Time Series Analysis of Permanent GNSS Station Positions, Case Study: Western Canada

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Summary

This paper analyzes the position of permanent GNSS base stations in Western Canada over a period of 5 years to study plate tectonic displacements. The control stations are located throughout British Columbia, Canada, near several oceanic and continental plate boundaries and faults. The published plate motion models would suggest noticeable movements. The paper analyzes this network to determine the possible deformation between one epoch to another.

This study takes advantage of mostly free software and simple methodology in order to determine the deformation. Precise Point Positioning (PPP) software from NRCan Canada is used as the main GNSS data processing tool, and the deformation will be calculated using the Iterative Weighted Similarity Transformation (IWST).

The results from this investigation show an estimate for the magnitude, speed and direction of the movement of base stations. Further, it discusses all possible systematic errors (tidal influences, precipitation, ext.) associated with GNSS data, and how those can be taken out of the new GNSS measurements. Finally, it discusses the next steps being done in order to improve the method and get more optimum results in the future.

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Jordan PALK and Mohammad RAJABI, Canada

1. Introduction

It is well documented that the west coast of Canada, the province of British Columbia, is a very seismically active area, with five plates meeting one another. These five plates are the North American Plate, Explorer Plate, Juan De Fuca Plate, Pacific Plate, and the Gorda Plate (Figure 1). These boundaries are all within a few hundred kilometers of the coast of British Columbia, meaning that movement at these plate boundaries will translate to movement within the province. This movement can have a profound impact on positions within the province and specifically survey benchmarks. There a numerous organizations that have studied these types of interactions and have come up with plate velocity models. These models represent the movement of positions due to plate tectonics functions. In Canada, this research is done by Natural Resources Canada (NRCan), and they publish the velocity measurements throughout the country.

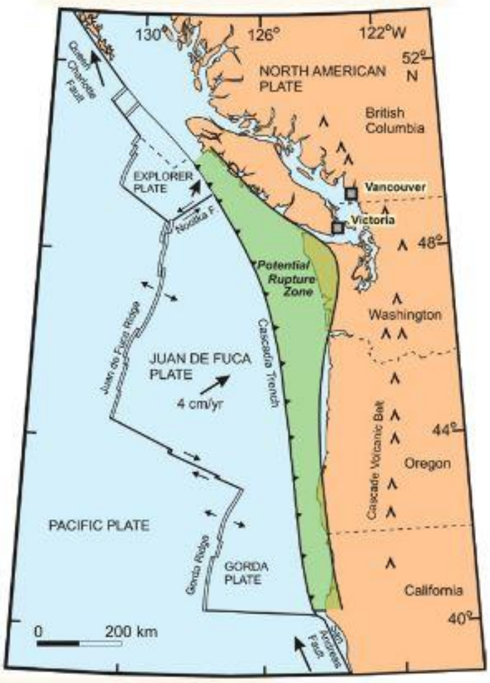


Figure 1: Geological Plates along the West Coast of BC, Canada (NRCan, 2011)

1.1 Background

Since Global Navigational Satellite Systems (GNSS) were created over sixty years ago, it has become an extremely important asset to the scientific community. It has allowed for accurate real time worldwide positioning as well as the ability to constantly monitor positions. Many governments have taken advantage of GNSS technology and have set up continuously operating stations which allow for scientific research, surveying, and monitoring. These continuously operating stations or active control stations operate twenty-four hours a day, and three hundred and sixty-five days a year. They are monitoring their positions, and because their positions are known, they are able to determine what the bias is and broadcast the correction. They may also be used as a means of differential corrections. Meaning if you connect to it with your GNSS receiver, it will tell you position relative to it, and providing accurate results. But, if the positions of the active control stations are not correct, then they are provided people with incorrect positions. Earth is a dynamic environment, always changing because of plate tectonics, sea level rise, as well as astronomical effects. To account for this, one must update or positions regularly.

Furthermore, over the last decade recent advancements in the field of Precise Point Positioning (PPP) software has allowed the general public to have access to accurate and free GNSS solution. Anyone accessing a computer has the ability to submit their GNSS data to one of these numerous PPP software and typically in less than half an hour, the user can receive accurate positons.

This study looks at the effectiveness of using free PPP software in order to view deformation on active control network caused by plate tectonic movements and see if it matches the published models.

2. Study Overview

2.1 Study Area

The area which this study takes place is in British Columbia, Canada. There is an active control system known as British Columbia Active Control System (BCACS), which has 21 stations (GeoBC, 2020) located all around the province and is operated by a provincial agency called GeoBC (Figure 2). The four stations chosen for this study are located in Prince George (BCPG), Williams Lake (BCWA), Denny Island (BCDI), and Prince Rupert (BCPR) an are represented by red circles on Figure 2. These stations are located along the central coast and central interior of British Columbia, with BCDI and BCPR on the coast, and BCPG and BCWA in the interior. As a reference, the distance between BCPR to BCPG is 500 km, BCPG to BCWA is 200 km, BCWA to BCDI is 400 km, and BCDI to BCPR is 300 km. Table 1 represents the coordinates in NAD83 (CSRS) 2010.0 of the locations mentioned above.

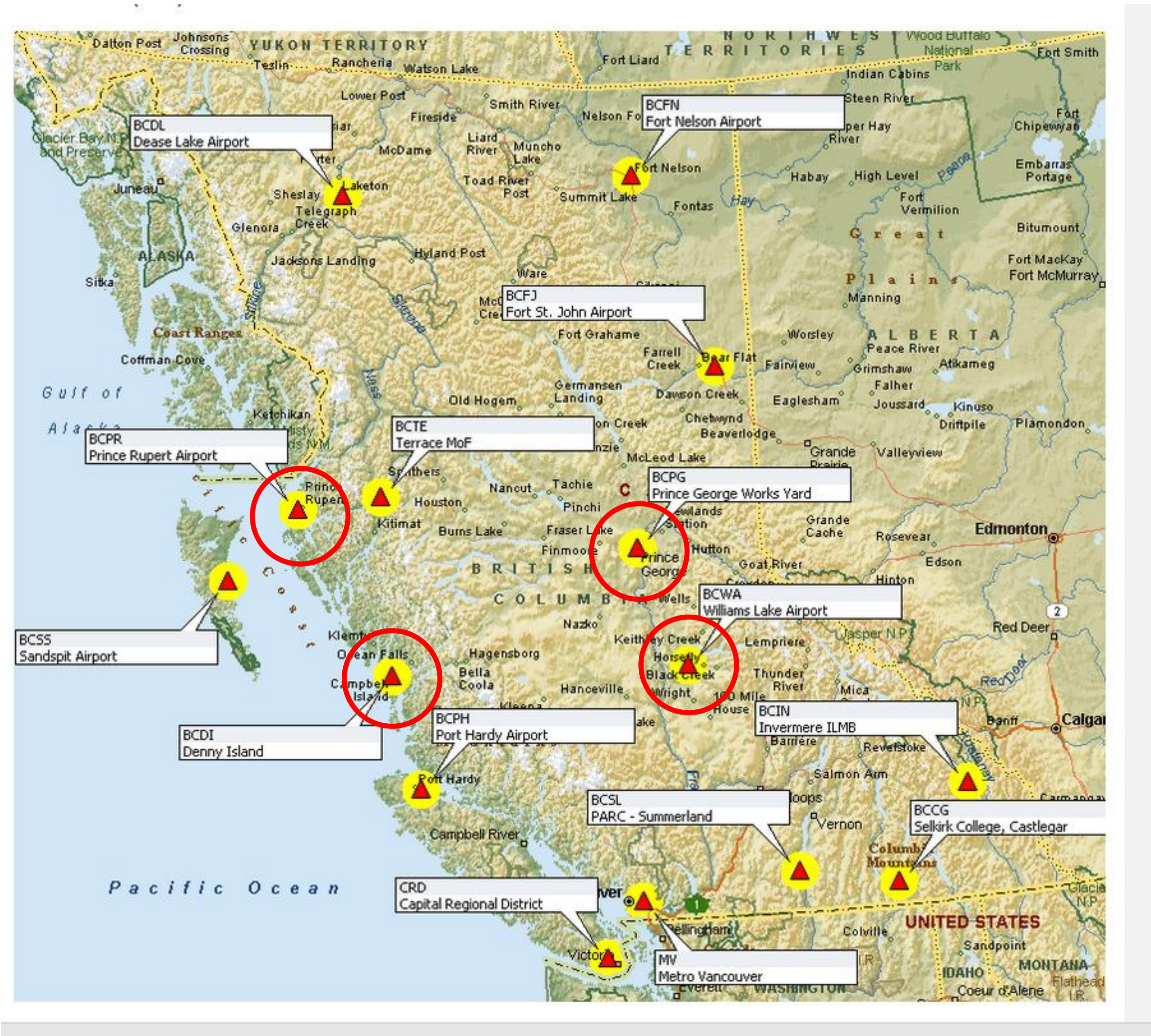


Figure 2: British Columbia Active Control System Location (GeoBC, 2020)

Table 1: Case Study British Coloumbia Active Control Locations

STN	CITY	LATITUDE	LONGITUDE	ELIIPSOID HEIGHT
BCPR	Prince Rupert	N 54°16’36.61684”	W 130°26’04.47809”	28.965 m
BCPG	Prince George	N 53°54’29.24580”	W 122°47’46.36966”	601.845 m
BCWA	Williams Lake	N 52°11’14.71005”	W 122°03’51.84322”	927.352 m
BCDI	Denny Island	N 52°09’28.84236”	W 128’06’37.59760”	22.400 m

2.2 Raw Data

The data being used for this study is dual frequency (L1 and L2) Multi-GNSS (GPS and GLONASS) RINEX 2.11 data. This data has been collected using Leica 1200 receivers with a sampling rate of one second. In this study, data was chosen for a period of five years, 2015-2019, with four samples taken form each year. These four samples were taken approximately ninety days apart from each other in order to have a sample in each season (fall, winter, spring, and summer). However, due to data availability the samples are not always exactly ninety days and in the extreme case of 2015 to 2016 the interval is only sixty days. Table 2 shows the data used and their associated year and GPS date.

Table 2: Case Study Data Dates (Year and Day No.)

2015	2016	2017	2018	2019
091	001	005	001	001
181	091	091	091	091
275	181	181	181	181
300	271	272	272	271

3. Error Sources

Before any data could be processed it is important to identify possible errors that could be present in the data and how they can be eliminated or minimized. These errors can be broken down into three main categories; gross (blunder), random, and systematic.

3.1 Gross Errors (Blunders)

Gross errors are errors which are generally large in magnitude, but can be avoided. When using GNSS data there are a few gross errors that can be present. The first error is referred to as cycle slip. This occurs when the signal is lost at a GNSS receiver and it can no longer resolve all the ambiguities of the position (Hofmann-Wellenhof, Litchenegger, & Wasle, 2006, pp. 194-195). These errors generally occur when there is a disruption in the receiver's line of sight to the sky. However, with an active control system the stations are usually set up in locations (like mountain tops and tops of building) that always have direct line of sight to the sky. Other errors that may be present deal with the RINEX file. Wrong antenna heights or antenna names can cause for improper antenna calibration file to be used in the PPP algorithm.

3.2 Random Errors

Random errors are errors that are unavoidable and cannot be eliminated, however, they may be reduced through redundancy and adjustments. In this study random errors are assumed to be minimized by the PPP algorithm as well as though the iterative weighted similarity transformation discussed in section 4.4.

3.3 Systematic Errors

Systematic errors are errors that can be eliminated from the data using proper models and techniques. When dealing with GNSS data these errors can be very extreme and if not properly removed they will cause large discrepancies in the data. There are six main systematic errors that have to be addressed; ionospheric, tropospheric, ocean tidal loading, seasonal conditions, satellite clock, and orbital errors.

The first two errors deal with the atmospheric conditions. The ionosphere is the layer located within the upper atmosphere that when it comes into contact with solar energy it cause ions to be created which cause numerous free electrons to be present. These electrons interact with the GNSS signal and cause them to refract which affects the horizontal position (Hofmann-Wellenhof, Litchenegger, & Wasle, 2006, pp. 128-136). The ionosphere is a dispersive medium which fluctuations in size depending on the time of year and day (largest in the winter and during the day and smallest in the summer and at night). There are models which address and compensate for this problem.

The next problem is with the troposphere. The troposphere is the lower level of the atmosphere and is considered a non-dispersive medium. This layer often has a high concentration of water vapour which causes a delay in the signal which has an effect on the vertical position (Hofmann-Wellenhof, Litchenegger, & Wasle, 2006, pp. 137-138). Similar to the ionosphere the tropospheric errors can be corrected for using models. It should be noted that these errors are often looked at as the limiting factor of GNSS technology today.

The third error deals with the effect of ocean tide on GNSS positions. When the oceans tide comes to shore, it forces the earth's crust down into the mantle, and when it recedes the crust rebound from the mantle. Depending on the proximately to the of the GNSS station to the shore of the ocean, and the magnitude of the tide, the vertical position may be affected by over 5 cm and the horizontal potion by 2 cm (Natural Resources Canada, 2019). This phenomenon can be modeled through ocean title loading models (OTL) and eliminated.

The next error deals with seasonal conditions. These seasonal conditions deal primarily with precipitation and how it affects GNSS positions. It is possible that the weight of rain and snow in the soil force the crust down into the mantle and therefore affects the positions. However, this is extremely difficult to model and varies depending on the time of year. In order to eliminate this, signal processing would have to be done and then verified with local precipitation reports.

The final two errors deal with satellite clock and orbital errors. Each of these errors has a major impact on the position received by the GNSS receiver. The clock error has to do with the shift or error in time between the receiver and the satellite (Hofmann-Wellenhof, Litchenegger, & Wasle, 2006, pp. 105-106). Because positions are calculated based on the time it takes the signal to reach the receiver, the slightest error can have a profound effect. Satellite orbit error comes from not knowing the exact position of each satellite, which again can influence the position received by the GNSS receiver (Hofmann-Wellenhof, Litchenegger, & Wasle, 2006, p. 109). However like ionospheric error, clock error and satellite orbit error can be removed through using published precise clock and ephemerides files.

4. Methodology

4.1 TEQC

The raw RINEX data comes in twenty-four files (a-x) which need to be combined into a single file in order to be processed. In order to do this, TEQC was used (UNAVCO, 2020).

TEQC is a free, command line based RINEX editing software developed by UNAVCO. It is an industry standard that has numerous tools for manipulating raw RINEX data.

4.2 NRCan CSRS-PPP

Natural Resources Canada (NRCan) is a government agency that is responsible for federal resource matters. They also offer numerous geodetic tools that are extremely useful to surveyors. The tool used in this study was the CSRS-PPP (Natural Resources Canada, 2019). This is a free Precise Point Positioning software that allows the user to submit a RINEX file and within a short time the data has been processed and sent back to the user in the form of a .zip file. In this file are numerous returns, however for the purpose of this study the summary file (.sum) was the one used. This summary files contains information about what models were used as well as the final coordinated computed with their standard deviations and correlations.

For this study all data was processed using NAD83 (CSRS) with an epoch of 2010.0 and the Cartesian x, y, z coordinates along with the standard deviations and correlations were extracted and used in future data analysis. Table 3 shows the published and computed coordinates of the stations involved in this study at different epochs along with their corresponding 95% confidence level accuracy in metres. To save space only the first and final epoch of data's coordinates are displayed in Table 3.

Table 3: Published and PPP Computed Coordinates of Stations along with 95% Confidence Interval Accuracy

PUBLISHED							
	Station	**x**	**y**	**z**	**sdx(95%)**	**sdy(95%)**	**sdz(95%)**
	BCDI	-2420024.654	-3085213.517	5013626.346	0.006	0.011	0.005
	BCPG	-2039776.157	-3165572.419	5131212.727	0.002	0.002	0.005
	BCPR	-2420666.249	-2840797.986	5154819.164	0.007	0.012	0.005
	BCWA	-2080527.666	-3321227.545	5016348.077	0.002	0.002	0.005
2015							
GPS Day	**Station**	**x**	**y**	**z**	**sdx(95%)**	**sdy(95%)**	**sdz(95%)**
091	BCDI	-2420024.6466	-3085213.5191	5013626.3850	0.0037	0.0039	0.0050
091	BCPG	-2039776.1545	-3165572.4270	5131212.7550	0.0037	0.0041	0.0054
091	BCPR	-2420666.2725	-2840798.0169	5154819.1956	0.0057	0.0057	0.0076
091	BCWA	-2080527.6456	-3321227.5441	5016348.0867	0.0037	0.0041	0.0050
2019							
GPS Day	**Station**	**x**	**y**	**z**	**sdx(95%)**	**sdy(95%)**	**sdz(95%)**
271	BCDI	-2420024.6518	-3085213.5237	5013626.3991	0.0039	0.0042	0.0054
271	BCPG	-2039776.1562	-3165572.4308	5131212.7611	0.0037	0.0041	0.0055
271	BCPR	-2420666.2904	-2840798.0325	5154819.2029	0.0055	0.0057	0.0076
271	BCWA	-2080527.6503	-3321227.5513	5016348.0956	0.0038	0.0043	0.0053

4.3 Data Preparation

In order to perform the deformation analysis, a preparation steps must be done first. The first one involves calculating the initial displacement between epochs. This can be done simply by subtracting the x, y, z coordinates of each station between epochs; as seen in equation 1 below.

$$\text{Displacement} \begin{bmatrix} dx \\ dy \\ dz \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \text{Epoch1} - \begin{bmatrix} x \\ y \\ z \end{bmatrix} \text{Epoch2} \quad (1)$$

Next, the cofactor matrix for each epoch must be created. The standard deviations in the PPP solution summary file are given at 95% confidence. This means that the standard deviation is not what was actually determined, but rather a maximum discrepancy. Therefore, this value must be divided by the z-score; as seen in equations 2 and 3.

$$\delta 95\% = \delta \times z95\% \quad (2)$$

$$\delta = \frac{\delta 95\%}{z95\%} \quad (3)$$

Where:

$\delta 95\%$ is the standard deviation at 95% confidence,
δ is the standard deviation, and
z95% is the z-score at 95% confidence which is 1.96.

The next step is to determine the covariance between x, y, z. The PPP solution summary file gives the correlation between x-y, x-z, and y-z, which then must be converted to covariance. This can be done by rearranging the correlation equations; as seen in equations 4 and 5.

$$Correlation(x, y) = \frac{cov(x, y)}{(\delta x)(\delta y)} \quad (4)$$

$$Cov(x, y) = Correlation(x, y) \times \delta \mathrm{x} \times \delta y \quad (5)$$

Where:

Cov(x, y,) is the covariance between x and y,
δx is the standard deviation in x,
δy is the standard deviation in y.

It should be noted that equation 5 is used to determine he covariance between x-y, x-z, and y-z.

Next the cofactor matrix can be created. This involves the standard deviations of x, y, z as well as the covariance between them; as shown in equation 6.

$$Q_x = \begin{vmatrix} \delta x^2 & \delta x,y & \delta x,z \\ \delta x,y & \delta y^2 & \delta y,z \\ \delta x,y & \delta y,z & \delta z^2 \end{vmatrix} \quad (6)$$

Where:

δx,y is the covariance between x and y,
δx, y is the covariance between x and z, and
δy,z is the covariance between y and z.

Finally, the cofactor matrices between two epochs must be combined in order to do the iterative weighted similarity transformation. This can be simple done by adding the cofactor matrix from epoch one, to the cofactor matrix of epoch tow; as seen in equation 7 below.

$$Q_d = \begin{vmatrix} \delta x^2 & \delta x,y & \delta x,z \\ \delta x,y & \delta y^2 & \delta y,z \\ \delta x,y & \delta y,z & \delta z^2 \end{vmatrix} \text{Epoch 1} + \begin{vmatrix} \delta x^2 & \delta x,y & \delta x,z \\ \delta x,y & \delta y^2 & \delta y,z \\ \delta x,y & \delta y,z & \delta z^2 \end{vmatrix} \text{Epoch2} \quad (7)$$

4.4 Iterative Weighted Similarity Transformation (IWST)

Now that the data has been prepared, it can be run through the iterative weighted similarity transformation. This has to be done in order to determine the deformation. Because there may be datum defects between each epoch, the displacement calculated cannot be considered deformation (Ogundare, 2016, pp. 299-303). The methodology behind the IWST is discussed further in (Ogundare, 2019, pp. 565-566). Finally, for this study Matlab code was developed and used to do this computation (Mathworks Inc., 2020).

$$\hat{d}^{(k+1)} = S_k \text{ x } d^k \quad (8)$$

$$Q_{\hat{d}}(k+1) = S_k \text{ x } Q_{\hat{d}}(k) \text{ x } S_k^T \quad (9)$$

Where:

$$S_k = I - G(B_k^T \text{ x } G)^{-1} \text{ x } B_k^T \quad (10)$$

$$B_k = E_k \text{ x } G \quad (11)$$

$$E_k = \left(\begin{bmatrix} \frac{1}{sqrt(dx1^2+dy1^2+dz1^2+c)} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \frac{1}{sqrt(dxk^2+dyk^2+dzk^2+c)} \end{bmatrix} \right) \quad (12)$$

The I variable in equation 10 represents the identify matrix. For a singular point, this matrix is a 3 x 3.

$$I = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \quad (13)$$

The G variable in equation 10 represents the datum deficiency matrix. Identifying a three dimensional datum requires seven parameters. These parameters are, scale, orientation in x, y, z axes, and translation in x, y, z origin. When choosing the G matrix one should keep in mind the number of datum deficiencies present. For GNSS data the deficiencies occur in the translation of the x, y, z origin (Ogundare, 2019). So the G matrix will be a 3 by n matrix with n being the number of coordinates.

$$G^T = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \tag{14}$$

*Singular point (x, y, z)

The E_k matrix is used in order to remove the effects of datum deficiencies. This is done through an iterative process using equations 8 through 12 until the change in displacement is less than a specified threshold. This threshold can be set to any value; for the purpose of this study it is 0.0001. Further, the c in E_k represents a constant to ensure that the equations never drop below zero making it an invalid equation. For this study c is set as 0.0001 to match the threshold value. Finally, the k values thought equations 8 to 12 represent the number of iterations.

4.5 Assumptions

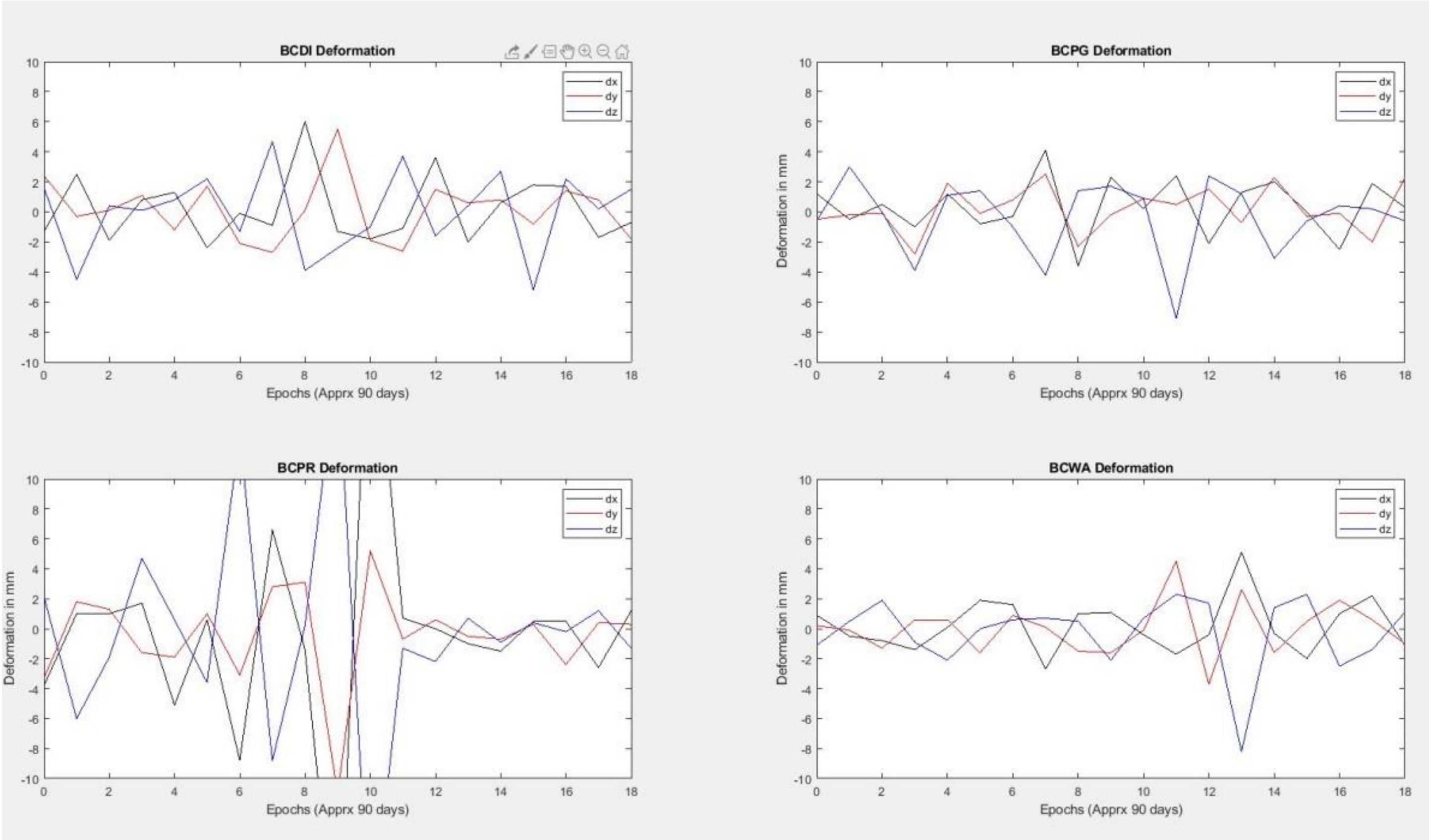
In order for this methodology to be used, a few assumptions had to be made. The first assumptions deal with the systematic errors and gross errors. It was assumed that there were no gross errors associated with the data (cycle slip, wrong antenna file, ext.) and that the NRCan PPP software algorithm removed all the systematic errors through the corresponding models (Ionosphere model, Troposphere model, ext.)

The second assumption deals with the Iterative Weighted Similarity Transformation (IWST). Generally, this step requires a least squares adjustment for each epoch and there will be an a-posterior variance factor. This factor assesses the quality of the adjustment and values near one are generally considered acceptable. Then the user would compare the a-posterior values form each epoch to check if each data set was comparable to the other (Ogundare, 2016, pp. 299-303). But because a least squares adjustment was not done on this data, it was assumed that each data set was compatible with one another and that the corresponding a-posteriori value was one.

5. Results

5.1 Deformation

The IWST was done a total of nineteen times, with the deformation being competed between each adjacent epoch. For example, the first deformation was computed between 2015-091 and



2015-181 and the second deformation was computed between 2015-181 and 2015-275 and so on.

Figure 3: Plot of x, y, z deformation in BCDI, BCPG, BCPR, and BCWA where the x axis is time in epochs (90 days apart) and the y axis is deformation in mm (black is dx, red is dy, and blue is dz)

It can be seen from Figure 3 that the deformation does not follow a specific trend, rather it appears to vary. This is likely and indication that there may be some errors present in the data, which will be discussed later in this section.

Further, it should be noted that this deformation is with respect to a Cartesian earth centred coordinated system in NAD83 (CSRS) 2010.0. So the deformation directions are not very meaningful and are not directly related to the movement on the ground in the north-south, east-west, and up-down direction. It is possible to bring these coordinates to a local geodetic system using a Geodetic to Local Geodetic transformation. However, the coordinates were not transformed from geodetic to local geodetic for the purpose of this study due to the presence of large systematic errors which should be removed from the data first.

5.2 Comparison to Published Plate Velocity Models

As discussed in the introduction, Natural Resources Canada has published plate velocity models for control stations throughout Canada. Table 4 illustrates the published velocities for the areas per year, and the ones computed in this study. The units for each velocity are in mm per year. The values for the study were computing taking the sum of all the deformations and dividing it by the total number of years which had past (for this study it is five years).

Table 4 NRCan Published Veolcites vs Study Calculated Veolcities (mm/year)

	NRCan Published			Calculated			Difference		
Station	**vx**	**vy**	**vz**	**vx**	**vy**	**vz**	**dvx**	**dvy**	**dvz**
BCDI	1.05	0.33	1.11	0.61	0.48	0.11	-0.44	0.15	-1.00
BCPG	1.34	-1.50	1.93	1.31	0.64	-1.49	-0.03	2.14	-3.42
BCPR	4.25	2.32	2.04	-1.93	-1.72	-1.25	-6.18	-4.04	-3.29
BCWA	2.52	-0.72	1.38	0.71	-0.04	-0.93	-1.81	0.68	-2.31

Table 4 shows that the calculated displacements in this study do not match those published. Even when doing a simple hypothesis test, the values are not statistically the same. Little effort was put into doing statistically analysis of the data due to the presence of large errors.

5.3 Positional Variations

In an attempt to identify possible errors present in the data, the computed coordinates at each epochs were graphed and analyzed to see if there were any noticeable errors. The mean was removed from each data set in order to plot the data from each station on top of each other and visualize the trends. Figure 4 illustrates this analysis.

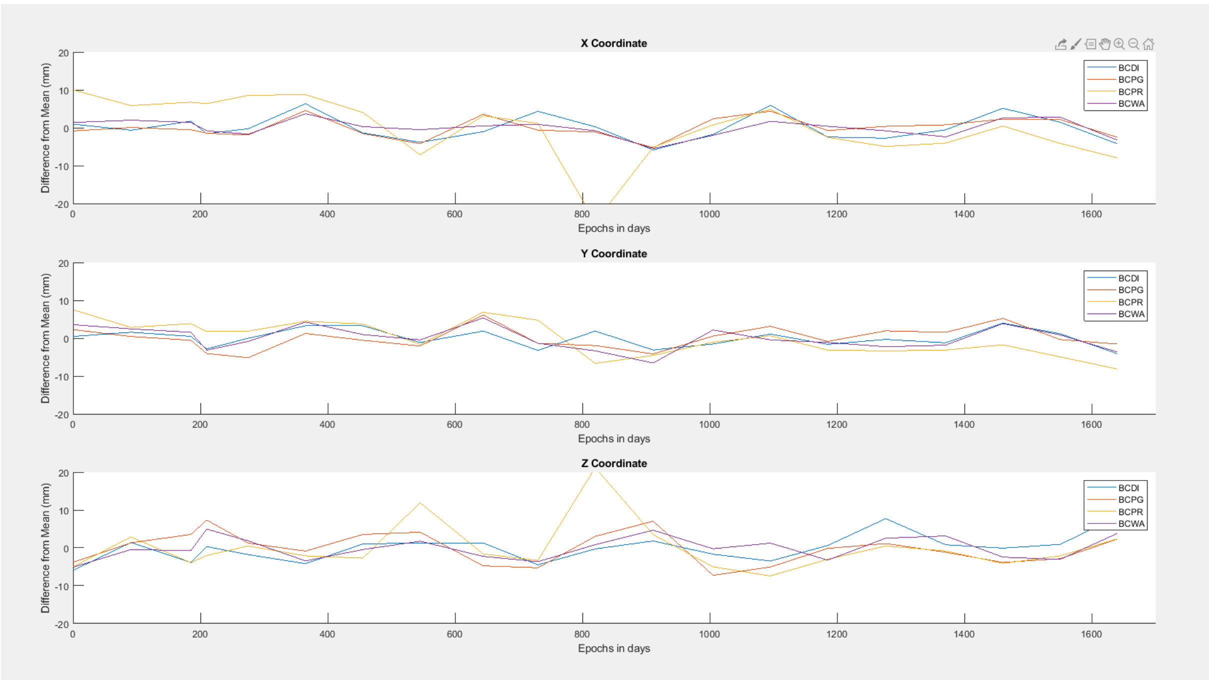


Figure 4: Plot of x, y, z coordinate variations form the mean for BCDI, BCPG, BCPR, and

BCWA where the x axis is epochs in days and the y axis is difference form the mean in mm (BCDI is blue, BCPG is orange, BCPR is yellow, and BCWA is purple)

It can be noticed from Figure 4 that there is definitely some sort of systematic error in the data as well as a possible gross error. Each station appears to follow a trend which is consistent with either a sinuosoidal curve. This indicates that all of the sytematic errors were not removed by the CSRS-PPP algortihm, which cause the defroamtion results gotten form the IWST to be inconsistent to the published ones. Like a least squares adjustemnt, the IWST is unable to handle systematic errors and therefore, incorrecntly distributed the errors. Furthermore, it can be seen from Figure 4 that in the midpoint of the BCPR station there is a rather large spike in the dataset. Though further analysis it was determined that this spike was caused by a cycle slip in the data which caused errors in the x an z positions of over 3 cm.

6. Future Analysis

The next step with this study is to analyze the data to try and identify systematic errors, like ionospheric and tropospheric errors, and try and remove them. This can be done using signal processing analysis like Least Squares Spectral Analysis (LSSA) (Vanicek, Wells, & Pagiatakis, 1985). However, due to sampling intervals of ninety days it only allows for signals with periods coinciding with these sampling intervals (90 days, 181 days, ext.) to be removed. And it is highly likely that some of these errors have periods that are more frequent.

7. Conclusion

The paper tried to examine the idea of using Precise Point Positioning software to determine deformation. The study shows that the systematic errors were too large and therefore deformation was not able to be seen. However, it may be possible to use this method in areas that have large positional changes (areas with lots of earthquakes) which render the systematic errors marginal.

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BIOGRAPHICAL NOTES

Jordan Palk is a Bachelor of Science graduating student of the Geomatics program at the British Columbia Institute of Technology. He currently works as a hydrographic survey technician with the department of public works and government services Canada. He currently is focusing his studies towards studying deformation of active control points in is local region, and how this will affect physical benchmarks in the area.

Mohammad Rajabi is a faculty member at the British Columbia Institute of Technology (BCIT), Burnaby, BC, Canada since 2014. His main research interests include Geodetic Positioning, Reference Systems, Global Navigation Satellite System, and Geospatial Information Systems (GIS).

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