set to 1. The algorithm proceeds to the next baseline and checks the flag number of each station of the second baseline. If one station has flag 0 and the other 1, both flags will be set to 1 and the "maximum flag" remains 1. The algorithm proceeds to the next baseline again. This procedure is repeated until $m-1$ independent baselines have been formed.

The Bernese software provides a sophisticated baseline formation function, which is called the "observation baseline strategy". According to this strategy, baselines are created by taking into account the number of common observations for the associated stations. A set of baselines with maximum common observations is chosen from all possible combinations. Then, the software automatically generates all the baselines.

During GPS baselines processing, correlations within or among the baselines also need to be considered. In the processing, all correlations within baselines and between baselines, as well as between different frequencies and linear combinations are handled correctly by Bernese.

2.3.2 Coordinate Adjustment

In order to estimate the coordinates of each RTK network station from the processed baseline measurements, the authors have used both the Bernese GNSS Software and have developed a baseline adjustment utility called RTKNetworkAnalysis (described in Section 3.3). This section discusses these two different coordinate adjustment methods in two subsections, respectively. The Topcon RTK network was chosen to be the studying network, which consists of 42 GPS stations inclusive of 5 ACP stations (Figure 13).

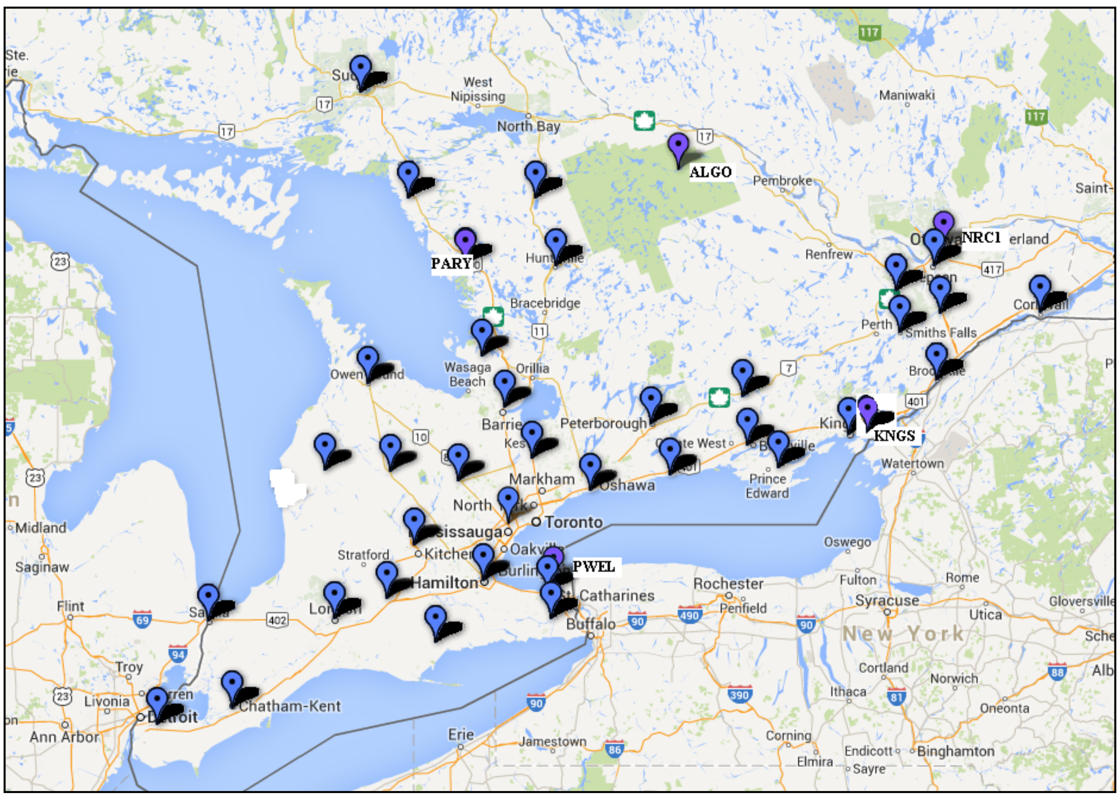


Figure 13: Topcon network with ACPs.

In the first subsection, the Bernese GNSS software is used to perform both a minimum constrained adjustment and a generic parametric adjustment to obtain all 148 daily solutions. The second subsection shows one adjustment performed using the RTKNetworkAnalysis utility and the comparison between Bernese solutions and utility results.

2.3.2.1 Network Adjustment Using Bernese GNSS Software

Bernese data processing produced the adjusted coordinates for each RTK station by using the minimum constrained adjustment technique to check the station behaviour through 148 days. Then all control stations were fixed to perform network integration process. The fixed stations for each RTK network were selected according to the following criterion:

1) All ACPs locate in southern Ontario.
2) In minimum constrained adjustment, each selected ACP close to the centre of the RTK network.
3) The longest separation between selected ACPs and service providers' reference stations should not exceed 100 km.

The Bernese GNSS Software can directly provide the daily solution for each of the stations. A user can decide how to combine those individual daily solutions to coordinate the RTK network stations, especially how much data are necessary and if any abnormal behaviour exists in the used data. However, the accuracy provided from the daily solution of a network as a minimum constraint or free network is the internal accuracy, because there are no redundant baseline measurements available due to the particularity of the simultaneously logged data from all of the stations. Only redundant control stations can bring external constraints to generate misclosures. But the number of the redundant control stations is limited, so one can use the multiple daily solutions to perform error analysis about the quality of the coordinates. The utility RTKNetworkAnalysis developed for this project can perform network adjustment using the baselines from different days, e.g., from two consecutive days. But one should choose different groups of the maximum independent baselines from different days in order to appropriately introduce geometrical conditions for error analysis.

However, only a few GPS data processing users have access to Bernese, as it is a financially costly choice and requires significant expertise to operate. Hence, any GPS commercial GPS software with the capability to derive high-quality long baseline solutions can be used in Stage 1. Then, the developed software tool RTKNetworkAnalysis from this project can perform the network adjustment using the baselines as measurements (refer to Section 3.3).

Sample time series plots for each service provider's network were generated. The following two figures show the sample plot of the daily coordinate variations of reference station OSHA from the Topcon network. Figure 14 shows the coordinate discrepancies from the minimum constrained adjustment with the fixed station KNGS. Figure 15 shows the coordinate variations on the daily basis by fixing all ACPs for the network integration.

From Figure 14, it can be seen that all biases were computed against the first day. The green, red and blue dots represent the east, up, and north components, respectively. This plot shows that all the biases range from several millimetres to 1.7 cm. The up component is, as expected, much noisier than the east and north component.

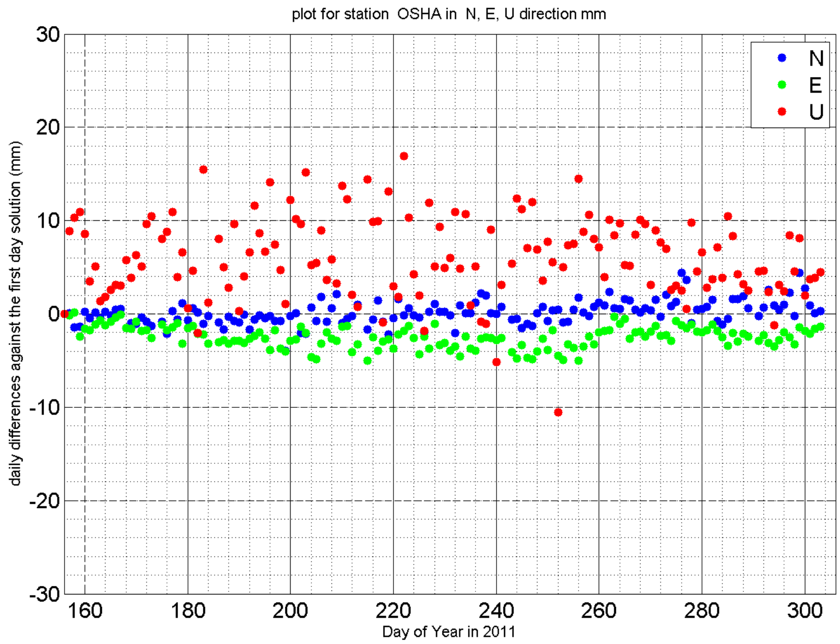


Figure 14: Daily coordinate variations at station OSHA after minimum constrained adjustment (fixing ACP KNGS).

After step one of Stage 2 was performed, a generic parametric adjustment was performed with six CPs were held fixed. The corresponding daily coordinate variations for station OSHA are given in Figure 15. In this network adjustment, all six ACPs were fixed during the adjustment. This step is designed to accomplish Stage 2 of situation 1.

By comparing Figure 14 and Figure 15, some differences in daily coordinate variations are observed. In Figure 14, the up and north components present noisier distribution from DOY of 200, 2011 to DOY of 280, 2011. In Figure 15, it shows some days between DOY 180, 2011 and DOY 220, 2011 have relatively big differences against same days present in Figure 14. These two figures show that the two different adjustment methods produce different results of daily coordinate variations. The differences are due to the fact that redundant control stations can bring external constraints to the adjustment.

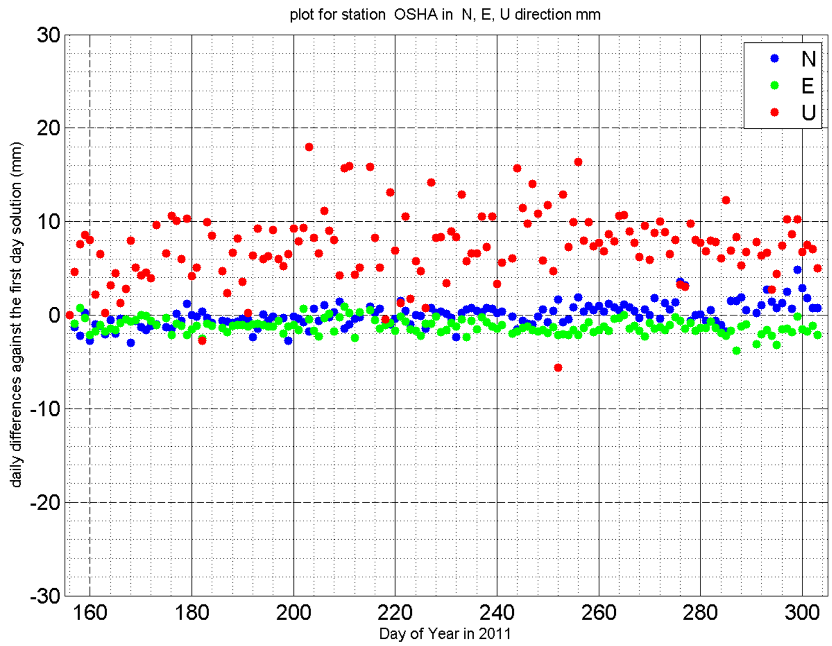


Figure 15: Daily coordinate variations at station OSHA by performing parametric adjustment by fixing all six ACPs.

Two days of Bernese solutions are provided below so as to be compared with the solutions from the RTKNetworkAnalysis utility in the next subsection. Table 6 lists the statistical information for the adjusted results from DOY 220 and DOY 221.

Table 6: General information of 2 days examples of Bernese processing.

DOY in 2011	DOY 220	DOY 221
The number of stations	40	42
The number of baselines	39	41
The number of the fixed control stations	5	5
A posterior of unit weight	0.0016 M	0.0017 M

The Bernese software was used to complete Stage 1 and Stage 2 without performing a free network adjustment. The major tasks of the Bernese software are to determine the maximum number of independent baselines and perform a minimal constraint adjustment in order to make sure no external conflicts exist between ACP stations. But the software defines its own concept of "free network adjustment" and it is different from what was discussed here, thus the RTKNetworkAnalysis software was developed. The purpose of developing the utility RTKNetworkAnalysis was to ensure that users can adjust the whole network by using the fully constrained or partially constrained free network adjustment technique and coordinate new stations to the existing network as well. Users may not require any training or advanced knowledge to use this utility, which makes it a sophisticated and user-friendly GPS RTK network adjustment tool.

2.3.2.2 Network Adjustment Using RTKNetworkAnalysis Software Utility

This subsection first focuses on network adjustment using the developed software utility RTKNetworkAnalysis. Then, the comparison between the results from Bernese GNSS Software and this utility is given.

During GPS data processing, the minimum constraint adjustment technique or the free network adjustment method is first implemented. This adjustment technique can produce "adjusted" coordinates for all GPS stations. In the minimum constrained adjustment method, only one control point (or ACP) is held fixed in order to determine the coordinates of the rest of points. If the network of the observed lines is adjusted with minimum constraints, then the point error ellipses tend to get larger the further the point is from the fixed point. The positional accuracies of the stations will vary with the selection of the fixed point in the minimum constraint network adjustment.

The free network adjustment method is another adjustment strategy for station monitoring. Free network conditions are optimal in defining the geodetic datum with a minimum number of constraints, but without fixing or constraining particular site coordinates, in which the accuracy datum is based on the weighted geometrical centre of the network. In normal least squares adjustments, it must hold that a certain number of parameters be "fixed" so that a solution is possible. The "free network" adjustment is a special solution technique, where no points are held fixed, but the network centre. A free network datum is also called "minimum trace datum" or "inner constraint datum", which allows a solution without having to fix any coordinate parameters to meet the rank defect of the network. This adjustment technique will also generate a cofactor matrix with the smallest standard deviations and error ellipses or ellipsoids. The baseline adjustment software utility RTKNetworkAnalysis, described in Section 3.3, has been developed using the free network adjustment concept.

Two example results are provided from the RTKNetworkAnalysis utility to further explain the procedures of coordinate adjustment by using the free network adjustment method and how to coordinate new stations within an existing network.

Table 7 illustrates the basic information of this network and the date when measurements were collected. The example network consists of 41 stations. As the first stage, the maximum number of independent baselines for these two days were determined using Bernese. The reference coordinates were determined at the date 05 June 2011 and the initial adjusted coordinates and covariance matrices were obtained by performing a minimum constrained adjustment (station KNGS was fixed) with Bernese.

From the measurements logged on day 220 and day 221, 77 independent baselines were generated. The baseline measurements are given in Appendix A. With the same raw data, the maximum number of independent baselines measurements and adjusted coordinates for RTK network stations were derived using the Bernese software. They are treated as input values of RTKNetworkAnalysis utility.

Table 7: General information of network in Example 1 and 2.

Network Name	Topcon
Number of stations	42
Coordinate Datum	WGS84
Epoch of datum	2000.00
Date of reference coordinates	DOY 156, 2011
Dates of measurement collection	DOYs 220 and 221, 2011
Type of the adjustment	Minimum constrained

In the first processing example illustrated below, the full free network adjustment method was chosen to process the baselines as a network, named Example 1. In this case, no station is fixed and all stations are equally weighted. Thus, no external constraints would affect the adjustment process.

The input text file and the adjustment results are given in Appendix A. From the results, it can be seen that the standard deviation in north and east are significant smaller than in vertical. Accuracies for both horizontal and vertical components are at the millimetre-level. This step can process multiple days' data in order to detect any possible "misbehaving" stations within the network, since no stations were fixed or constrained and all stations were treated equally in terms of a priori coordinate weights, thus no external constraints were applied. The objective of this example demonstrates the basic features of the free network adjustment.

An overview of Example 1 is given in Table 8. From the baseline residuals (see Appendix A), one can identify the two baselines (one is between KINC to MOUN and the other is HAMI to OSHA) as outliers. For outlier baseline KINC to MOUN, the standardized residual in the X component reached -3.5 mm. For HAMI to OSHA, the standardized residuals in the Y and Z components reached 3.3 mm and -3.4 mm, respectively.

A careful treatment was employed to deal with potential outlier baseline measurements. The baseline with largest standardized residuals is to be first removed. After the baseline from KINC to MOUN was removed as an outlier, the baseline network was readjusted (Appendix A). The biggest standardized residual was -3.7 mm (for the baseline HAMI to OSHA).

These two outliers were removed from baseline measurements list sequentially. Table 8 illustrates the general information of free network adjustment results from Example 1 and its outliers removing process (3 cases). From the table, it can be seen that the standard deviation of unit weight and total redundancies are decreased without the presence of outlier baselines.

Table 8: Example 1 – overview information with and without outlier baseline.

	Case (1)	Case (2)	Case (3)
Number of stations	42	42	42
Number of baselines	77	76	75
Number of unknowns	126	126	126
Total redundancy	108	105	102
Rank deficiency	3	3	3
Standard deviation of unit weight	1.8102	1.7029	1.4953
Baseline removed	none	KINC to MOUN	HAMI to OSHA

Figure 16 demonstrates the two days baseline formation strategies. The red lines represent the shortest baseline formation method for DOY 220, 2011, and the blue lines represent the pre-defined baseline formation for DOY 221, 2011. This solution was accepted for further network adjustment by fixing all of the CBN stations as shown in Example 2 below.

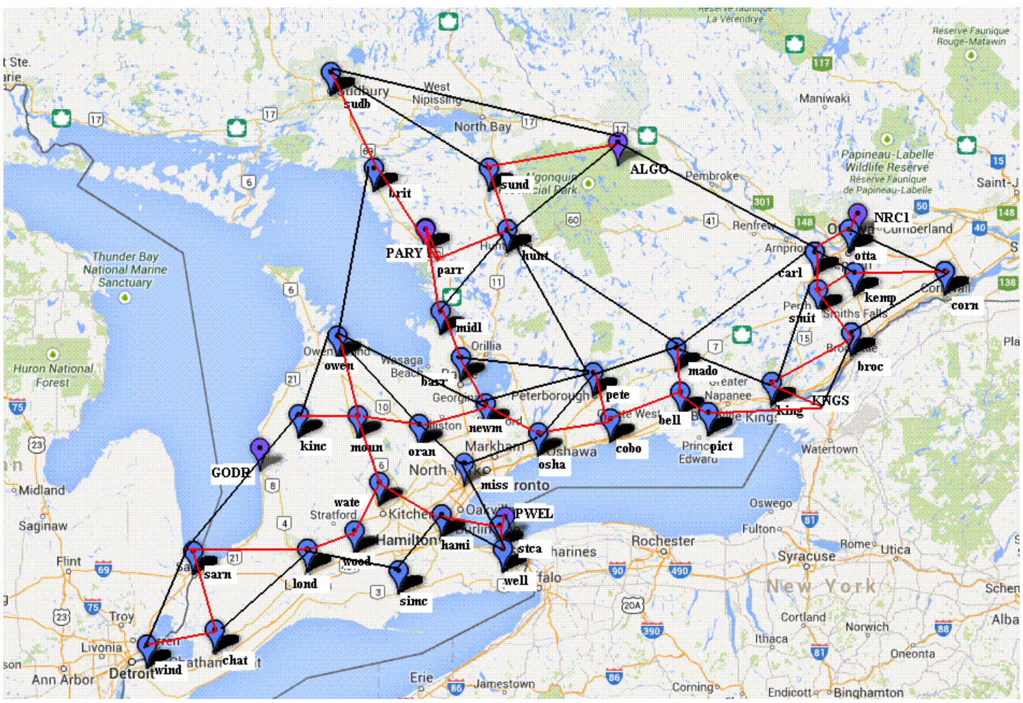


Figure 16: Baseline formations for two-day scenario.

The objective of Example 2 was to simulate a situation of how to coordinate new stations under the existing control stations. On the basis of acceptance of the 75 baseline measurements from Example 1, all of the five ACP stations were held fixed (stations ALGO, GODR, NRC1, PWEL and KNGS) and the coordinates of the other 37 RTK network stations were treated as unknowns and were therefore estimated As shown in the results, the largest standardized measurement residual was -2.42 mm in Z direction with the baseline measurement from MIDL to PARY. Therefore, no outliers were rejected.

Table 9 illustrates the basic statistical information from the processing results of Example

2.

Table 9: Example 2 – statistical information.

Number of stations	42
Number of the fixed control stations	5
Number of baselines	75
Number of unknowns	111
Total redundancy	111
Standard deviation of unit weight	1.4845

The network in Example 2 was also adjusted using the Bernese software. Then a comparison between the results from the utility RTKNetworkAnalysis and the Bernese software was made. Table 10 shows the differences between the adjusted coordinates from the utility and the day 1, day 2 and two days averaged results derived using Bernese GNSS. All 5 ACPs were held fixed during the process.

From this table, it can be seen that the differences are at the millimetre to sub-millimetre level. The differences between single day Bernese results and utility results are much larger. The reason for these large discrepancies is that the Bernese GNSS only can produce single day network adjustment results, while the RTKNetworkAnalysis utility can combine two days baseline measurements to produce combined network adjustment results. This table also shows the Bernese two-day averaged values are closer to the values derived from utility. This explains that the utility's two days combined solutions are averaged network results for two days. The small discrepancies are due to the fact that Bernese single day solutions do not have enough external constraint to generate misclosures. The above two example demonstrate the general procedure of GPS network integration process by using different approaches.

Table 10: Discrepancy between Bernese results and utility results. Units in mm.

Station	Dx (day 1)	Dy (day 1)	Dz (day 1)	Dx (day 2)	Dy (day 2)	Dz (day 2)	Dx (2days)	Dy (2 days)	Dz (2 days)
BARR	-0.9	1.7	0.4	-0.5	4.5	-3.6	-0.7	3.1	-1.6
BELL	0.8	3.8	0.3	0.3	-1.6	-0.1	0.5	1.1	0.1
BRIT	0.0	1.1	-1.4	-0.2	3.6	-2.6	-0.1	2.3	-2.0
BROC	-0.8	-0.7	2.2	-0.4	0.1	-0.2	-0.6	-0.3	1.0
CARL	-0.5	0.2	1.6	0.0	-3.5	2.7	-0.3	-1.6	2.2
CHAT	0.4	-1.1	2.0	-0.1	9.5	-7.0	0.2	4.2	-2.5
COBO	-1.4	0.5	1.0	1.2	-1.0	-0.7	-0.1	-0.3	0.2
CORN	-0.6	0.1	0.2	-0.2	3.6	-2.2	-0.4	1.8	-1.0
HAMI	0.3	-9.2	9.7	-0.1	1.7	-0.3	0.1	-3.7	4.7
HUNT	0.0	0.5	0.1	0.3	3.0	-3.0	0.1	1.7	-1.5
KEMP	0.0	-0.8	3.0	-1.0	1.6	-1.9	-0.5	0.4	0.5
KINC	3.7	3.5	2.9	0.2	1.3	-0.5	1.9	2.4	1.2
KING	0.3	2.0	1.2	-0.4	0.2	-1.1	-0.1	1.1	0.0
LOND	-0.8	1.5	0.7	-0.1	3.8	-3.1	-0.5	2.7	-1.2
MADO	-0.4	3.5	-2.7	0.8	-3.0	2.4	0.2	0.3	-0.1
MIDL	-1.2	1.8	-0.5	1.5	-0.2	0.8	0.1	0.8	0.1
MOUN	-0.4	-2.3	2.8	0.3	2.4	-1.0	-0.1	0.0	0.9
NEWM	-0.1	1.2	-0.6	-0.3	4.3	-2.5	-0.2	2.7	-1.6
ORAN	0.5	1.0	1.0	-0.2	3.4	-2.1	0.1	2.2	-0.5
OSHA	0.1	2.2	-0.4	-0.3	-3.0	1.4	-0.1	-0.4	0.5
OTTA	0.2	2.4	-0.3	0.0	-1.9	1.2	0.1	0.2	0.5
OWEN	-0.5	2.0	-0.2	1.4	0.7	-0.1	0.5	1.3	-0.1
PARR	-0.9	3.0	-0.3	0.6	3.0	-3.1	-0.1	3.0	-1.7
PARY	-0.1	0.4	0.9	0.8	3.0	-3.0	0.4	1.7	-1.1
PETE	0.0	2.0	-0.5	1.2	-0.9	-0.5	0.6	0.5	-0.5
PICT	-0.6	0.4	1.0	0.1	0.3	-0.2	-0.3	0.4	0.4
SARN	-0.5	1.8	1.2	-0.2	5.8	-5.1	-0.4	3.8	-1.9
SMIT	0.2	5.2	-3.5	-0.5	-1.7	1.4	-0.1	1.7	-1.1
STCA	0.9	3.2	-1.7	0.0	0.2	1.2	0.4	1.7	-0.2
SUDB	0.0	-0.6	1.2	-0.5	5.0	-4.2	-0.2	2.2	-1.5
SUND	-0.4	0.6	0.1	0.4	0.6	-1.1	0.0	0.6	-0.5
WATE	-0.9	1.8	-0.6	-0.1	1.3	0.1	-0.5	1.6	-0.3
WELL	-0.9	1.7	0.1	1.0	0.0	2.0	0.1	0.9	1.1
WIND	-1.2	2.7	-1.4	0.2	8.5	-5.4	-0.5	5.6	-3.4
WOOD	-0.2	3.1	-1.8	0.1	1.9	-0.6	-0.1	2.5	-1.2

2.3.3 Effectiveness and Practicality of Method

In order to assess the effectiveness and practicality of the York Bernese RTK solutions, the results are compared with the NRCan RTK solutions and York PPP results. The objective of this section is to verify the correctness and consistency of York Bernese results.

2.3.3.1 Comparing the Bernese results with NRCan solutions

The GSD solutions serve as reference data to compare the York Bernese and PPP processing solutions against. The NRCan solutions are weekly averaged solutions and are labelled as corresponding week number for each station. Both the Bernese daily solutions and weekly averaged solutions are compared against the NRCan solutions. The biases calculated can indicate how well the York Bernese solutions are compatible with the NRCan solutions. An example using data from the station SARN, in Sarnia, is provided to check the biases between these two solutions.

Figure 17, Figure 18 and Figure 19 show the differences between station SARN daily solutions from the Leica, Cansel and Topcon network, respectively, and NRCan weekly solutions for the GPS week 1639 in the year 2011.

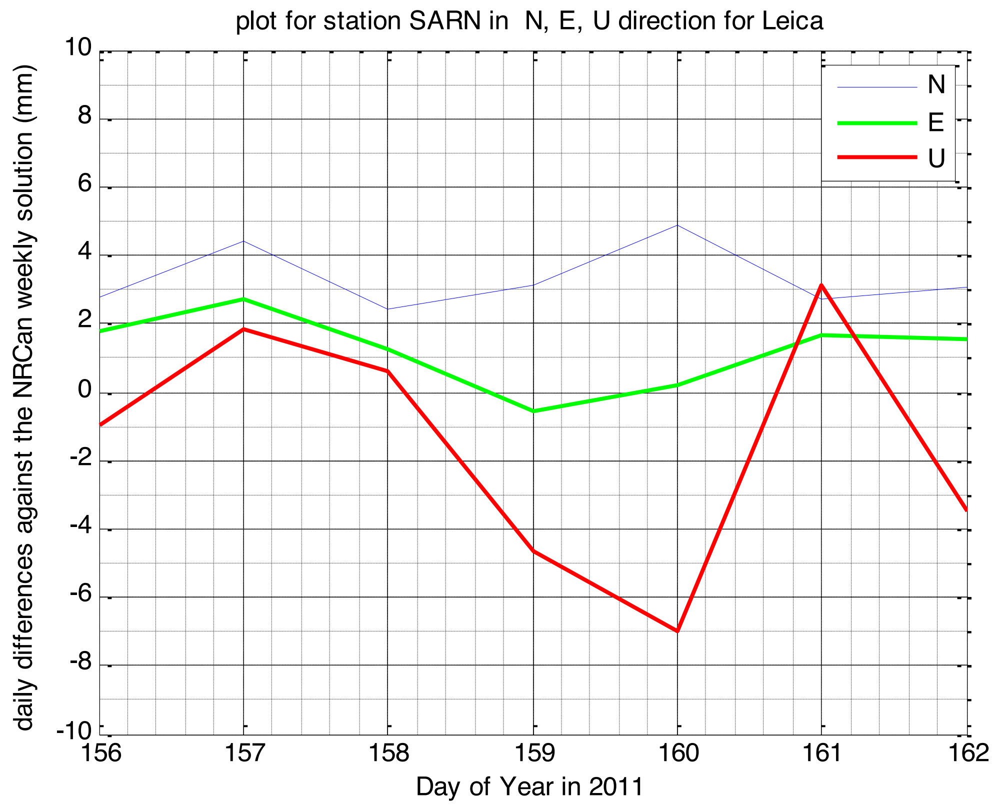


Figure 17: Differences between daily solutions and NRCan weekly solutions for Leica.

Table 11: Differences between Bernese daily solutions and NRCan weekly solutions for station SARN from Leica network. Units in mm.

component	Std	rms	Abs max	Mean
N	0.9	0.9	4.9	3.3
E	1.1	1.1	2.7	1.2
U	3.7	3.7	7.0	-1.5

Figure 18: Differences between daily solutions and NRCan weekly solutions for Cansel.

Table 12: Differences between Bernese daily solutions and NRCan weekly solutions for station SARN from Cansel network. Units in mm.

component	Std	rms	Abs max	Mean
N	1.7	1.7	5.0	-2.2
E	1.0	1.0	4.0	2.6
U	4.2	4.2	8.4	-1.2

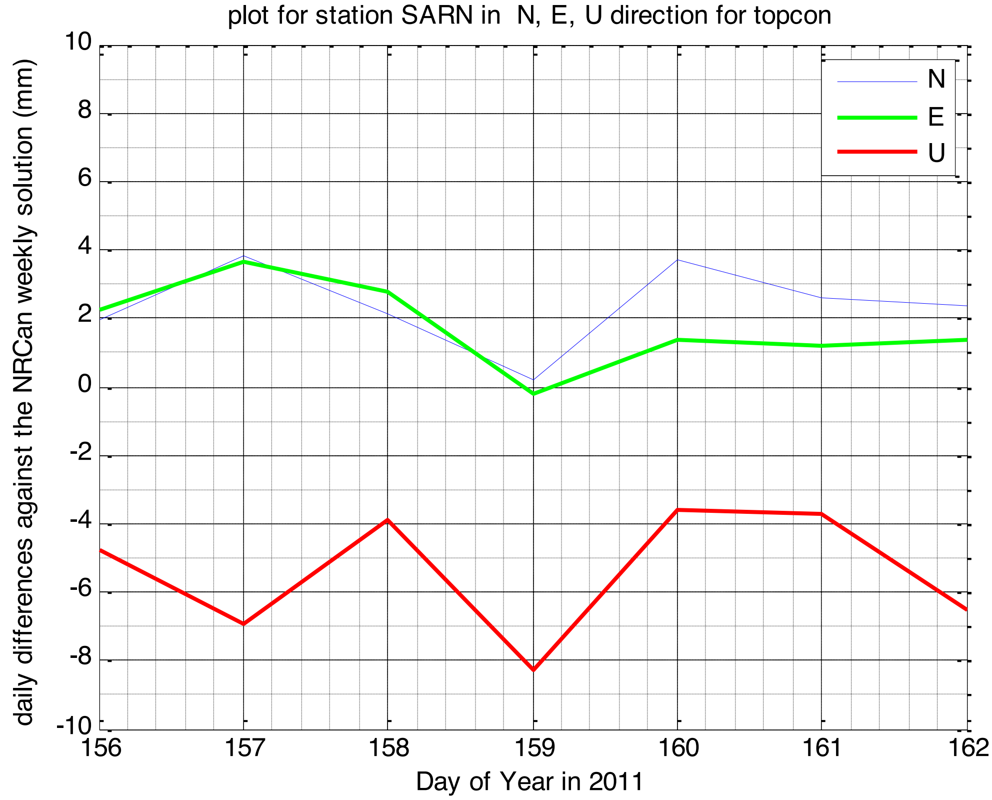


Figure 19: Differences between daily solutions and NRCan weekly solutions for Topcon.

Table 13: Differences between Bernese daily solutions and NRCan weekly solutions for station SARN from Topcon network. Units in mm.

component	Std	rms	Abs max	Mean
N	1.2	1.2	3.8	2.4
E	1.2	1.2	3.6	1.8
U	1.9	1.9	8.3	-5.4

Figure 17, Figure 18 and Figure 19 illustrate the differences between York Bernese daily solutions and NRCan weekly solutions for SARN station from the three networks' base stations. The figures show that the biases between York Bernese solutions and NRCan solutions are at the millimetre level for most days. The standard deviation and rms values in the up component are, as expected, higher than the values in the north and east components. From the standard deviation values, it also can be seen that station SARN from the Topcon network has overall better accuracy. By comparing the daily solutions from Bernese results and NRCan solutions, it can be verified that the York Bernese daily solutions are very close to the NRCan solutions, although the biases were calculated based on the differences between NRCan weekly solutions and Bernese daily solutions.

Next is a comparison of the Bernese averaged weekly solutions against the NRCan weekly solutions. In order to compare York Bernese solutions with NRCan weekly solutions, the York Bernese daily solutions combined by applying the weighted averaging method for each week. 10 weeks of data were used from week 1639 to 1648.

Figure 20, Figure 21 and Figure 22 illustrate the biases between the Bernese weekly solutions and NRCan solutions for the Leica, Cansel and Topcon networks at statin SARN. Table 14, Table 15 and Table 16 show the biases computed between York Bernese averaged weekly solutions and NRCan solutions for the three service providers' networks. As it can be seen from these figures and tables, the biases are within the few millimetre level. However, the overall biases in the Topcon network seem larger than those in the Leica and Cansel networks. These three plots share similar characteristics. It can be seen that the discrepancies are larger in the vertical direction and smaller in the horizontal direction. Overall the Bernese weekly solutions and NRCan solutions are very close to each other.

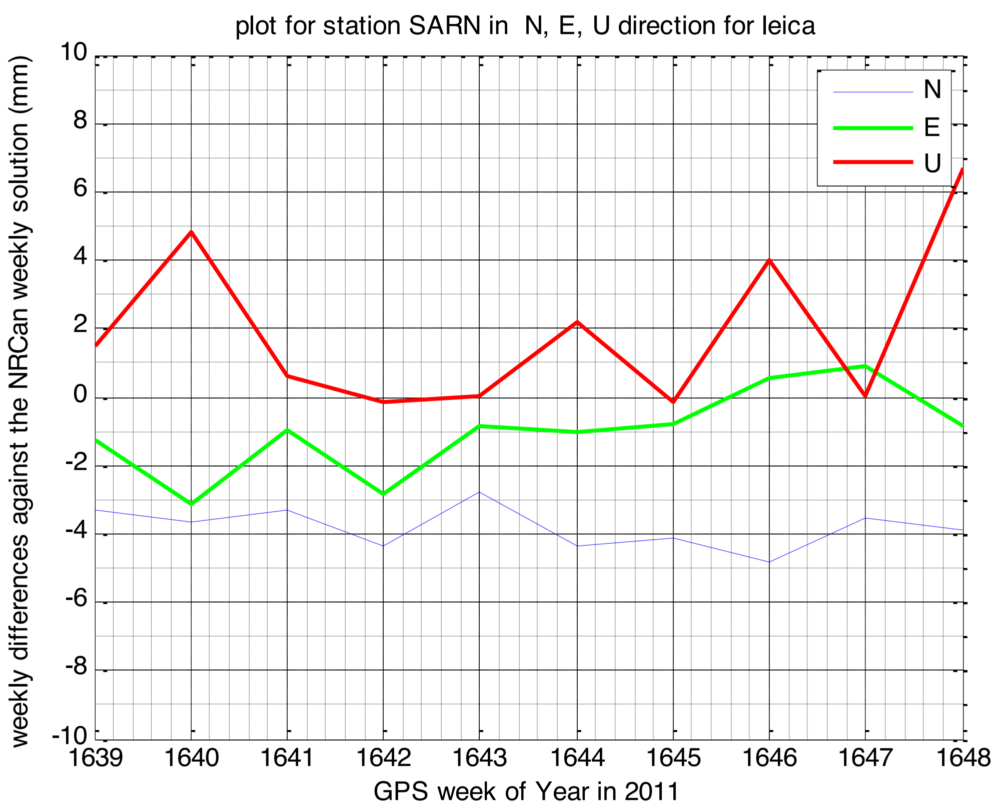


Figure 20: Differences between Bernese weekly solutions and NRCan weekly solutions for Leica.

Table 14: differences between Bernese weekly solutions and NRCan weekly solutions for station SARN from Leica network. Units in mm.

component	Std	rms	Abs max	Mean
N	0.6	0.6	4.8	-3.8
E	1.2	1.2	3.1	-1.0
U	2.4	2.4	6.7	2.0

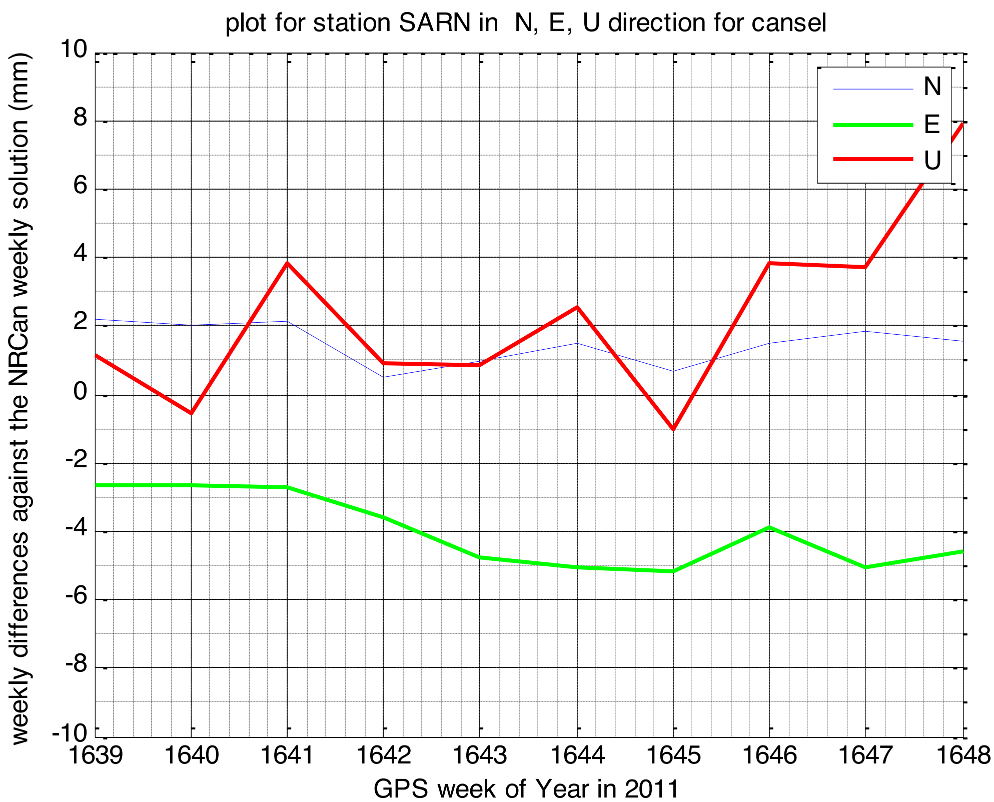


Figure 21: Differences between Bernese weekly solutions and NRCan weekly solutions for Cansel.

Table 15: differences between Bernese weekly solutions and NRCan weekly solutions for station SARN from Cansel network. Units in mm.

component	Std	rms	Abs max	Mean
N	0.6	0.6	2.2	1.5
E	1.0	1.0	5.2	-4.0
U	2.6	2.6	7.9	2.3

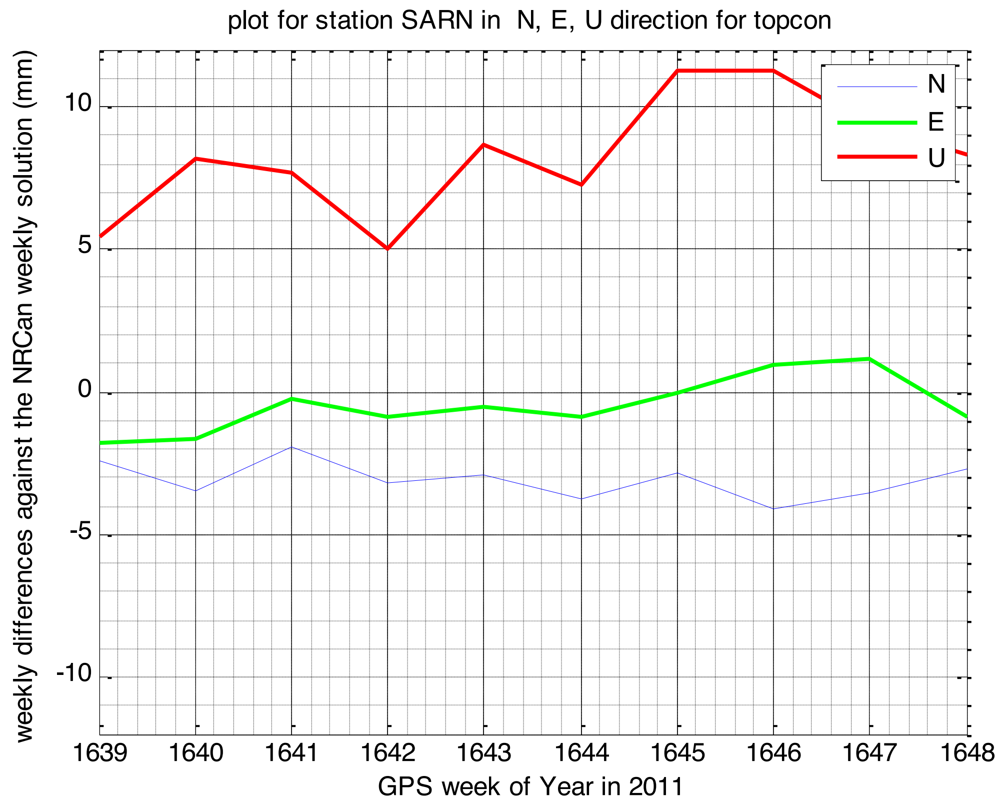


Figure 22: Differences between Bernese weekly solutions and NRCan's weekly solutions for Topcon.

Table 16: differences between Bernese weekly solutions and NRCan's weekly solutions for station SARN from Topcon network. Units in mm.

component	Std	rms	Abs max	Mean
N	0.6	0.6	4.1	-3.1
E	1.0	1.0	1.8	-0.5
U	2.1	2.1	11.3	8.2

Variations between the York Bernese and NRCan weekly solutions are further analysed. The following is the comparison between the Bernese weekly coordinate variations plot (Figure 23) and NRCan's weekly solutions plot for the Sarnia station from the Leica RTK network (Figure 24). From these figures, the general comparison between York Bernese solutions and NRCan solutions can be made to assess the potential discrepancies between them. It can be seen that the York Bernese weekly solutions have lower rms in the up and east components. The general trend in the weekly coordinate variations for the north, east and up components are similar for both solutions. Table 17 also shows the similar statistical information for York Bernese solution and NRCan solution. This comparison verifies that the differences between these two solutions is at the few millimetre-level.

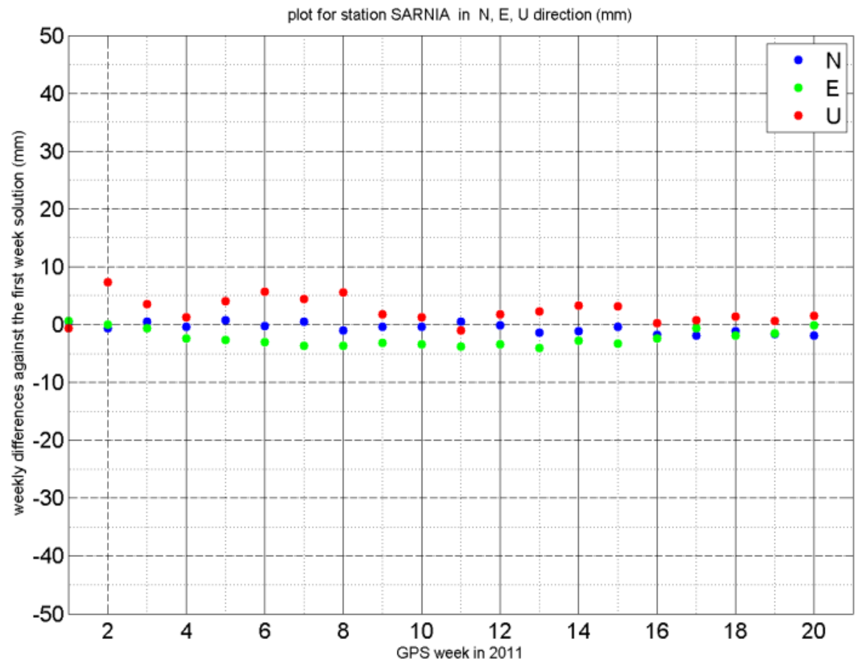


Figure 23: Bernese weekly coordinates variations SARN from Leica.

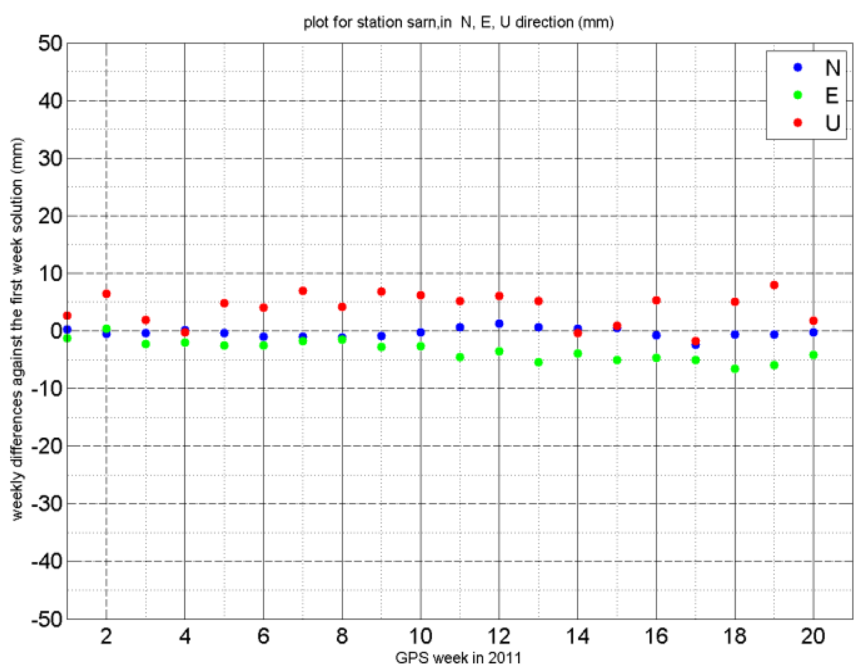


Figure 24: NRCan's weekly coordinates variations plot for SARN from Leica.

Table 17: Comparison between Bernese weekly solutions and NRCan solutions for station SARN from Leica network. *A* stands for Bernese solutions and *B* stands for NRCan weekly solutions. Units in mm.

Component	Mean		Std dev		rms		Max	
	A	B	A	B	A	B	A	B
N	-0.6	-0.3	0.9	0.8	1.0	0.9	1.9	2.4
E	-2.3	-3.4	1.4	1.8	2.7	3.8	4.0	6.6
U	2.4	4.0	2.2	2.8	3.2	4.8	7.4	8.0

Next is to compare weekly solutions of station SARN from the Cansel network in order to assess the discrepancy between York Bernese solutions and NRCan solutions. Figure 25, Figure 26 and Table 18 show that both solutions follow the similar trend except that the NRCan weekly solutions display more noisy results than York Bernese solutions. In both solutions, the east component and up component are significant more noisy than the north component. This comparison shows that York Bernese weekly solutions provide less noisy results when compare with the NRCan weekly solutions. The general trends for both solutions are similar.

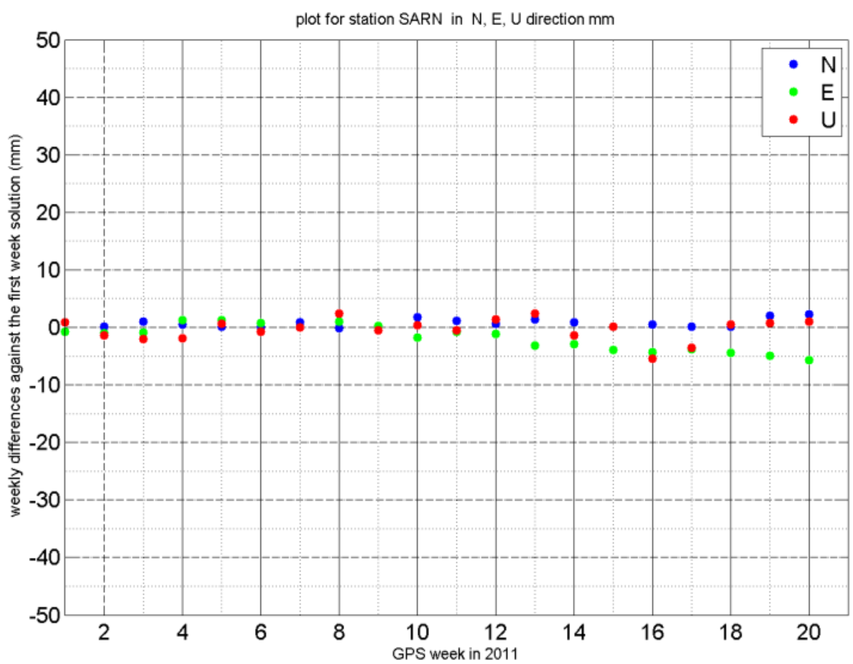


Figure 25: Bernese weekly coordinates variations for SARN from Cansel.

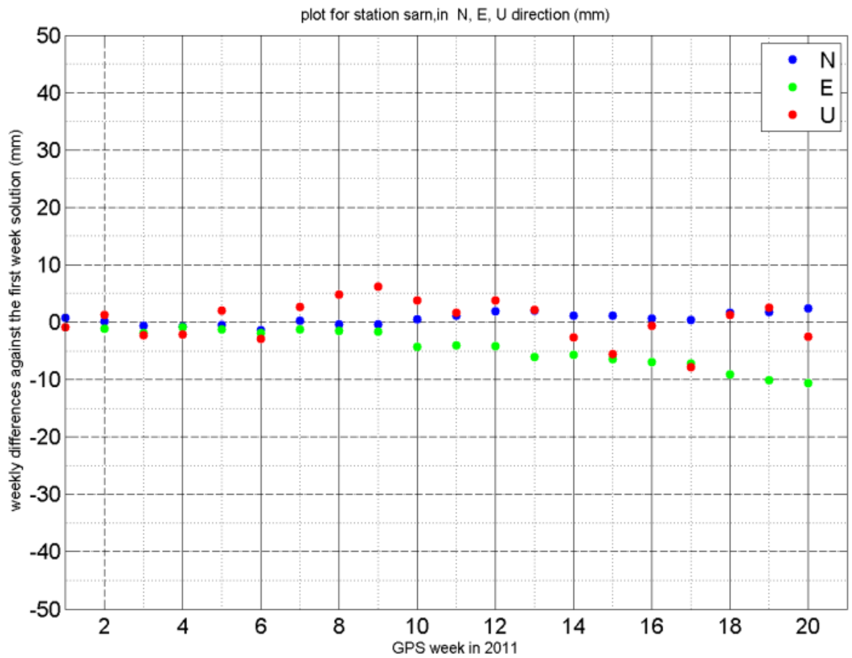


Figure 26: NRCan weekly coordinates variations plot for SARN from Cansel.

Table 18: The statistical information comparison between Bernese weekly solutions and NRCan solutions for station SARN from Cansel network. *A* stands for Bernese solutions and *B* stands for NRCan weekly solution. Units in mm.

Component	Mean		Std dev		rms		Max	
	A	B	A	B	A	B	A	B
N	0.7	0.6	0.7	1.0	1.0	1.2	2.3	2.3
E	-1.7	-4.4	2.2	3.3	2.8	5.4	5.7	10.6
U	-0.4	0.2	1.9	3.6	1.9	3.5	5.5	7.8

The last comparison was made based on SARN station from the Topcon network. Two weekly time series plots (Figure 27 and Figure 28) and their corresponding statistical information (Table 19) were generated as follows. These results indicate that the general trends from two solutions are slightly different. The discrepancy between York Bernese solutions and NRCan solutions may be due to the different fixed active control points and baseline formation strategy. The baseline formation strategy and fixed ACPs for the York Bernese solutions were mentioned before. The statistical information indicates that the east component in the NRCan weekly solutions is much noisier than the other York solutions. The north and up component statistics are very similar in both solutions.

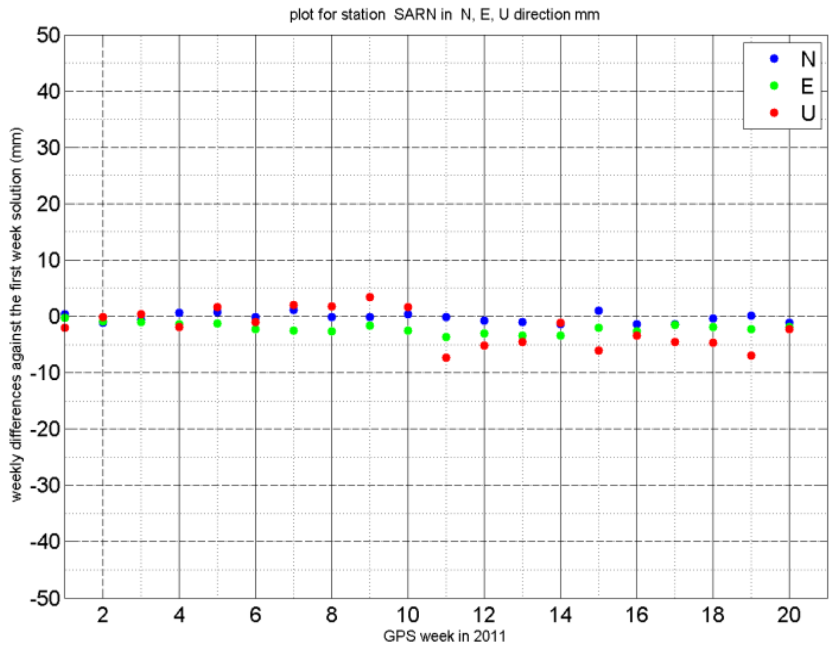


Figure 27: Bernese weekly coordinate variations for SARN from Topcon.

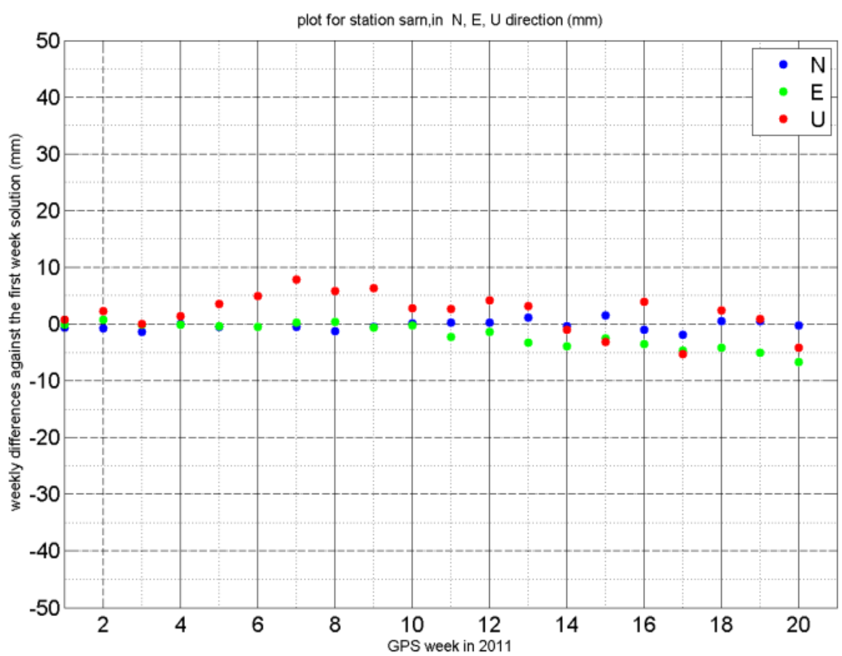


Figure 28: NRCan weekly coordinates variations plot for SARN from Topcon.

Table 19: The statistical information comparison between Bernese weekly solutions and NRCan solutions for station SARN from Topcon network. *A* stands for Bernese solutions and *B* stands for NRCan weekly solutions. Units in mm.

Component	Mean		Std dev		rms		Max	
	A	B	A	B	A	B	A	B
N	-0.3	-0.3	0.8	0.8	0.8	0.9	1.4	1.9
E	-2.1	-1.9	0.9	2.2	2.3	2.9	3.7	6.7
U	-2.0	2.0	3.2	3.4	3.7	3.9	7.3	7.9

2.3.3.2 Comparing the Bernese results with PPP results

In the first part of this section, the York Bernese solutions were compared with NRCan weekly solutions, which gives the user insight into the quality of the baseline processing results. Another comparison can be also made between the Bernese solutions and newly generated PPP solutions in order to check the discrepancy between these two solutions.

Figure 29, Figure 30 and Table 20 illustrate the daily differences between the York Bernese solutions and PPP solutions. Figure 29 shows the daily differences between these two solutions for station BAR2 from the Cansel network. From these figures, it can be seen that the differences range from a few millimetres to 1.5 cm in the north, east and up components. The up component is nosier than the north and east components. But the differences in the east components are the largest among these three.

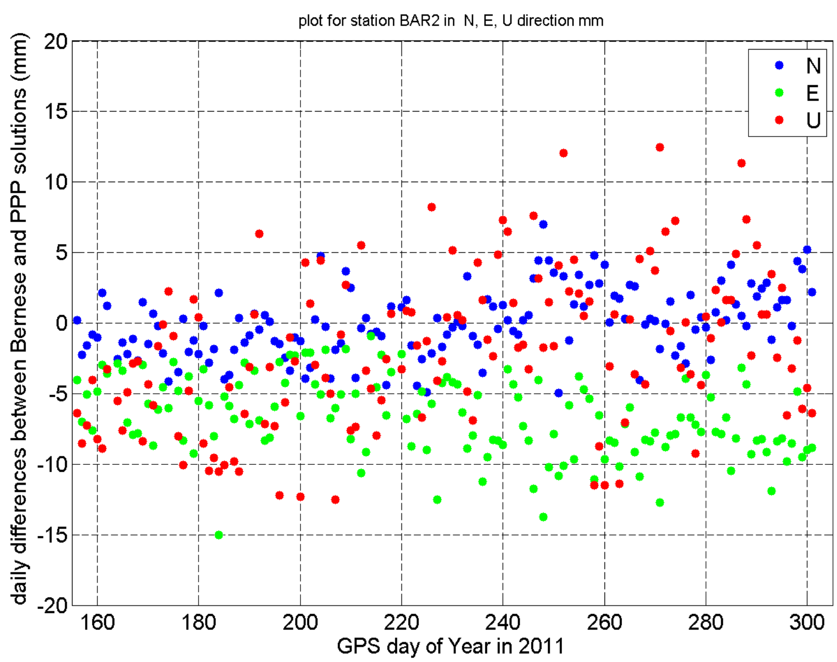


Figure 29: Daily differences between Bernese and PPP solutions for BAR2 from Cansel.

Figure 30 shows the differences between two different daily solutions for station AURO from the Cansel network and illustrates a similar trend as Figure 29. The east and up components are significantly nosier than the north component. These differences may be caused by phase centre offset. Also, quasi-linear trends can be seen in the time series, which may be related to differences in the point positioning and relative positioning reference frames.

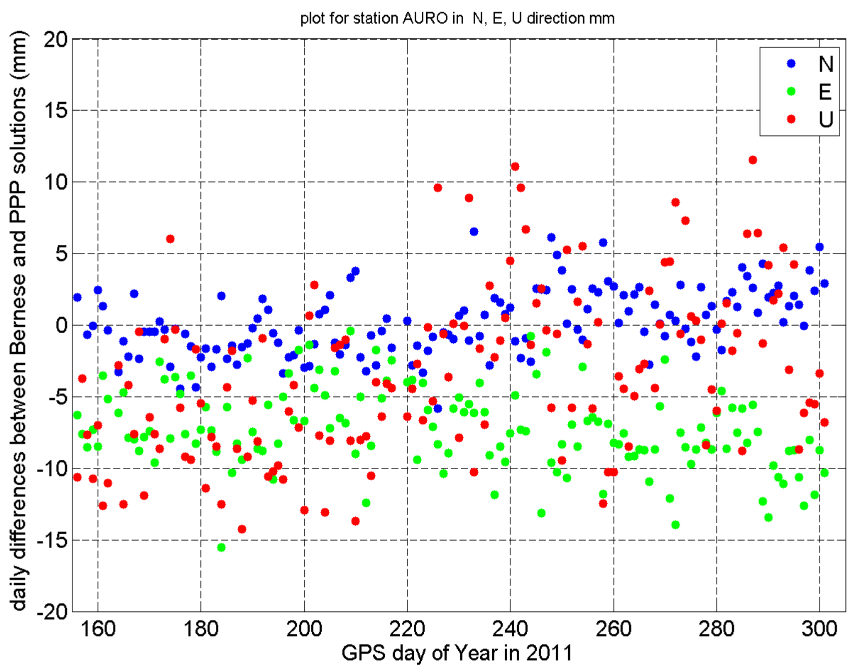


Figure 30: Daily differences between Bernese and PPP solutions for AURO from Cansel.

Table 20: The statistical information of the daily differences between Bernese and PPP solutions for BAR2 and AURO from Cansel. A stands for BAR2 and B stands for AURO. Units in mm.

Component	Mean		Std dev		rms		Max	
	A	B	A	B	A	B	A	B
N	0.0	0.2	2.4	2.3	2.4	2.3	7.0	6.6
E	-6.7	-7.3	2.8	2.9	7.2	7.8	15.0	15.6
U	-1.9	-3.5	5.4	5.8	5.7	6.7	12.5	14.2

Figure 31 shows the discrepancy between two solutions for station BARR from the Topcon network, where it can be seen that the differences are much larger for stations in this network. The differences range from a few millimetres to several centimetres. This phenomenon indicates that there is significant offset between Bernese baseline solutions and PPP solutions. The reason for this large discrepancy may be due to that the service provider did not report the antenna phase centre values in the IGS format used in the York PPP software, which could cause the large offsets in all directions in PPP solutions.

The Bernese baseline solutions were produced in the relative positioning technique that may cancel the antenna phase centre offsets.

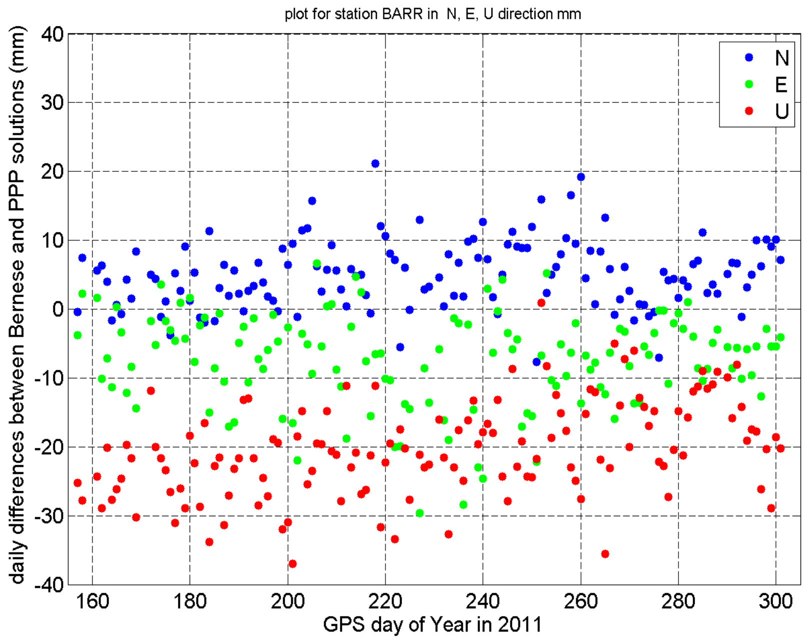


Figure 31: Daily differences between Bernese and PPP solutions for BARR from Topcon.

Figure 32 shows the differences for station BELL from the Topcon network. From this figure, it can be seen that the differences between these two solutions are smaller than the ones shown for station BARR. But the overall discrepancy is much larger than the ones from stations in the Cansel network. This phenomenon suggests that the provided Topcon station antenna metadata be reviewed.

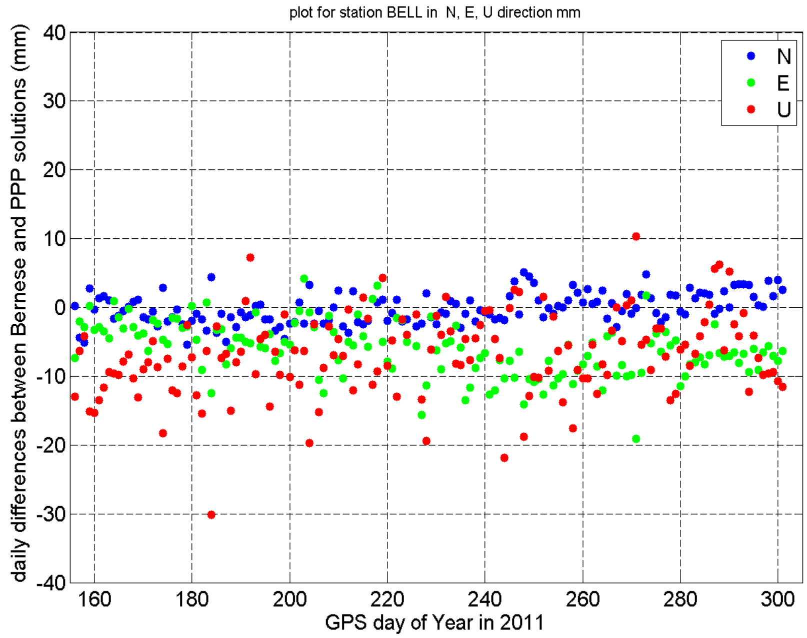


Figure 32: Daily differences between Bernese and PPP solutions for BELL from Topcon.

2.3.4 Recommendations

RECOMMENDATION 3: Given the complexity to process baseline solutions to their maximum effectiveness, as well as in the network adjustment of these solutions necessary to integrate NRTK reference stations, it is recommended, aside from Recommendations 1 and 2, that a service provider can utilize a commercial GNSS software with the capability to derive high-quality long baseline solutions can be used as prescribed. Then, an adjustment software tool, such as RTKNetworkAnalysis, can be used to perform the network adjustment using the estimated baselines as measurements.

3 Monitoring of Reference Stations

Related and as important to common coordination of reference stations is the ongoing, perhaps continuous monitoring of these reference stations and new reference stations added to networks. The monitoring of reference stations can be performed at some level internally by the service provider's NRTK software; however, this section focuses of external approaches to the frequent estimation of reference station coordinates for the primary purpose of monitoring the stability of existing and new stations within the reference frame. These means include PPP processing, relative positioning processing, and network analysis of relative positioning results.

3.1 Monitoring by Means of PPP Processing

From the integration of reference stations by means of PPP processing, PPP processing methodologies are proposed here for the monitoring of the coordinates of existing and integration of new reference stations. A key question is: How much data must be processed with PPP to determine accurate coordinates for a new station? This question has been investigated and answered in Section 2.2.3. Two other significant challenges are issues in day-to-day station monitoring, and the existence of trends in the daily PPP-based station coordinate time series.

3.1.1 Station Monitoring with PPP

One station that went offline during the study period was used for further analysis to simulate real-time PPP monitoring. This site produced the maximum bias in the horizontal components presented in Table 1. The time series shown in Figure 33 was generated by comparing the estimated float PPP solution in static mode to the PPP solution from DOY 156. Over DOY 157 to 163, the rms error in the north, east and up components were 2, 2 and 4 mm, respectively. From DOY 164 to 167, the rms error for the north, east and up components increased to 87, 66 and 5 mm, respectively, indicating a shift primarily in the horizontal component occurred.

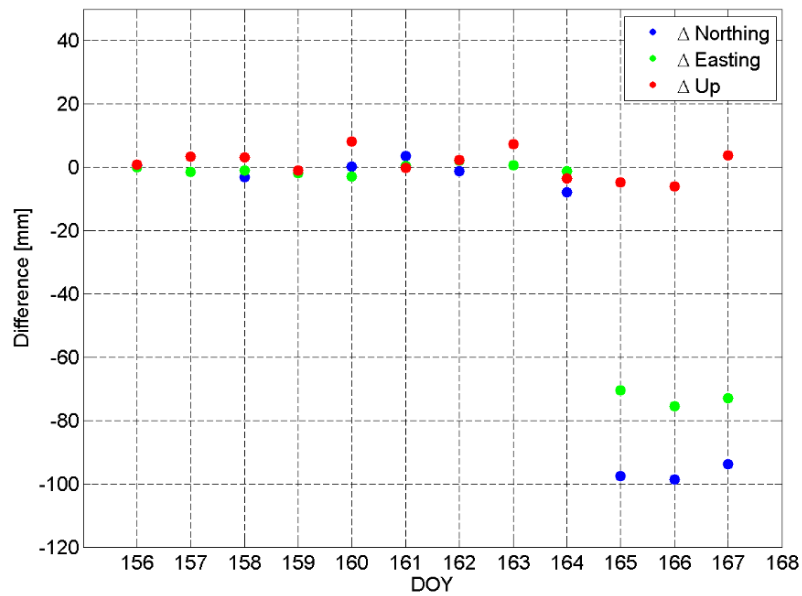
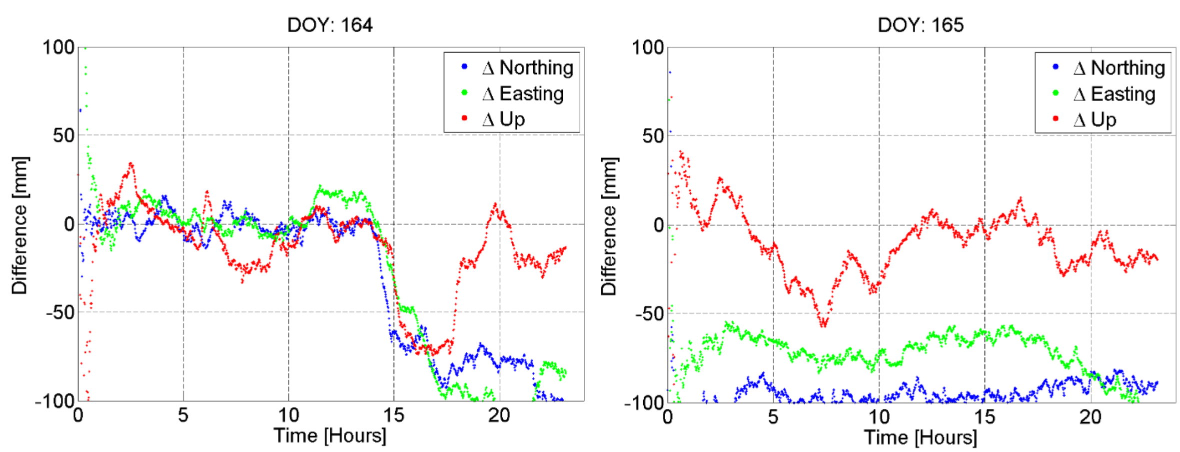


Figure 33: Station with maximum horizontal and 3D error.

To examine the feasibility of using PPP as a real-time monitoring tool, the datasets were reprocessed in kinematic mode with a process noise of 0.01 ms^{-1}. The difference between static and kinematic mode in PPP primarily exists in the variation of the process noise models in the sequential least-squares (in this case) or Kalman filter. The process noise for the coordinates serves as a priori weighted constraints to the parameters. Presented in Figure 34 is an overview of the kinematic solution for DOY 164 to 167. The disturbance is easily visible on DOY 164 at 14:00 GPS Time. This example shows the possibility of using PPP as a real-time monitoring tool for coordinate changes, detecting station movement.



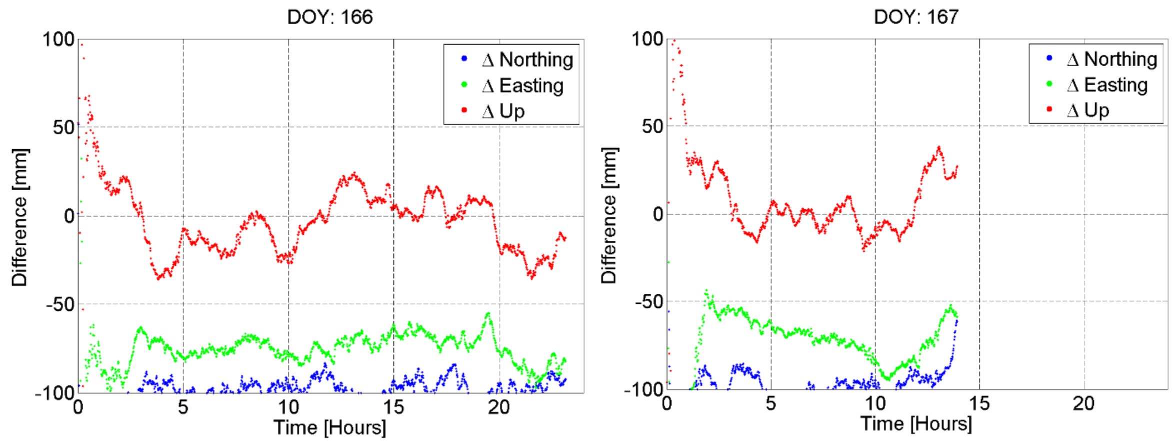


Figure 34: Station monitoring using PPP processing in kinematic mode with a process noise of 0.01 ms^{-1} for DOY 164-167.

3.1.2 Station Monitoring for Long-Term Drift

Network RTK reference stations are susceptible to long-term drift as a result of the movement of the North American plate at a rate of 2.3 cm per year, local geological features such as faults and landslides bodies within the vicinity of the stations, as well as lower cost GNSS antenna monumentation type for, e.g., reference stations mounted on rooftops of buildings. The relative motion of each of the stations was determined with respect to the estimated PPP coordinates for DOY 156. The position differences were determined from the estimated PPP solution for 24 hour data arcs allowing the PPP solution to attain a stable state and attain PPP positioning accuracy specifications of few mm in the horizontal and centimetre in the vertical. The precision of the vertical component is 2-3 times lower than that of the horizontal component (inherent in all forms of GNSS positioning), and as such, the vertical displacements are not of sufficient precision to determine accurate, long-term drift. The effects of the plate motions were not removed from the solution, and as a result they are one of the contributing factors to the drift present. The stations illustrated in Figure 35 to Figure 38 highlight some of the most noticeable trends present. Illustrated in Figure 35 is an example of an antenna shift as the receiver was taken offline on DOY 233 and turned back on DOY 241 of 2011, possibly due to maintenance as the documented receiver and antenna remained consistent. The effects of an antenna shift are clearly visible in all three components with an average difference of -3.3, -2.1 and 0.6 mm in the northing, easting and up components, respectively, before the datum shift and 5, 22 and 0.5 mm northing, easting and up components, respectively, after the datum shift. The most noticeable effect was in the easting component with an average shift of 20 mm. Presented in Figure 36 is an example of a linear drift in the northing component from DOY 279 to 302 from 3 mm to 1.4 mm. Illustrated in Figure 37 is an example of a quasi-linear drift in the easting component from DOY 256 to 302 from 3 mm to 12 mm with a maximum difference on DOY 276 of 22 mm. Figure 38 illustrates a linear drift in both the northing and easting component from DOY 206 with a difference of -3 and -1 mm, respectively, and continues drifting in a quasi-linear manner to a maximum difference of 16.5 and 10 mm in the northing and easting components, respectively.

Preliminary results indicate that the application of PPP for determining long-term drift is feasible and effective. However, further investigation is required with data covering a larger chronological span to examine the nature and periodicity of the drifts present, as well as examination of local environment features of where the station is situated. It is recommended that geological information be taken into account when any new RTK reference stations are being established. PPP can be used to examine and monitor the data quality, stability of the antenna and solution accuracy. Also, PPP can be utilized in the analysis of both absolute and relative displacements of the network RTK reference stations. It is anticipated that a specialized PPP utility can be developed for real-time monitoring of solution performance, as well as monitoring for long term station drifts.

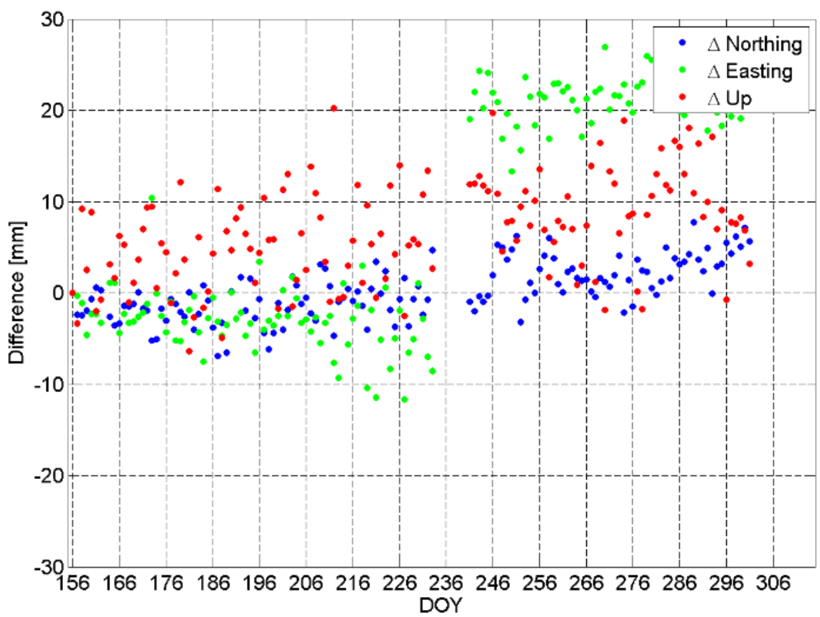


Figure 35: Relative displacement of network RTK solution from DOY 156 to 302 illustrating a datum shift after DOY 241.

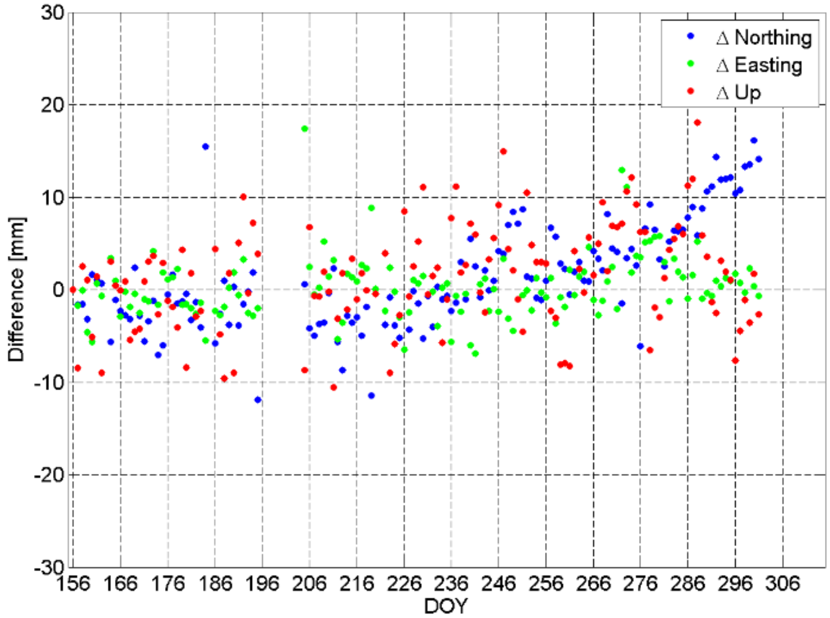


Figure 36: Relative displacement of network RTK solution from DOY 156 to 302 illustrating a linear shift in the northing component from DOY 279 to 302.

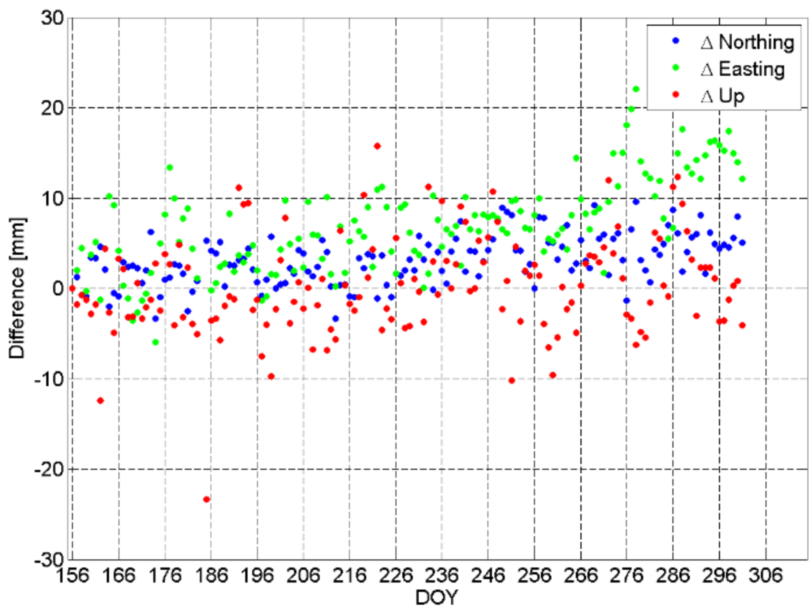


Figure 37: Relative displacement of network RTK solution from DOY 156 to 302 illustrating a quasi-linear drift in the easting component from DOY 256 to 302.

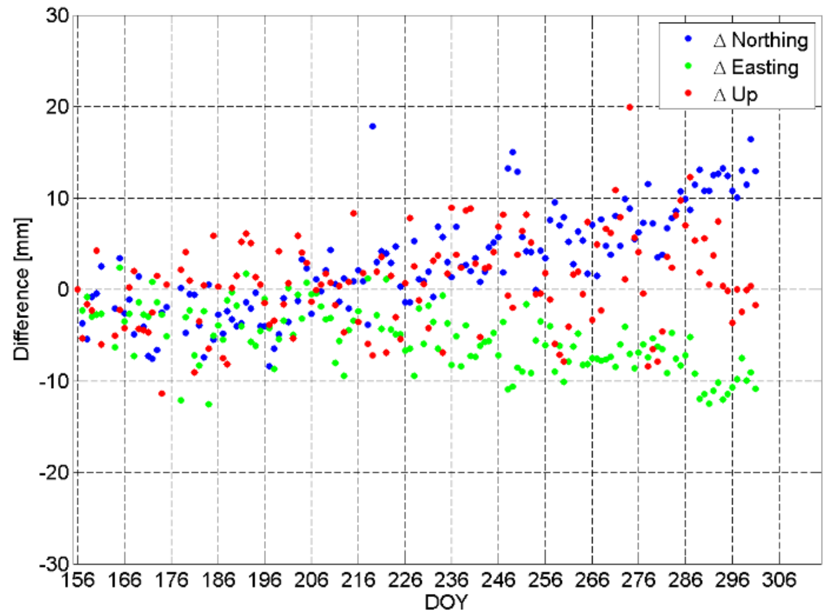


Figure 38: Relative displacement of network RTK solution from DOY 156 to 302 illustrating a quasi-linear drift in the northing and easting component from DOY 206 to 302.

3.1.3 Recommendations

RECOMMENDATION 4: Static PPP processing can be used to monitor network RTK reference station and integrate new stations by means described in Recommendation 2. Static and kinematic PPP processing can adequately provide continuous and independent monitoring of network RTK stations; however, offsets and drifts must be treated carefully. To provide uniformity, all service providers can use the NRCan on-line PPP processor, CSRS-PPP, with set processing parameter settings.

3.2 Monitoring by Means of Network Baseline Processing

The NRTK service providers claimed that a positioning accuracy of a few centimetres horizontally and vertically is attainable in real time within their networks with a single RTK GPS unit, cellular modem, and the subscription-based corrections. The task of this work is to analyse the position changes of their reference stations in the networks through the given months. For instance, the differences in positions from day to day are checked for any possible discontinuity through the given time period.

In order to investigate the performance of these network RTK services, it is very important to compute and estimate the biases among these reference stations. This process will also help the users to realize the quality of these commercial network RTK services, which will help the development of better network systems in the country.

On the basis of the given reference coordinates of the RTK network stations, the baseline vectors can be used as measurements to monitor the coordinates of each reference station in the GNSS network. In this project, the coordinate monitoring of RTK network stations was studied through the daily network adjustment by Bernese GNSS software and also by using the developed software utility RTKNetworkAnalysis.

3.2.1 Effectiveness and Practicality of Method

In this section, the main task is to monitor the performance and reliability of RTK reference stations from these commercial service providers' networks. The minimum constrained adjustment technique will be used to check any position biases estimated at the reference stations. The generic parametric adjustment by fixing multiple control stations will be used for station coordination.

Figure 39 and Figure 40 show the sample plots of the daily coordinate variations of reference station SARN and HAWK (Hawkesbury) from the Leica network by performing a minimum constraint adjustment (station KNGS was held fixed). Table 21 lists the standard deviation, rms, absolute max value and mean value in the north, east, and up directions. From Figure 39, it can be seen that all biases were computed against the first day. The green dots represent the east component, the red dots the up component, and the blue dots the north component. This plot shows that all biases range from several millimetres to 1.5 centimetres. The results also illustrate that the up component is, as expected, noisier than the east and north component. There is a small jump in the easting direction from day 264 to 280. Overall, this plot shows reasonable continuity in the coordinates over 148 days.

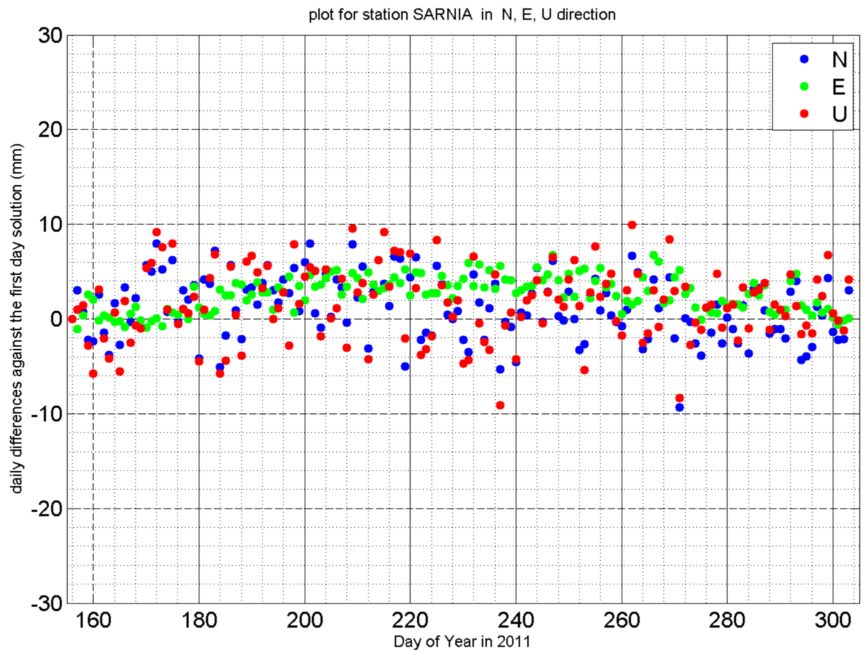


Figure 39: Daily coordinates variations for station SARN.

Table 21: Statistics for daily coordinate variations for station SARN. Units in mm.

component	Std	rms	Abs max	Mean
N	3.3	3.5	9.3	1.1
E	1.8	3.2	6.8	2.6
U	3.8	4.1	10.0	1.6

Figure 40 displays the daily coordinate variations of reference station Hawkesbury from the Leica network over 148 days. From this plot, it can be seen that there are discontinuities in the east component. The coordinate differences against the first day in the east component drift away over time. From day 220, the coordinate differences in the east tend to get larger. This phenomenon is most likely caused by real movement of antenna with respect to the reference frame.

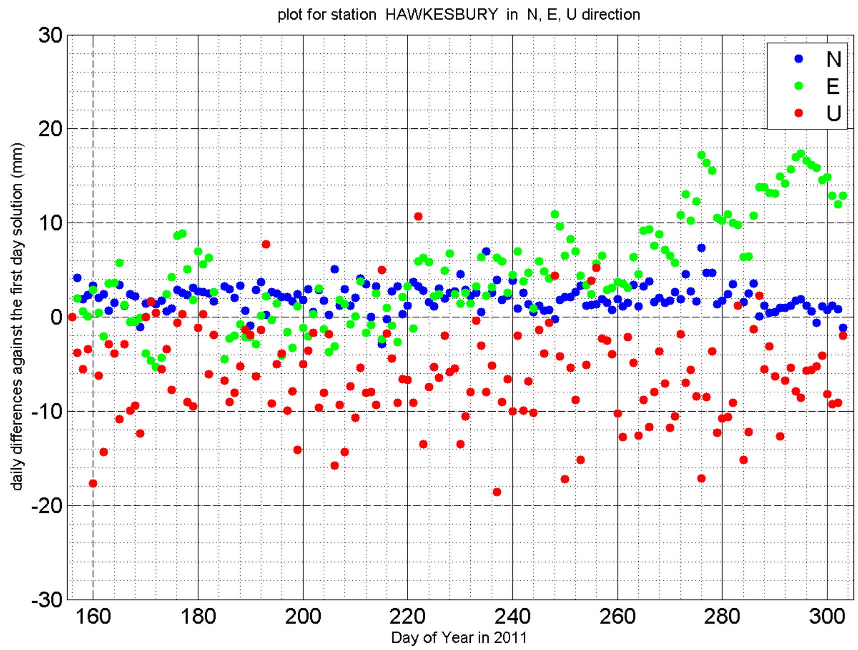


Figure 40: Daily coordinates variations for station HAWK.

From Table 22, it can be seen that the standard deviation and rms values in the east and up directions are significant larger than those in the north component. These results also verify the trend seen in the east direction.

Table 22: Statistics for daily coordinate variations for station HAWK. Units in mm.

component	Std	rms	Abs max	Mean
N	1.4	2.5	7.4	2.0
E	5.7	7.4	17.4	4.8
U	5.0	8.1	18.5	-6.3

The next two plots, Figure 41 and Figure 42, show the daily coordinates variations of stations AURO and GODE in the Cansel network over 148 days. Figure 41 and Table 23 display the daily coordinates variations over 148 days for station AURO and the biases were computed against the starting day. The time series plot and statistical table illustrate that all biases are within 1.5 cm and the up component is significant noisier than the north and east component. This plot shows good continuities over the given time period, which means that the reference station AURO is stable and reliable through 148 days.

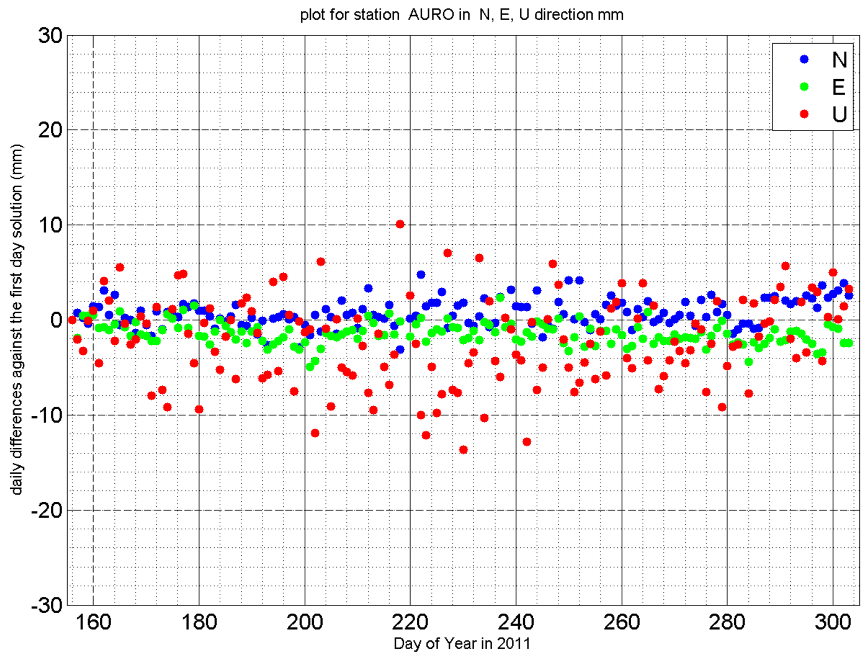


Figure 41: Daily coordinates variations for station AURO from Cansel.

Table 23: Statistics for daily coordinate variations for station AURO. Units in mm.

component	Std	rms	Abs max	Mean
N	1.5	1.6	4.8	0.7
E	1.2	1.8	5.0	-1.4
U	4.5	5.0	13.7	-2.2

Figure 42 shows the sample plot of the daily coordinates variations of reference station GODE from the Cansel network over 148 days. From this plot, it can be seen that there are discontinuities in the east component. From day 240, the east component has a very large offset of ~3 cm. This phenomenon may be caused by an antenna change without equipment metadata updating.

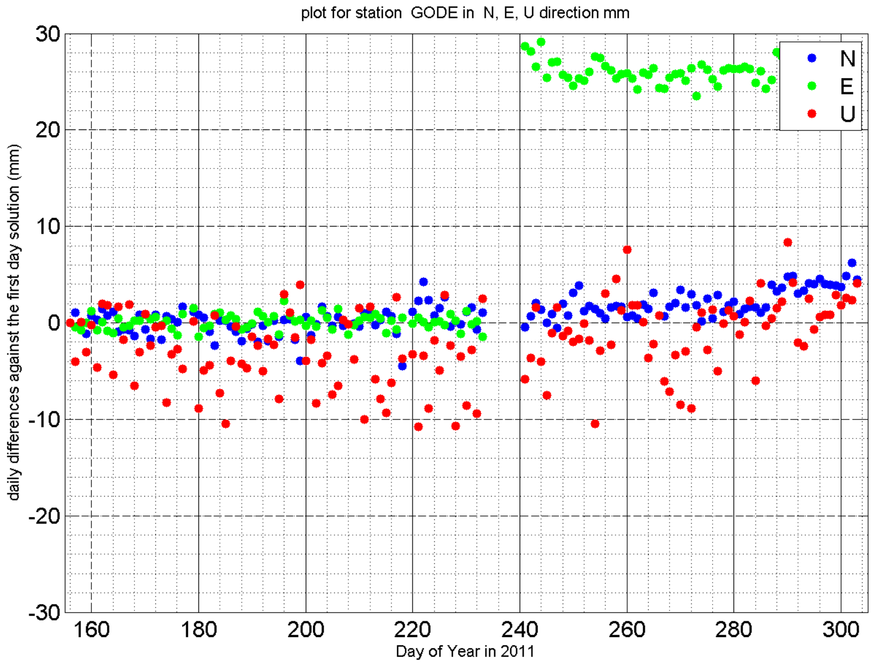


Figure 42: Daily coordinates variations for station GODE from Cansel.

The statistical information in Table 24 also shows that the standard deviation and rms value are significant large in the east component, which indicates the coordinate jump which occurred for this reference station.

Table 24: Statistics for daily coordinate variations for station GODE. Units in mm.

component	Std	rms	Abs max	Mean
N	1.8	2.1	6.2	1.0
E	13.0	17.6	29.2	11.9
U	4.0	4.5	10.7	-2.1

Figure 43 shows the time series plot of coordinate variations of station SIMT from the Topcon network. From this plot, it can be seen that the coordinates for this station are quite consistent throughout the period. The statistical information in Table 25 also indicates that this station's performance is very good.

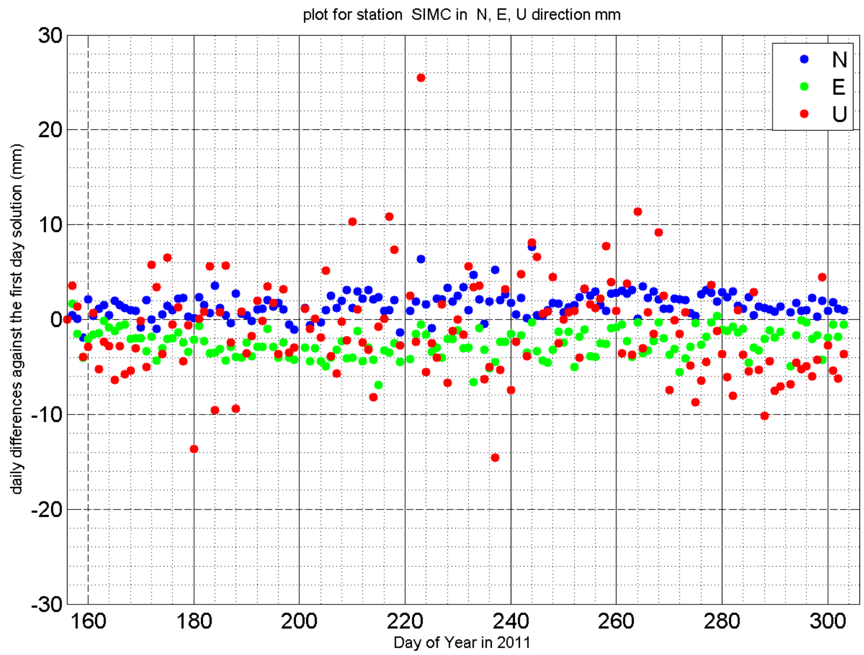


Figure 43: Daily coordinates variations for station SIMT from Topcon.

Table 25: Statistics for daily coordinate variations for station SIMT. Units in mm.

component	Std	rms	abs_max	Mean
N	1.3	2.0	7.6	1.6
E	1.5	2.9	6.9	-2.5
U	5.2	5.3	25.5	-1.1

The above plots present the network adjustment results from the station monitoring task, where a minimum constrained adjustment was performed (station KNGS was held fixed). These results show the behaviour of reference stations through 21 weeks. Figure 39, Figure 41 and Figure 42 detect the misbehaving of the reference stations within the network. Station coordinate monitoring can aid users in understanding the quality of performance of network RTK system.

By fixing all existing ACP stations, the coordinates of RTK stations can be determined and coordinated to the existing active control system. The following example illustrates this concept. From Figure 44 and Table 26, it can be seen that the station BELL does not have any abnormal behaviours through 148 days time period. This figure displays the adjusted reference stations coordinates by using minimal constraints adjustment method. By implementing the minimal constraints condition, this method ensures no internal structure distortion of the network and possible conflicts among ACPs.

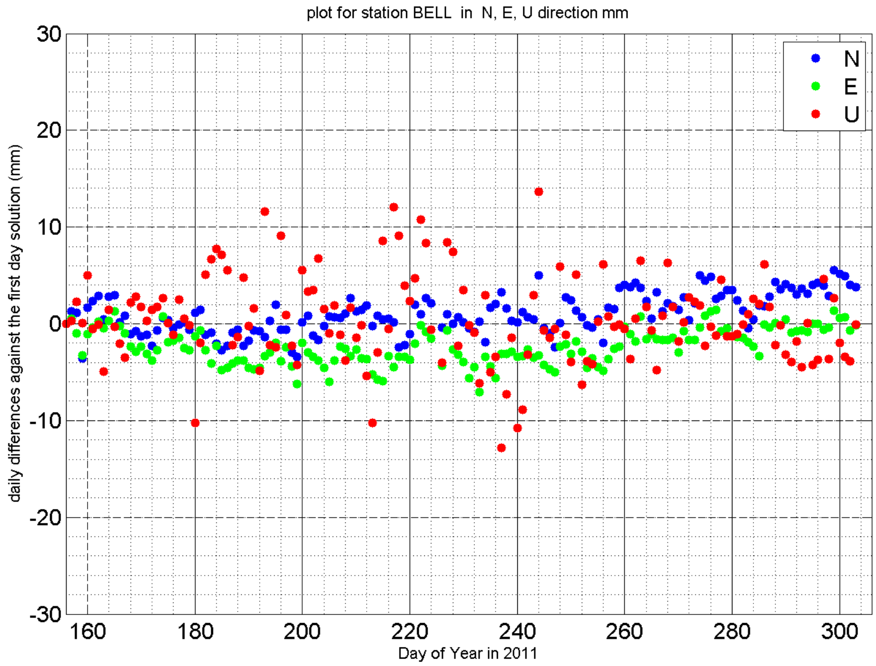


Figure 44: Daily coordinates variations for station BELL from Topcon.

Table 26: Statistics for daily coordinate variations for station BELL. Units in mm.

component	Std	rms	Abs max	Mean
N	2.0	2.3	5.5	1.1
E	1.8	3.0	7.1	-2.3
U	4.5	4.5	13.7	0.4

The next task is to fix all six ACP stations to perform a parametric adjustment to adjust the network. Figure 45 to Figure 48 illustrate the comparison between solutions of minimum constrained adjustment and general parametric adjustment by fixing all six ACPs for two stations. Figure 45 and Table 27, and Figure 47 and Table 29 shows the adjusted results from the network adjustment of minimum constrained for station BROC and SPAR from network Topcon and Cansel, respectively. Figure 46 and Table 28, and Figure 48 and Table 30 show the adjusted solutions of fixing all existing ACP stations near the network.

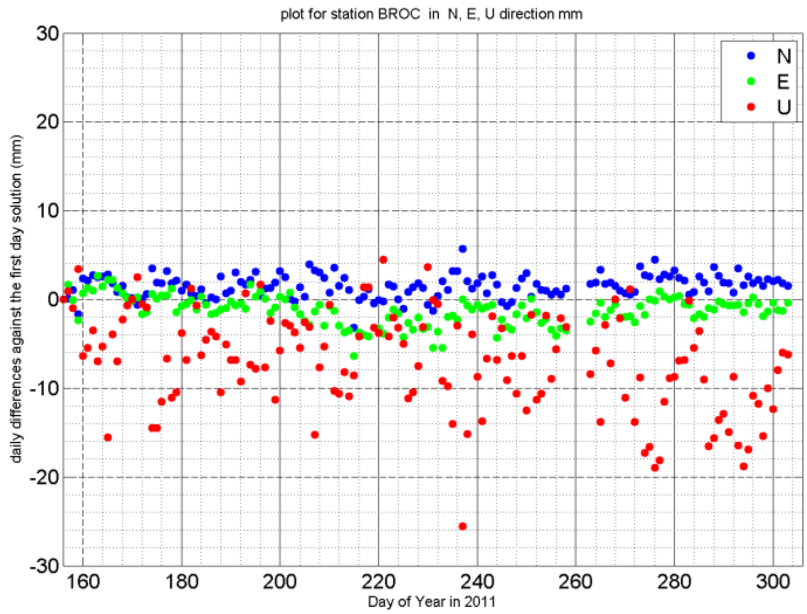


Figure 45: Coordinate variations for station BROC from Topcon (minimum constrained).

Table 27: Statistics for daily coordinate variations for station BROC. Units in mm.

Component	Std	rms	Abs max	Mean
N	1.3	2.0	5.7	1.5
E	1.6	2.0	6.3	-1.2
U	5.5	8.9	25.6	-7.0

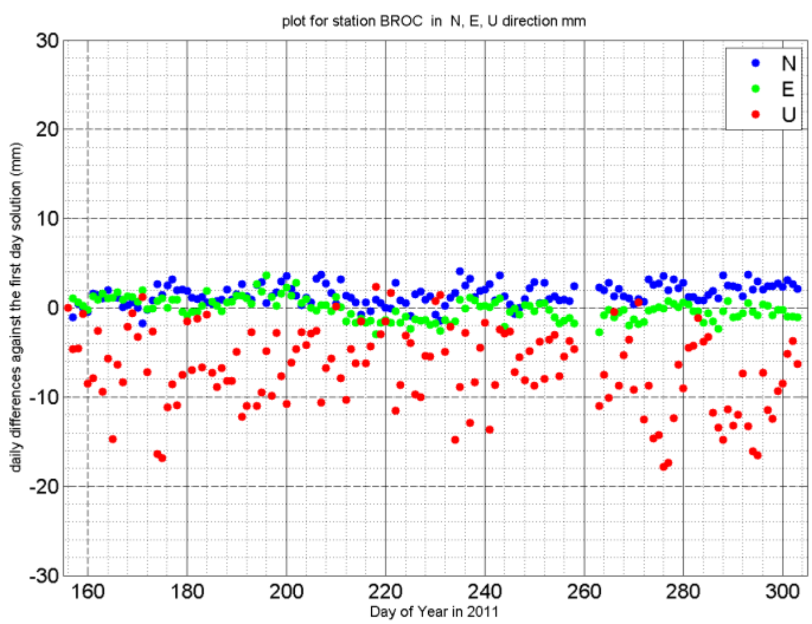


Figure 46: Coordinate variations for station BROC from Topcon (6 ACPs fixed).

Table 28: Statistics for daily coordinate variations for station BROC (6 ACPs fixed). Units in mm.

Component	Std	rms	Abs max	Mean
N	1.2	1.9	4.1	1.5
E	1.2	1.2	3.7	-0.1
U	4.5	8.2	17.8	-6.9

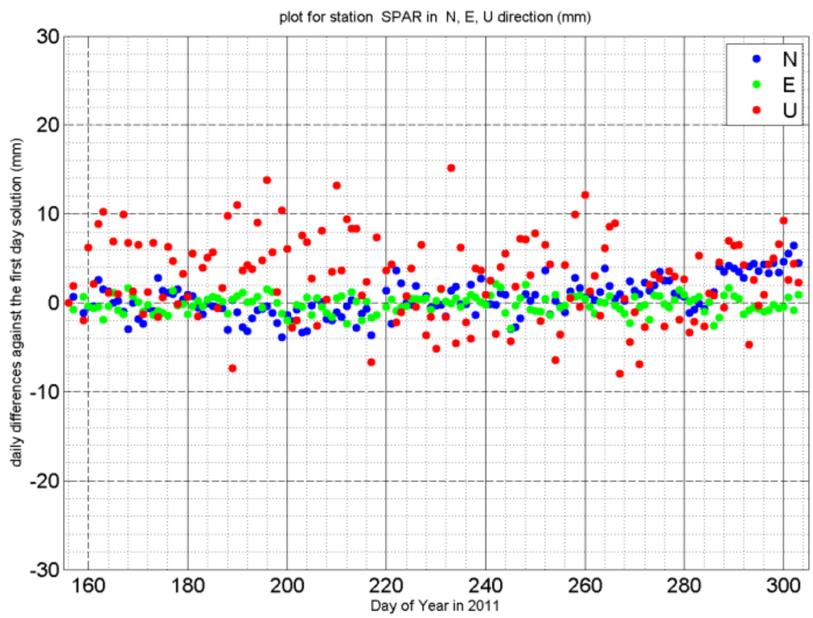


Figure 47: Coordinate variations for station SPAR from Cansel (minimally constrained).

Table 29: Statistics for daily coordinate variations for station SPAR (minimally constrained). Units in mm.

Component	Std	rms	Abs max	Mean
N	2.1	2.1	6.4	0.5
E	1.0	1.0	2.9	-0.2
U	4.6	5.4	15.2	2.8

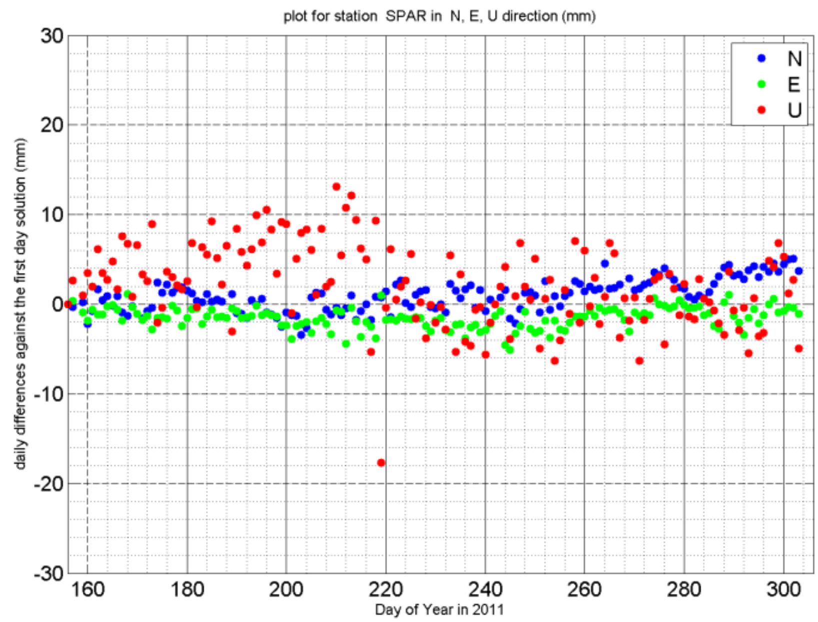


Figure 48: Coordinate variations for station SPAR from Cansel (6 ACPs fixed).

Table 30: Statistics for daily coordinate variations for station SPAR (6 ACPs fixed). Units in mm.

Component	Std	rms	Abs max	Mean
N	1.8	2.0	5.1	1.0
E	1.2	1.9	5.1	-1.5
U	4.6	5.0	17.7	2.1

From Table 27 to Table 30, it can be seen that for station BROC, the rms values and standard deviations of the 3D components are smaller for the generic parametric adjustment by fixing all ACPs. The average biases and the maximum biases are also smaller in both the horizontal and vertical components. For station SPAR, the rms and standard deviations are larger in the east component and smaller in the north and up components in the generic parametric adjustment results. These results show that by fixing all ACPs near the network, the adjustment can produce improved solutions with respect to the minimum constrained adjustment solutions.

3.2.2 Recommendations

RECOMMENDATION 5: Given the complexity to process baseline solutions to their maximum effectiveness, as well as in the network adjustment of these solutions necessary to integrate network RTK reference stations, it is recommended, aside from Recommendations 1 and 3, service providers can process new station data with commercial GPS software capable of deriving high-quality long baseline solutions as prescribed and adjust these baselines with adjustment software such as RTKNetworkAnalysis, or wait for proposed routine, e.g., daily or weekly, GSD station coordinate processing result.

3.3 Geodetic Network Analysis Utility and Analysis

A software tool, named "RTKNetworkAnalysis" after RTK network analysis, has been designed and developed by the York team in C/C++ for RTK network users to be able to perform generic 3D network analysis using 3D GPS baseline measurements. Normally, users are capable of processing the raw GPS data from multiple GPS stations to determine the individual baselines between any specific pair of stations. In order to analyse the overall quality of a group or all of the GPS stations in a RTK network, the network constructed by these baselines is adjusted.

If the independent baselines are generated using the raw data acquired from a group of stations simultaneously for the same time period, there will be no misclosure possible out of any geometrical condition within the network. In this case, no adjustment is necessary because there are no redundant measurements. Hence, how to construct a GPS baseline network for least squares adjustment remains a challenge, just as how to optimally selected a group of maximum independent baselines in a GPS network.

The utility RTKNetworkAnalysis consists of the following functionalities:

- Module 1: Free network adjustment (no fixed station)
- Module 2: Partially-constrained, free network adjustment with respect to the specified stations (free network quasi-stable adjustment)
- Module 3: Coordinate new stations with respect to the given fixed control stations
- Module 4: Coordinate new stations with respect to the equally-constrained given control stations.

An overview of the utility is given in Figure 49.

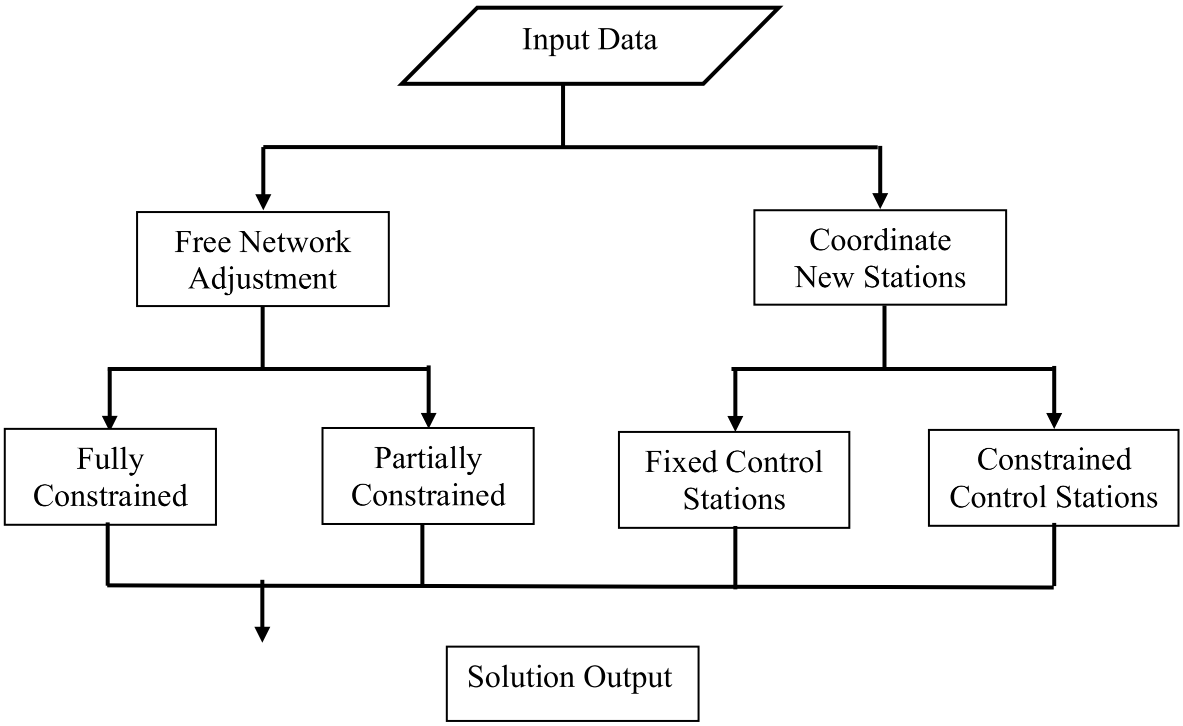


Figure 49: Overview of the software utility “RTKNetworkAnalysis”.

Module 1 allows the adjustment of a GPS baseline network as a free network, in which no station is fixed and all of the stations are free or equally constrained. It provides a capability to monitor a RTK GPS network from time to time without any a priori assumption of which stations are more stable than the others. Also, the adjustment solution does not suffer from any external forces or constraints as in a minimum constrained network.

Module 2 further allows to adjust a GPS baseline network with respect to a group of stations, with which one may have enough a priori knowledge about their stability in contrast with the rest of stations, or when one has to isolate any suspicious abnormally behaved stations. With this model, no station is fixed, but the specified stations will be equally constrained as what is done with all stations in Module 1, while the rest of stations are treated as new stations. It is also referred as to the partially-constrained, free network adjustment, or quasi-stable, free network adjustment.

Module 3 is used to integrate new GPS stations into the existing network. All existing GPS stations can be fixed whilst the coordinates of the new stations are estimated. In order to validate if there is any conflict among the existing stations, a minimum constrained network adjustment or a free network adjustment can first be introduced in the way how any other geodetic network is usually processed. And then, Module 3 is executed and then may be repeated after removal of any conflicted external constraint until no conflicted external constraint can be identified.

Module 4 allows a user to coordinate new stations not by fixing all of the existing GPS stations, but by equally constraining them to estimate the coordinates of the new stations. It can be run before the execution of Module 3. In fact, module 2 and module 4 are principally the same.

3.3.1 Description of Utility and Use

RTKNetworkAnalysis was developed in the fashion of object oriented programming and consists of four main classes: CDataIO, CleastSquares, CFreeRTKGPSNetwork, and CCoordinateNewStations together with three existing static libraries: TextIO, Math and GeodeticTools. The focus is here only on how to prepare the input file and use the utility.

RTKNetworkAnalysis is a Win32 console application. An input data file in ASCII format must be prepared in order to run RTKNetworkAnalysis. There are eight data blocks defined with the following block titles, which will briefly be described:
PROJECT_ATTRIBUTES,
NETWORK_ATTRIBUTES,
DATA_ATTRIBUTES,
STATION_LIST,
CONTROL_STATION_LIST,
SPECIFIED_CONSTRAINT_STATION_LIST,
STATION_CORDINATE_LIST,
BASELINE_MEASUREMENT_LIST.

PROJECT_ATTRIBUTES: allows a user to define the project name, the output kernel name and the full path name for output, which tell where and with which name kernel the output files are written.

NETWORK_ATTRIBUTES: allows a user to specify the network information, e.g., FREE_NETWORK or COORDINATE_NEW_STATIONS, followed by the selection how the network is constrained: ALL_STATIONS or SPECIFIED_STATIONS for FREE_NETWORK and FIXED_CONTROL_STATIONS or FREE_CONTROL_STATIONS for COORDINATE_NEW_STATIONS. The information of this block decides which program module is to be called.

DATA_ATTRIBUTES: consists of five parameters: the used coordinate datum, the epoch of the datum, the date when the reference coordinates were generated, the date when the baseline measurements are determined, and the type of the network adjustment from which the baselines are output if not the single baseline approach is used.

STATION_LIST: will first define the number of the stations in the network followed by the list of station names (assumed to use the four character standard for a station name).

CONTROL_STATION_LIST: will first define the number of the control stations in the network followed by the name list of the control stations (assumed to use the four character standard for a station name).

SPECIFIED_CONSTRAINT_STATION_LIST: is used to specify which stations will be constrained in the partially-constrained free network adjustment. The number of the specified stations is given first followed by the individual names of the specified stations.

STATION_COORDINATE_LIST: is the data block in which the station coordinates, either the reference coordinates in a free network adjustment, the known coordinates of the fixed control stations, or the approximate coordinates of new stations while a user is coordinating new stations, that the program can identify by combining the information from the other relevant data blocks. The coordinates are listed in ECEF Cartesian coordinates in metres and ordered from X, Y to Z with the station name before them.

BASELINE_MEASUREMENT_LIST: allows one to provide all of the baseline measurements associated with their variance matrix (upper triangle). The number of the baselines is provided first and then the baseline measurements one after the other. Each baseline measurement record starts with the name of its "From" station followed by the name of its "To" station, followed by the incremental X, Y and Z coordinate components in metres, and then the six upper triangle elements of its 3x3 variance matrix in units of m^2.

Refer to the Appendix for more details about how to prepare the input data file. With this console application, a bat file can easily be created, for example: "RTKNetworkAnalysis [input file name with the full path]".

3.3.2 Results from Application of Utility

Two examples are given in this section to demonstrate how to utilize this software tool to analyse a RTK network:

Example 1: free network adjustment
Example 2: coordinate new stations with respect to the fixed stations

The baseline network used here is the Topcon RTK GPS network in Southern Ontario (see Figure 16). The raw data were logged over 42 stations in 2011. The reference coordinates of these 42 stations were derived from the raw data on the 5th day in week 6, 2011. The network based on the raw data from these two days was analysed. By using the Bernese software, the maximum independent baselines with the shortest distances were derived for the 1st day (220th day in 2011) as the maximum independent baselines specified manually were generated for the 2nd day (221th day in 2011). There were 76 baselines available in total for the network analysis.

Example 1 (columns 1 to 3 in Table 31): The free network adjustment was introduced to the RTK GPS network. The solution details are provided in Appendix B. The baselines HAMI-OSHA and KINC-WELL were identified as outliers sequentially, as the standardized residuals were 3.29 mm and -3.38 mm in the Y and Z components, respectively, for the baseline HAMI-OSHA, and -3.68 mm in the X component for the baseline KINC-WELL. The reasons that may cause these large residuals were not further analysed within this project.

Example 2 (columns 4 to 6 in Table 31): Under the assumption that the stations ALGO, PARY, NCR1, PWEL and KNGS were control stations, the baseline network was processed with respect to these fixed control stations. Before the five known control stations were fixed, the network was processed in the same way as Example 1, so that any possible internal conflict among the baseline measurements could be identified. Based on the solution of the free network adjustment (column 3 in Table 31), two baselines as outliers and the baseline between two fixed station KNGS and PARY were removed, i.e., only 74 baselines used in the overdetermined network adjustment. From the measurement standardized residuals, only the Z component of the baseline GODR-PARY was 2.80 mm larger than the critical value of the t-test (2.62 mm, Type I Error of 0.01 mm with two tails). So this baseline was removed as an outlier again (column 4 in Table 31). Obviously, the fixed control stations could also cause conflict to the measurements. In reality, the user may need to further analyse what the reason was and then decide how to adjust the network again. The a posteriori standard deviation from this network was clearly different from unity; hence, it was necessary to readjust the baseline network using the scaled measurement variance matrices by (1.5651^2). Thus, the finalized network adjustment had the a posteriori standard deviation of unity. The input data files and their output results from both of the examples are given in Appendix B.

Table 31: Summary of network adjustment from Example 1 and Example 2.

Type	Example 1 (Free network)			Example 2 (Overdetermined)		$s_0=\pm1.57$ (scaled)
iteration	(1)	(2)	(3)	(4)	(5)	(6)
stations	42	42	42	42	42	42
fixed stations	0	0	0	5	5	5
baselines	77	76	75	74	73	73
unknowns	126	126	126	111	111	111
degrees of freedom	108	105	102	111	108	108
deficiency	3	3	3	0	0	0
s_0(a posteriori)	1.70	1.70	1.50	1.64	1.57	1.00
outlier baseline(s)	N/A	HAMI-OSHA	HAMI-OSHA	HAMI-OSHA	HAMI-OSHA	HAMI-OSHA
			KINC-WELL	KINC-WELL	KINC-WELL	KINC-WELL
					GODR-PARY	GODR-PARY
known baseline(s)				KNGS-PARY		

The raw data on the day 281 and 282 in 2011 from the same network were also processed and summarized in Table 32. Three baseline measurements were sequentially identified as outliers from the free network adjustment, and another three baselines were identified as outliers as the control stations: KNGS, PARY and PWEL were fixed.

Table 32: Adjustment summary of Topcon RTK network (DOY 281 and 282, 2011).

Type	Free network			
iteration	(1)	(2)	(3)	(4)
stations	39	39	39	39
fixed stations	0	0	0	0
baselines	74	73	72	71
unknowns	117	117	117	117
degrees of freedom	108	105	102	99
deficiency	3	3	3	3
s_0(a posteriori)	1.02	0.98	0.92	0.89
outlier baseline(s)	N/A	MISS-MOUN	MISS-MOUN	MISS-MOUN
			CARL-MOUN	CARL-MOUN
				BROC-SMIT

As a free network, three baseline measurements were sequentially identified as outliers. Three baselines were further identified as outliers, while three control stations were being fixed. As Table 32 shows, the a posteriori standard deviation of unit weight was quite close to unity, i.e., the a priori and a posteriori accuracies agreed well.

3.3.3 Recommendations

RECOMMENDATION 6: An adjustment software tool, such as RTKNetworkAnalysis (developed for this report), should be used to perform the network adjustment using the estimated baselines as measurements for, e.g., free network adjustments and coordination of new stations with respect to fixed stations.

4 Certification of RTK Networks

Certification of RTK networks has the connotation to mean review and acceptance of the infrastructure and user performance by some certification body in terms of set standards. However, there can be a wide spectrum for the meaning of certification. What is ideally required in Ontario is some means for provincial authorities to confirm that the privately created and maintained RTK networks perform as advertised and can be used by MTO for its work, and it a broader sense, by the provincial, surveying, engineering and construction communities.

For this report, certification will consist of: a review of the limited available literature concerning government certification of network RTK services in other jurisdictions; a review of guidelines for reference station design and installation specifications; a review of guidelines for the maintenance and expansion of networks; and suggestions for user coordinate verification options.

Governments, businesses, communities and individuals, are increasingly attracted to establishing or using network RTK due to the significant utility, productivity and cost savings that can be achieved. Network RTK, if properly managed, may well also become a fundamental part of society's general infrastructure, delivering accurate positions reliably, conveniently, ubiquitously and affordably, in the same way that telecommunications and electricity are delivered (Hale, 2007). In fact, some jurisdictions, such as Australia, are proposing that network RTK be a major component of a national positioning infrastructure strategy (Hausler, 2014), linking the public institutional need with technical requirements to regional and national economic growth.

Internationally, governments have historically managed spatial control by coordinating ground marked geodetic networks to unify local survey and mapping activities. Traditional geodetic networks are also normally managed as hierarchical sub-networks and as an inherent part of an overall national network. A significant challenge for governments is to optimise network RTK management to benefit nationally significant industries and activities (Hale, 2007). These developments have occurred very differently in different jurisdictions. National (e.g., U.K., Germany, Japan, Singapore, etc.) or local, regional, or partial / complete state / provincial (Canada, U.S., Australia, China, etc.) networks have been established. Unlike traditional geodetic control, network RTK infrastructure is more sensitive to population density and economic conditions than technical requirements; hence, the rather local, ad hoc incorporation of this technology. While Ontario has multiple privately constructed and maintained networks in populated areas, the U.K. has a national network, where the monumentation was constructed by and is managed by the national government, and private industry equipment and processing software is used to deliver the positioning service (Ordnance Survey, 2015).

The adoption of consistent management arrangements can facilitate unification of multiple RTK networks. A key requirement of consistent CORS network management is datum harmonization across participating jurisdictions. Once unified and harmonized, discrete jurisdiction CORS networks can be combined to deliver NRTK services supporting homogeneous positioning and navigation over regional areas, regardless of administrative boundaries. To date, considerable research has focussed on the technical development of reference stations and authoritative organisations have request network RTK providers to follow these guidelines. Less attention has been given to the management arrangements required to optimize network RTK reference stations (Hale, 2007). In this context, certification of network RTK stations consists of two components: 1) reference station design and installation; and 2) maintenance and expansion of RTK networks.

Standardized, consistent, unified and integrated CORS network services across jurisdictions will also promote wider acceptance and maximise the benefits that can be delivered by high precision GNSS technology (Hausler, 2014). An example of a market sector that was initially slow to adopt GNSS in some parts of the world is the land (cadastral) surveyors, typically those operating small companies. Reasons for slow uptake include relatively high GNSS equipment costs compared to traditional survey equipment, need for specialised training, lack of standard operating procedures, perceived lack of accuracy over short base lines, and legal status of position measurement (Hale, 2007).

4.1 Guidelines for Reference Station Design and Installation

The first phase in the certification of Network RTK involves creating guidelines for establishing and installing reference stations. Table 33 provides a unique digest of guidelines for reference station design and installation, following specifications from NRCan (Donahue et al., 2013), the IGS (IGS, 2013b), the U.S. National Geodetic Survey (NGS) (NOAA, 2012), EUREF (EPN, 2013), and UNAVCO (Fisher, 2011).

Table 33: Synthesis of reference station design and installation guidelines.

<table>
<tr><td rowspan="5">Site Characteristics</td><td rowspan="3">Site Foundation</td><td>Local geology – consider proximity to faults, landslides, subsidence areas, etc.</td></tr>
<tr><td>Bedrock foundation is preferred</td></tr>
<tr><td>Rooftops are sometimes the only option -- near support structures on bearing wall buildings is best, if roof top location is required</td></tr>
<tr><td>Horizon mask</td><td>Rule of thumb: minimize obstructions above 15°</td></tr>
<tr><td>Site security, ownership and permission</td><td>Location must be secure and viable over long term</td></tr>
</table>

		Data accessibility via internet or phone line
		Continuous electric power
	Multipath	Rule of thumb: site should be at least 15 meters from reflective sources
		Antenna height: Recommendation?
		Avoid creating cavity between backplane and monument top
		Avoid mounting the GPS antenna within 24.4cm (9.6in), or exact multiples of this distance, of a potentially reflecting horizontal surface.
Monuments	Radio Frequency Interference (RFI)	Rule of thumb: site should be at least 1 km from powerful microwave sources, independent of the frequency that they operate at
	Weather	Corrosion resistance
		Design monument to be higher than snowfall levels.
		Use materials with low coefficients of thermal expansion when high temperature variations are expected
		Prepare lightning surge protection.
		Install vertical and horizontal stability measurement instruments (tiltmeters, inclinometers, strainmeters) when high accuracy (sub-mm level) is desired.
	Types	Deep drilled braced
		Shallow drilled braced
		Shallow braced (non-drilled)
		Concrete pillar
		Thermopile
		Polar mast
		Shallow foundation mast
		Stainless steel pin w/ mast
		5/8" all-thread
GNSS Receiver	GNSS observables	Track GPS L1/L2 signals and GLONASS L1/L2 signals and be capable of tracking modern signals (GPS L2C/L5, Galileo, Compass).
	Performance measures	99%+ of expected data
		Cycle slips/observations <0.1%
		MP1 and MP2 <0.5 m at elev. >10°
		Zero baseline phase precision < 1 mm
		Short baseline precision 2 mm horizontal/4 mm vertical
	Features and Specifications	Power consumption 3-10 W
		Memory up to many GB
		Multiple I/O ports
		Log and output multiple formats simultaneously
		Raw, RINEX, BINEX, RTCM SC104, etc.
		Command and control interface
		Built in server technology supports http and ftp over TCP
		Configuration over network by uploading configuration file
		Serial commands and custom interface applications
		Environmental specifications: -40 to +60 C, humidity sealed

		Power management: ability to cycle power remotely and automatic restart in same configuration after power loss
		Ability to log and stream data from external sensors (met, tilt)
		Code and carrier multipath rejection and ability to disable
		External timing frequency input
		Highly reliable: Mean Time Between Failure (MTBF) ~60,000 hours
		Disable pseudorange and/or phase smoothing.
Antennas	Features and Specifications	Stable, well defined phase pattern -- consistent between like models
		Backplane that rejects multipath
		Absolute calibrations of antenna and radome pair are now considered standard by IGS
		Horizontal eccentricities (northing and easting) of 0 are preferred.
Antenna Mounts	Features and Specifications	Securely attach antenna to monument/tamper resistant
		Ability to center, level and orient antenna in azimuth
		Reduce potential for multipath by minimizing surface area (do not create resonant chamber behind antenna ground plane)
Radomes	Features and Specifications	Material should be homogeneous and of uniform dimension
		Hemispherical shape with center of curvature at average (absolute) L1/L2 phase centre radome should be calibrated along with antenna
		Current best practice: Do not use radome unless required for weather, debris or vandal protection
Power Systems	Features and Specifications	Power budget is typically 6-20 W, depending on receiver model and communications

Considering the somewhat unique situation in Canada and Ontario of multiple privately constructed and maintained RTK networks, rather than, e.g., government constructed reference station monuments and CORS equipment, limited options exist for the provision of reference station design guidelines. Almost all commercial reference stations in Ontario are rooftop mounted and individual station monitoring information is not publically available. Therefore, it is not realistic to ask competing companies to replace their monumentation and provide station monitoring transparency. However, MTO can encourage companies to:

a) Attempt to satisfy as many of these guidelines as is realistically possible for their existing sites, and potentially, to supply their reference station design and installation records for each site to MTO. This formalism would be of benefit to the company as well, in the form of CORS quality control.

b) Attempt to apply these guidelines when maintaining existing sites and erecting new sites. And again, providing installation and maintenance records.

4.2 Guidelines for the Maintenance and Expansion of RTK Networks

To date, considerable research has focussed on the technical development of reference stations and related GNSS technologies. Less attention has been given to the management arrangements required for initial coordinating, maintenance and expansion of network RTK reference stations – the primary subjects of this report.

From the literature, operational standards and principles for CORS networks need to particularly focus on the following areas, expansions of which follow. Note that all service providers perform most of these activities to some extent through their operational procedures and processing options in their commercial network RTK reference station data processing / correction generation / user coordinate estimation software (Powell, 2013; Ayers, 2013).

a) Secure and reliable data communication links between reference stations and the main data processing node.

b) Robust network operation.

c) Adequate infrastructure maintenance, renewal, and upgrade.

d) System monitoring regimes and alerts to operators.

e) Adjacent jurisdiction network integration arrangements.

f) Service availability.

g) Antenna coordinates, computation, monitoring, adjustment, transformation.

h) Commissioning and decommissioning of stations.

a) Secure and reliable data communication links between reference stations and the main data processing node.

In Nova Scotia (Bond, 2013), RTK service providers use redundant server infrastructure for delivering data to users. Each server should be connected to an uninterruptible power supply that can deliver at least 2 hours of operation time in the event of a power outage. The service delivery system should be scalable to support potentially thousands of users. Also in Nova Scotia (Bond, 2013), all data transfers between the active control stations and the NRTK service provider's site is to be carried out via the Internet. Real-time GNSS corrections data is transmitted using Network Transport of RTCM Internet Protocol (NTRIP). The data are retrievable immediately after the hour if logging hourly or after 24h00 GPS time. The NRTK service provider's web and FTP server shall operate 24 hours a day with data available in RINEX format (Version 2 or higher) indefinitely, as well as stored in the native data format.

b) Robust network operation.
Robustness involves minimum configuration standards, and control centre arrangements including duplication, staffing, data transfer standards, action in the event of loss of node/s) (Hale, 2007; Bond, 2013).

c) Adequate infrastructure maintenance, renewal, and upgrade.
Including equipment age mapping and regular site inspections. For example, the IGS (2013b) requires firmware upgrades to be installed within 6 months of being released from the manufacturer.

d) System monitoring regimes and alerts to operators.
In Australia (Hale, 2007), GPSnet CORS sites and operations are monitored continuously with automated alerts provided by email to GPSnet staff if predetermined quality assurance thresholds are exceeded. Thresholds include, less than 95% data completeness, L1 pseudorange multipath exceeding 2 m, cycle slips exceeding thirty per hour at each CORS site, and CORS antenna coordinates exceeding 50 mm from the fixed initial three-dimensional network position. GPSnet staff respond to network alerts.

In Nova Scotia (Bond, 2013), data integrity checks are performed on a daily basis to detect unstable ACS sites. An ACS that has sudden apparent movements is reported as unstable. As a rule of thumb, ACS that move more than 5 mm horizontally or 10 mm vertically in less than 1 hour or more than 10 mm horizontally and 15 mm vertically in a 24 hour period should be regarded as unstable. And a report is issued to clients with any data performance issues affecting normal GNSS NRTK services within 24 hours.

Service provider's software also provides for various levels of reference station integrity monitoring (Powell, 2013; Ayers, 2013) and third party CORS monitoring software is also available (e.g., Alberding, 2015).

e) Adjacent jurisdiction network integration arrangements.
Care needs to be taken when users must work between jurisdictions, be they geographic or governmental. Arrangements include seamless provision of consistent corrections and maintenance of uniformity of coordinate datum.

f) Service availability.
The target uptime for the Australian GPSnet service, using one reference station is 99.8 percent. This target is routinely met as a consequence of the reference station having duplicated servers within the one cluster. When a second reference station facility becomes available, the target uptime is to become 99.98% during business hours, Monday to Fridays, excluding public holidays (Vicmap, 2007). An improvement from 99.8% to 99.98% uptime (primarily achieved by incorporating a second Internet service provider) is being pursued by GPSnet managers as a result GPSnet coordinate monitoring

(Hale, 2007).

g) Antenna coordinates, computation, monitoring, adjustment, transformation.
In the Netherlands, to coordinate reference stations, 72 hours of data are required. Stations are coordinate using Bernese Software v4.2 with fixed reference stations coordinates. Coordinates are published in ETRS89 of AGRS.NL (Buren et al., 2004). EUREF's recommendation requires computation of ETRS89 coordinates to guarantee so-called Class B accuracy. Complementary information such as station owner, manager, location, monumentation, and equipment are to be provided. Stations may be physically inspected to ensure monumentation specifications have been met. A certificate of validity is provided by the national mapping agency and the information recorded in a registry (Torres and Kösters, 2003; Torres, 2004).

h) Commissioning and decommissioning of stations.
Given the integrated nature of network RTK corrections, the addition or removal of CORS can potentially alter user coordinates. Therefore care must be taken in these situations to provide centimetre-level continuity in user positioning through accurate integration (reference station measurement processing, network adjustment, etc.) of new / replacement equipment or monuments.

In the current Ontario context, aspects a, b, c, d, f, and h are completely managed by the individual service provider through their processing and monitoring software and operational procedures. It is in each company's best interest to maximize efficient and RTK performance through their network. In this situation, it would not be recommended for the government post-development to impose standards or guidelines, but rather work with all service providers to clarify, consolidate, codify and publicizes these procedures and perhaps maintain records of these activities. Aspects e and g have been studied and discussed in earlier sections of this report, and there is clearly a roll to play for governments with industry partners in these CORS coordinate determination and datum issues.

The legal implications and responsibilities for CORS network management are significant and complex, as they relate to both technical and organizational requirements. The key aspects focus on the quality of user coordinates with respect to legislated datum requirements and traceability of these user coordinates:

a) Ensuring that compliance is maintained with respect to all relevant legislative requirements at national and state level and traceability of measurements of position.

b) Ensuring networks conform to the national geodetic network and support datum realisation at jurisdiction level. For example, in Australia, Geoscience Australia as a "verifying authority" of position coordinates certifies the base of each GPSnet antenna (Hale, 2007). Certification also provides legal traceability as the value standard for position in Australia. Certification is dependant on maintaining antenna stability and applies for five years. If the antenna is changed, antenna mount modified, recertification is required.

c) Ensuring networks achieve and maintain a status of state reference standard of measurement.

d) Ensuring legal traceability of measurement of position of antennas is achieved and maintained (Hale, 2007; Bond, 2013).

e) Maintaining a network data archive for a minimum period to accord with jurisdiction laws concerning limitation of action.

f) Standardising legal agreements to support hosting (Bond, 2013).

g) Standardising terms and conditions of provision of network data to users.

Of all the jurisdictions review, Australia appears to have some of the most clearly defined (and published) standards in place. It is required that a Regulation 13 (Reg 13) Certificate is issued for each CORSnet-NSW installation by Geoscience Australia (GA), a facility accredited by the National Association of Testing Authorities (NATA). The certificates are usually available 3-4 months after installation and are valid for 5 years and include verified and accurate GDA94 (2010) coordinates. This verification is important as it provides a reference to a standard of measurement in accordance with the National Measurement Regulation 1999 and the National Measurement Act 1960. Consequently, they assist users in establishing legal traceability of GNSS positions when CORSnet-NSW data are used (NSW Government, 2012).

While this report is not recommending that MTO consider all of these specific certification actions, they do highlight the level of detail that is being placed on network RTK CORS quality control in some jurisdictions. Given the mature state and industry-driven nature of Ontario's RTK network infrastructure and services, it is being suggested in this report that network RTK management in Ontario would benefit from MTO considering the development of a set of guidelines along with its industry partners in the form of guidelines or best practices in all of the listed aspects but not necessarily require strict certification of each activity.

4.3 User Coordinate Verification Options

One of the least discussed areas of network RTK validation is the verification of user-determined coordinates. The idea of "traceability" is considered as a means to be able to trace back from the user position to the measurements and network corrections used to generate that position. Depending on the network RTK service implementation, different commercial providers claim various levels of traceability. In practice, surveyors and other users rarely make use of these capabilities, and in many cases, do not record or store raw user GNSS measurements for potential verification processing. Large-scale user performance studies as was previously undertaken by the lead authors for MTO (Bisnath et al., 2012) are rare and time consuming. Therefore this section provides a number of user coordinate verification options that could realistically be applied to, e.g., MTO contractors using network RTK, or the wider network RTK user community in Ontario.

4.3.1 Localization

The primary approach that the commercial network RTK services provide approximating user coordinate verification is that of “localization”. Localization refers to the user recording short static rover RTK receiver sessions at a few survey monuments with published coordinates within or surrounding the survey area, and adjusting (via least-squares software within the receiver) the RTK-determined monument coordinates to the published coordinates, and subsequently using the estimated RTK-to-local coordinate transformation to adjust all other RTK-determined coordinates to fit the local reference frame.

While this method is efficient and practical in that it allows the user to produce coordinates in the local reference frame as well as remove potential biases in the RTK position solutions, it does not actually verify RTK user coordinates. One can argue that in an ideal world, the RTK-determine coordinates should match, within specifications, the published monument coordinates, but, as with all measurement technological developments, the new results tend to illustrate the shortcomings (i.e., lower accuracy and precision) of the old results.

4.3.2 Service provider / user self-assessment

One option for service provider or user self-assessment of network RTK user coordinate performance would be for user coordinate estimation at a known high-quality monument, e.g., a Canada Base Network (CBN) station. A short receiver occupation of, e.g., a local CBN station would allow for comparison of the RTK-determined station coordinates versus the published CBN coordinates and therefore verification of the user coordinates – of course in the appropriate reference frame. From the previous York University network RTK service assessment report to MTO (Bisnath et al., 2012), short occupation could be defined as, as little as one hour or even a few minutes.

Potential self-assessment scenarios include:

- An MTO contractor estimates network RTK user performance with survey equipment through observations with said equipment at the closest CBN to the project site before and after the project survey.
- A surveyor can perform the same self-assessment as above before and after a large project, without any additional specialized training, input from the service provider, or processing.

- Service providers can be requested by the government, as part of a certification process, to periodically occupy a set of monuments (e.g., CBNs) within their networks, and report the differences between their network RTK coordinates and the published CBN values.

Note that such assessments could potentially still have some geographic sensitivity / correlation effects, given the proximity of test stations to network RTK reference stations compared to the actually survey area's proximity to the nearest network RTK reference stations. But this test would be fairly independent and representative of overall service performance, while not being an onerous task.

4.3.3 User monitoring site(s)

Another independent user coordinate verification option would be the use of user monitoring stations independent from the service providers' reference networks. One or multiple sites could be established at central locations of high use, and maintained by neutral parties, such as governments or academic institutions. This option would be similar to the user self-assessment option, except rather than use a passive network site, one or multiple CORS is/are used instead. The raw data from such a site or sites would be used to continuously determine reference coordinates by which to assess the user RTK coordinates by.

4.4 Recommendations

RECOMMENDATION 7: The Ontario model of multiple commercial network RTK service providers does not lend itself well to unified and harmonized network management, but it is recommended that standardized, consistent, unified and harmonized (integrated) network services in the form of coordinate datums and datum transformations (e.g., as described in Recommendation 1) be achieved, and that these are publicized to the user community.

RECOMMENDATION 8: Some form of RTK network certification or operational guidelines should be established in Ontario, in order that the user community can access a standardized and consistent reference frame throughout the province. Refer to Recommendations 9 through 11.

RECOMMENDATION 9: Develop in partnership with industry a reference station design and installation guidelines for existing and new network RTK CORS based on a subset of the presented digest of existing standards, that are realistic, and beneficial for network RTK service provider system performance and users performance.

RECOMMENDATION 10: Develop in partnership with industry network RTK maintenance and expansion guidelines based on a subset of the presented existing standards, that are realistic, and beneficial for network RTK service providers and users.

RECOMMENDATION 11: Develop in partnership with network RTK operator and user guidelines based on any or all of the user coordinate verification options described.

5 Conclusions and Recommendations

While commercial network RTK use in Canada and abroad is no longer innovative in itself, the use of this technology by MTO to carry out its control and engineering surveys would be a technical and financial innovation for MTO. Also, other surveying and engineering groups in Ontario who are using network RTK would benefit from the stability and continuity that certification would bring.

The objectives set out for this project have been met and can be summarized as follows:

a) Integration of service providers' reference stations into the provincial network can be performed by means of Geodetic Survey Division (GSD), Natural Resources Canada (NRCan) baseline processing and network adjustment, Precise Point Positioning (PPP) processing, or independent baseline processing and network adjustment.
b) Monitoring of service providers' existing and new reference stations can be performed by means of GSD, NRCan baseline processing and network adjustment, PPP processing, or independent baseline processing and network adjustment with a software utility such as the developed RTKNetworkAnalysis software.
c) The various aspects of network RTK certification have been presented with examples of certification methodologies used elsewhere, and suggestions for components that should be implemented in Ontario.

The following recommendations have been made, based on the work involved in attaining the objectives:

RECOMMENDATION 1: Given the complex nature of reference station integration into the Canadian datum, have GSD continue with its processing of NRTK reference station data voluntarily supplied by companies. These few hundred pan-Canadian stations add density to GSD's on going North American velocity field estimation, even though the CORS are not necessarily of the highest monument stability. The frequency of data processing and coordinate updating will have to be decided by all parties, as well as the level of formality of the GSD processing and companies' usage of determined coordinates.

RECOMMENDATION 2: Given that daily static PPP processing of NRTK reference station measurements produce few millimetre-level horizontal coordinate differences with respect to relative positioning weekly averages, and that weekly averaging of daily PPP results further reduces these differences, it is recommended that for new sites, that the weighted average of one week of daily PPP-determined coordinates can be used for the initial reference station coordinates. To provide uniformity, all service providers can use the NRCan on-line PPP processor, CSRS-PPP.

RECOMMENDATION 3: Given the complexity to process baseline solutions to their maximum effectiveness, as well as in the network adjustment of these solutions necessary to integrate NRTK reference stations, it is recommended, aside from Recommendations 1 and 2, that a service provider can utilize a commercial GNSS software with the capability to derive high-quality long baseline solutions can be used as prescribed. Then, an adjustment software tool, such as RTKNetworkAnalysis, can be used to perform the network adjustment using the estimated baselines as measurements.

RECOMMENDATION 4: Static PPP processing can be used to monitor network RTK reference station and integrate new stations by means described in Recommendation 2. Static and kinematic PPP processing can adequately provide continuous and independent monitoring of network RTK stations; however, offsets and drifts must be treated carefully. To provide uniformity, all service providers can use the NRCan on-line PPP processor, CSRS-PPP, with set processing parameter settings.

RECOMMENDATION 5: Given the complexity to process baseline solutions to their maximum effectiveness, as well as in the network adjustment of these solutions necessary to integrate network RTK reference stations, it is recommended, aside from Recommendations 1 and 3, service providers can process new station data with commercial GPS software capable of deriving high-quality long baseline solutions as prescribed and adjust these baselines with adjustment software such as RTKNetworkAnalysis, or wait for proposed routine, e.g., daily or weekly, GSD station coordinate processing result.

RECOMMENDATION 6: An adjustment software tool, such as RTKNetworkAnalysis (developed for this report), should be used to perform the network adjustment using the estimated baselines as measurements for, e.g., free network adjustments and coordination of new stations with respect to fixed stations.

RECOMMENDATION 7: The Ontario model of multiple commercial network RTK service providers does not lend itself well to unified and harmonized network management, but it is recommended that standardized, consistent, unified and harmonized (integrated) network services in the form of coordinate datums and datum transformations (e.g., as described in Recommendation 1) be achieved, and that these are publicized to the user community.

RECOMMENDATION 8: Some form of RTK network certification or operational guidelines should be established in Ontario, in order that the user community can access a standardized and consistent reference frame throughout the province. Refer to Recommendations 9 through 11.

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RECOMMENDATION 10: Develop in partnership with industry network RTK maintenance and expansion guidelines based on a subset of the presented existing standards, that are realistic, and beneficial for network RTK service providers and users.

RECOMMENDATION 11: Develop in partnership with industry network RTK operator and user guidelines based on any or all of the user coordinate verification options described.

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7 Appendix A: Results from Bernese Processing

Adjusted coordinates from Bernese processing (DOY 220)

Station name	X (m)	Y (m)	Z (m)
SUND	820967.7135	-4380339.64	4547940.274
BARR	818533.9352	-4489780.63	4441023.835
MIDL	796876.8981	-4466962.1	4467606.517
NEWM	842642.733	-4512161.11	4413945.418
BROC	1125214.576	-4408309.58	4455147.066
KING	1068940.249	-4451485.93	4426182.292
SMIT	1093008.803	-4391549.71	4479534.805
BELL	997497.7321	-4473730.87	4420481.142
COBO	944605.7037	-4500389.8	4405082.248
MADO	988810.0456	-4449659.01	4446556.947
PICT	1022574.858	-4479803.57	4408648.778
BRIT	730615.7288	-4396255.53	4547784.997
PARR	777263.5634	-4422633.43	4514594.624
SUDB	688502.5161	-4348049.82	4600166.536
OSHA	888061.0915	-4519808.49	4397014.249
PETE	925487.1891	-4477704.12	4432162.63
CHAT	640862.0106	-4673953.46	4278167.481
SARN	617604.7424	-4632848.37	4325712.356
WIND	585894.7334	-4689810.06	4268747.646
CARL	1085253.423	-4371393	4500962.835
OTTA	1108934.082	-4352173.63	4513665.4
CORN	1188957.684	-4355411.12	4490208.762
KEMP	1118877.998	-4374936.96	4489292.275
HAMI	818576.0446	-4580152.7	4348147.996
STCA	866981.481	-4577462.41	4341610.947
WATE	763954.6718	-4571484.04	4367365.966
HUNT	841764.5041	-4411587.62	4513970.504
KINC	692310.4067	-4543699.77	4407772.317
MOUN	740303.836	-4537238.2	4406830.417
LOND	711420.4687	-4618111.48	4327138.301
WOOD	748605.4611	-4601576.71	4338474.191

ORAN	790959.469	-4533505.87	4401944.565
OWEN	716735.8225	-4495020.01	4453103.725
WELL	871631.07	-4590620.67	4327000.765

Adjusted coordinates from Bernese processing (DOY 221)

Station name	X (m)	Y (m)	Z (m)
HUNT	841764.5043	-4411587.619	4513970.507
SUND	820967.7134	-4380339.64	4547940.275
BROC	1125214.575	-4408309.574	4455147.064
CORN	1188957.683	-4355411.123	4490208.762
COBO	944605.7011	-4500389.797	4405082.247
BELL	997497.7326	-4473730.862	4420481.141
CHAT	640862.0117	-4673953.469	4278167.489
LOND	711420.4687	-4618111.479	4327138.304
CARL	1085253.423	-4371392.999	4500962.835
KEMP	1118877.999	-4374936.958	4489292.278
OTTA	1108934.082	-4352173.624	4513665.397
KINC	692310.4146	-4543699.774	4407772.323
SARN	617604.7449	-4632848.376	4325712.366
KING	1068940.249	-4451485.929	4426182.293
MADO	988810.0443	-4449659.006	4446556.94
PETE	925487.1881	-4477704.119	4432162.629
MIDL	796876.8978	-4466962.096	4467606.518
BARR	818533.9369	-4489780.634	4441023.839
MOUN	740303.8371	-4537238.207	4406830.423
MISS	831734.4215	-4548393.291	4378729.257
OSHA	888061.0915	-4519808.477	4397014.244
NEWM	842642.7345	-4512161.111	4413945.421
OWEN	716735.8226	-4495020.011	4453103.727
ORAN	790959.4712	-4533505.877	4401944.571
PICT	1022574.857	-4479803.567	4408648.778
PARR	777263.563	-4422633.434	4514594.626
BRIT	730615.7295	-4396255.533	4547784.997
STCA	866981.482	-4577462.403	4341610.942
HAMI	818576.0445	-4580152.711	4348148.002
SUDB	688502.5168	-4348049.824	4600166.537
SIMC	788669.1524	-4617401.499	4314527.17
WELL	871631.0688	-4590620.665	4327000.763
SMIT	1093008.804	-4391549.708	4479534.8
WATE	763954.6719	-4571484.038	4367365.961

WIND	585894.7327	-4689810.061	4268747.65
WOOD	748605.461	-4601576.704	4338474.189

Standard residuals for baseline measurements from free network adjustment of Example 1 (Section 2.3.2.3)

From	To	Vdx (mm)	Vdy (mm)	Vdz (mm)
ALGO	OSHA	-0.3	0.3	0.1
BARR	MIDL	-0.5	0.0	-0.7
BROC	COBO	-0.8	0.7	-0.7
BROC	KEMP	1.0	-0.1	0.5
BELL	OSHA	-1.1	-0.9	-0.4
BRIT	SUND	-0.6	-0.2	0.8
COBO	MIDL	0.4	1.0	-1.2
COBO	WATE	0.5	0.7	-1.0
COBO	WELL	1.2	0.6	-0.4
CHAT	OSHA	-0.7	1.9	-1.6
CARL	KEMP	0.8	-0.5	0.9
CARL	MOUN	-0.3	-1.2	0.4
CORN	OSHA	1.3	1.5	-0.4
GODR	PARY	0.9	-0.9	1.2
GODR	PWEL	0.8	1.0	-1.2
HAMI	OSHA	-0.1	3.3	-3.4
HUNT	SUND	-0.6	0.2	-0.1
KINC	WELL	-3.5	-0.5	-0.6
KING	OSHA	-0.3	0.0	-0.9
KNGS	PARY	-0.2	0.1	0.4
LOND	WELL	0.2	0.1	-0.3
MADO	OSHA	0.6	-0.8	1.3
MIDL	SUND	1.5	-0.5	0.2
NEWM	OSHA	0.3	0.0	0.7
NRC1	WELL	-0.1	0.5	-0.5
ORAN	OSHA	-0.4	0.3	-0.4
OSHA	OTTA	-0.1	-0.3	0.2
OSHA	OWEN	-1.2	0.0	-0.1
OSHA	PARR	-1.6	0.7	-0.2
OSHA	PETE	-0.1	0.0	-0.1
OSHA	STCA	1.0	1.2	-1.1
OSHA	SMIT	0.1	1.6	-1.8
OSHA	WELL	-0.8	-0.2	0.3
OSHA	WOOD	-0.5	0.6	-0.9
OWEN	PARY	0.7	-0.8	0.5
PICT	SARN	0.3	0.7	0.2
PICT	WELL	0.0	0.6	-0.4
SUDB	SUND	-0.6	0.8	-0.9
WELL	WIND	-0.8	0.6	-1.1
ALGO	SUND	0.3	-0.3	-0.2
BARR	NEWM	0.4	0.0	0.6

BROC	KING	0.0	0.1	-0.6
BROC	SMIT	-0.2	-0.9	0.8
BELL	COBO	1.1	0.3	-0.4
BELL	MADO	0.6	-0.7	1.3
BELL	PICT	-0.3	1.1	-0.1
BRIT	PARR	1.3	-0.5	-0.1
BRIT	SUDB	-0.6	0.8	-0.8
COBO	OSHA	-1.7	-1.0	1.1
COBO	PETE	0.1	0.0	0.1
CHAT	SARN	-0.1	-1.8	1.1
CHAT	WIND	0.8	-0.5	1.0
CARL	OTTA	0.0	0.7	-0.6
CARL	SMIT	-0.5	1.0	-0.6
CORN	KEMP	-1.3	-1.2	0.1
GODR	KINC	-1.8	0.2	-0.5
HAMI	MISS	-0.1	-0.9	0.7
HAMI	STCA	0.2	-2.8	3.1
HUNT	PARR	0.6	-0.2	0.1
KINC	MOUN	2.1	0.9	0.3
KEMP	SMIT	0.7	-1.6	1.6
KING	KNGS	0.3	0.1	0.5
KNGS	PICT	0.5	0.0	0.1
LOND	SARN	-0.2	1.0	-1.1
LOND	WOOD	0.0	-1.0	1.4
MIDL	PARY	-1.3	1.6	-2.0
MOUN	ORAN	-0.3	1.0	-0.8
MOUN	OWEN	2.0	-0.8	0.6
MOUN	WATE	-0.1	-0.5	0.8
MISS	NEWM	0.0	-0.1	0.2
MISS	ORAN	-0.1	-0.8	0.5
NRC1	OTTA	0.1	-0.5	0.5
PARR	PARY	0.0	0.0	-0.1
PWEL	STCA	0.8	1.0	-1.2
STCA	WELL	1.9	-0.6	0.8
SIMC	WOOD	---	---	---
WATE	WOOD	0.5	0.3	-0.3

Standard residuals for baseline measurements from free network adjustment of Example 2 (Section 2.3.2.3)

From	To	Vdx (mm)	Vdy (mm)	Vdz (mm)
ALGO	OSHA	0.2	1.3	-1.0
BARR	MIDL	-0.6	0.1	-0.9
BROC	COBO	-1.1	0.8	-0.9
BROC	KEMP	1.3	0.0	0.6
BELL	OSHA	-1.3	-1.1	-0.5
BRIT	SUND	-0.8	-0.4	1.1
COBO	MIDL	0.5	0.9	-1.1
COBO	WATE	1.0	0.9	-1.1

COBO	WELL	1.0	0.7	-0.6
CHAT	OSHA	-0.6	2.4	-1.9
CARL	KEMP	0.7	-0.7	1.0
CARL	MOUN	0.2	-1.6	0.8
CORN	OSHA	1.5	1.7	-0.6
GODR	PARY	0.6	-0.9	0.8
HUNT	SUND	-0.8	0.1	0.0
KING	OSHA	-0.4	0.1	-1.2
KNGS	PARY	-0.2	0.2	0.5
LOND	WELL	-0.1	0.1	-0.5
MADO	OSHA	0.8	-0.9	1.6
MIDL	SUND	1.5	-0.9	0.5
NEWM	OSHA	0.3	0.7	0.1
NRC1	WELL	-0.9	-0.6	-0.2
ORAN	OSHA	-0.9	0.8	-1.1
OSHA	OTTA	0.2	0.2	0.1
OSHA	OWEN	-1.1	-0.1	0.2
OSHA	PARR	-1.8	0.6	0.1
OSHA	PETE	-0.2	-0.1	-0.1
OSHA	STCA	1.4	0.7	-0.9
OSHA	SMIT	0.2	1.9	-2.1
OSHA	WELL	-1.5	-0.3	0.3
OSHA	WOOD	-0.6	0.7	-1.0
OWEN	PARY	0.7	-1.2	0.8
PICT	SARN	0.3	0.8	0.2
PICT	WELL	-0.4	0.8	-0.6
SUDB	SUND	-0.8	0.9	-1.0
WELL	WIND	-0.7	0.8	-1.3
ALGO	SUND	0.6	0.4	-0.7
BARR	NEWM	0.6	-0.1	0.9
BROC	KING	0.0	0.1	-0.6
BROC	SMIT	-0.2	-1.0	1.0
BELL	COBO	1.3	0.4	-0.4
BELL	MADO	0.8	-0.9	1.6
BELL	PICT	-0.4	1.3	-0.1
BRIT	PARR	1.6	-0.4	-0.3
BRIT	SUDB	-0.8	0.9	-0.9
COBO	OSHA	-2.1	-1.1	1.2
COBO	PETE	0.1	0.1	0.1
CHAT	SARN	-0.2	-2.2	1.3
CHAT	WIND	0.7	-0.7	1.2
CARL	OTTA	-0.1	1.1	-1.0
CARL	SMIT	-0.8	1.1	-0.8
CORN	KEMP	-1.5	-1.4	0.2
GODR	KINC	0.3	0.7	-0.3
HAMI	MISS	-0.2	1.2	-1.2
HAMI	STCA	0.2	-1.2	1.3
HUNT	PARR	0.8	0.0	0.0

KINC	MOUN	0.3	0.8	-0.3
KEMP	SMIT	0.8	-1.9	2.0
KING	KNGS	0.5	-0.1	0.7
KNGS	PICT	0.1	0.2	-0.1
LOND	SARN	-0.2	1.2	-1.3
LOND	WOOD	0.3	-1.2	1.7
MIDL	PARY	-1.4	2.0	-2.4
MOUN	ORAN	-0.9	0.7	-0.8
MOUN	OWEN	2.0	-1.1	0.6
MOUN	WATE	-0.8	-0.7	0.8
MISS	NEWM	-0.2	0.8	-0.7
MISS	ORAN	0.0	0.2	-0.4
NRC1	OTTA	0.0	-1.1	0.7
PARR	PARY	0.2	0.0	0.0
PWEL	STCA	0.0	0.1	0.6
STCA	WELL	1.6	-0.1	0.5
SIMC	WOOD	---	---	---
WATE	WOOD	0.3	0.4	-0.5
ALGO	OSHA	0.2	1.3	-1.0
BARR	MIDL	-0.6	0.1	-0.9