RESEARCH ACTIVITIES IN PRECISE POSITIONING AT LAVAL UNIVERSITY

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This review paper summarises the recent, on-going, and future research activities in precise positioning at Laval University. The projects undertaken by the GPS and Geodesy Research Group are presented following three main research topics. The first one deals with the use of precise positioning for deformation monitoring of engineering structures. The study of ice forces on dams using a robotic total station and the improvement of GPS height determination using multiple GPS antennas linked to a single receiver with calibrated fiber optics are presented. A second topic of research is the crustal deformation of the Charlevoix seismic zone in Quebec. This study uses GPS and levelling techniques and involves an investigation of the temporal stability of the GPS permanent stations available in the surrounding area. Finally, research on single GPS receiver positioning techniques is presented, namely, Precise Point Positioning (PPP) and Time Relative Positioning (TRP).

Cet article récapitule les activités de recherche récentes, actuelles et futures dans le positionnement de haute précision réalisées à l'Université Laval. Les projets entrepris par le groupe de recherche en GPS et géodésie sont présentés selon trois thèmes de recherche principaux. La première thématique concerne l'utilisation du positionnement précis pour le contrôle des déformations de structures d'ingénierie. Dans ce contexte, on présente une étude sur les forces exercées par les glaces sur les barrages utilisant des mesures effectuées avec une station totale robotisée ainsi qu'une méthode pour améliorer la détermination de l'altitude par positionnement GPS en utilisant de multiples antennes reliées à un seul récepteur à l'aide de câbles en fibre optique dont les délais de propagation sont calibrés. Un deuxième thème de recherche porte sur la déformation de la croûte terrestre dans la zone séismique de Charlevoix au Québec. Cette étude utilise le GPS et le nivellement de précision et comporte une analyse de la stabilité temporelle des stations GPS permanentes disponibles dans la région. Finalement, deux recherches sur les techniques de positionnement avec un seul récepteur GPS sont présentées, soit le positionnement ponctuel précis (PPP) et le positionnement relatif temporel (PRT).

1. Introduction: Research Activities in Precise Positioning

Over the last decades, geodesy has undergone major developments. The advent of space borne techniques has revolutionized positioning. By exploiting the phase measurements of Global Navigation Satellite Systems (GNSS) in a differential mode, geodesists were able to push the accuracy of relative positioning down to several millimetres even on baselines of over 1000 km. Also traditional instruments have evolved, leading to the development of reflectorless distance meter and of automatic targeting total stations. Inertial navigation systems (INS) become more miniaturized and cheaper thanks to the MEMS technology. They all contribute to improve the performance of precise positioning and to broaden their applications. This review paper summarises the recent, on-going, and future research activities in precise positioning at Laval University. They range from local through regional to global applications.

At a local scale, the deformation monitoring of engineering structures can be performed with precise positioning. A methodology using a robotic total station to measure the displacement of the ice sheet of a reservoir dam, and hence to better understand ice forces on dams, is presented in Section 2. A new hardware design is also described in this section, one using a multi-antenna configuration with integrated self-calibration in order to improve the GPS vertical performance for continuous monitoring.

At a regional scale, precise positioning has demonstrated its potential for measuring the deformation of Earth's crust allowing for the monitoring of tectonic plates which are moving at several centimetres per year. Intraplate deformations are generally smaller and require improved accuracy. A study of the crustal intraplate deformation of the Charlevoix seismic zone in Quebec—based on repeated GPS and levelling campaigns—is presented in Section 3.

At a global scale, single GPS receiver techniques can offer precise positioning in isolated areas where reference station infrastructure is not available. These techniques present definite advantages in terms of operational flexibility and cost-effectiveness, but still have some limitations. Research on Precise Point Positioning (PPP), Time Relative Positioning (TRP), and the combination of both techniques are discussed in Section 4.

2. Precise Positioning for Deformation Monitoring of Engineering Structures

As current engineering structures and infrastructure become older and new ones are more audacious in terms of dimensions and capacity; the need for three-dimensional high precision and autonomous, real-time monitoring of these structures increases. This is true during the construction, the commissioning, and the lifecycle of the works for purposes of security and maintenance. Deformation monitoring is also relevant to study natural phenomena such as volcanic activities, landslides, and ground subsidence (caused by the extraction of water and oil, mining activities, etc.). The advantage of deformation monitoring is the ability to determine the absolute movements of objects—or points—on the structures with respect to stable geodetic points in the vicinity. Instruments used to directly measure forces (e.g. sensors of stress or sensors of rotation) allow only relative measurements between points on the structure; these categories of measurements are often used together.

2.1 Monitoring of Ice Sheet in a Reservoir Dam

Laval University, in partnership with the *Institut de recherche d'Hydro-Québec (IREQ)*, the State University of New York (SUNY), and with the participation of BMT Fleet Technology, undertook a project whose objective was to improve the understanding of ice forces on dams to protect the public against potential dam failure. Measurement of ice displacements were carried out and the deformations and deformation rates determined. They have been combined with observations from various types of pressure and temperature gauges placed in the ice sheet of the reservoir and against the dam face to model the ice behavior and the resulting forces on hydraulic structures.

A robotic total station was used to monitor the displacement of several probes placed on the ice sheet of a dam reservoir during winter seasons. Two prisms were mounted on each probe to take into account the deflection variation of the probe during a complete winter season. A set of observations was automatically taken every hour by the robot on a set of reference prisms and the two prisms of all probes. Once the coordinates of the two prisms on each probe are adjusted, the coordinates of the probe tips can be extrapolated by knowing the distance between the two prisms and the distance between the lower prism and the probe's tip [*Bourgon et al*. 2004].

Three field campaigns were carried out during the 2009, 2010, and 2011 winter seasons. The 2009 campaign was conducted at Beaumont hydro-electric dam owned and operated by *Hydro-Québec*. The dam is located 14 km north of La Tuque (Québec, Canada) on the Saint-Maurice River. Results for the 2009 campaign are presented in Figure 1. The horizontal displacements are shown as trajectories over this period whereas the vertical displacements of the water level and of the probes are given as a function of the day of year (DOY). *Prat et al*. [2012] present more details and the results for the 2010 campaign.

Vertical displacements of the ice sheet (Figure 1) follow the reservoir water level fluctuation, especially for the probes far from the dam and the reservoir banks because the ice is restrained in its vertical movement by the ice frozen into the shore and the dam face. The large snowpack accumulation during the 2009 winter campaign and/or the increase in the ice sheet thickness is responsible for the systematic deviations visible from DOY 50 [*Morse et al*. 2009]. However, the probes' tips still continue to follow the reservoir water level fluctuations, but at a lower elevation.

Over the 2009 winter campaign, the global movement of the ice sheet was generally towards the middle of the reservoir and hence at a maximum toward the reservoir edges: a total of 18 cm away from the dam face over the 2009 winter campaign and 8 cm away from the reservoir banks. The horizontal displacements also depend on the distance from the dam and from the reservoir banks. The movement perpendicular to the dam is greatest near the dam face and diminishes with increasing distance from the dam face.

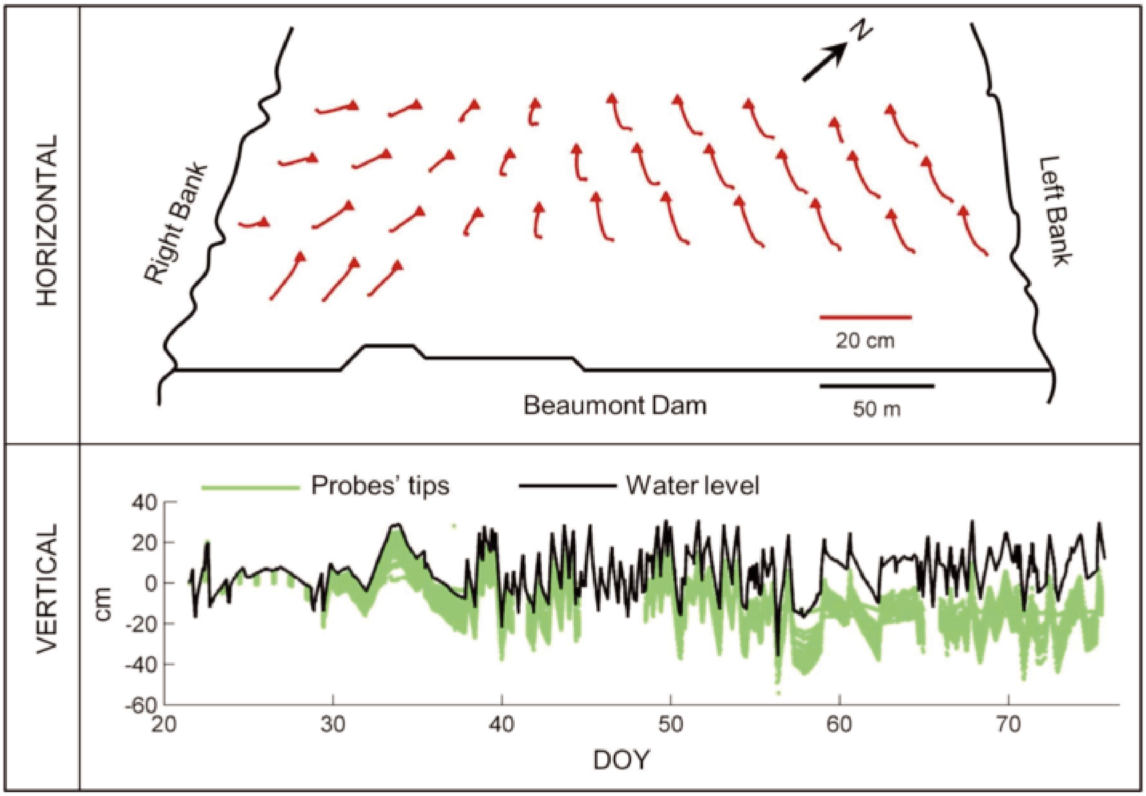

Figure 1: Horizontal and vertical displacements of the probes' tips from January 21 to March 16, 2009 (adapted from *Prat et al.*, 2012) / Déplacements horizontaux et verticaux de la pointe des pôles du 21 janvier au 16 mars 2009 (adaptée de *Prat et al.*, 2012)

The tracking of the ice movement allow for determining the spatial variability of forces in the ice sheet and, ultimately, for understanding the ice forcing process on the dam. For these forces, the in-ice stresses are proportional to the rate of deformation of the ice sheet. These can be calculated based on the speed of relative motion of the probe's tip to the next. This information is crucial for understanding the origin of the forces; for developing ice process and material models; and calibrating and validating numerical model approaches like, for example, finite element simulations which play a role in examining worst case scenarios that may lead to better dam designs.

2.2 *Improvement of Vertical Precision in GPS Positioning*

GPS receivers can be used as an alternative or a complementary technique to robotic total stations for deformation monitoring applications. GPS positioning allows real-time continuous monitoring and requires a minimum of human interventions, which reduces the logistics and the costs of operation. However, one of the main limitations of GPS positioning is that the vertical component is typically 2 to 3 times less precise than the horizontal components. The leading causes which explain this fact are: 1) the GPS satellites under the horizon cannot be tracked because they are masked by the Earth itself; and 2) the strong correlation between the GPS vertical component and the receiver clock bias.

The conventional relative GPS method uses at least two separate receivers. One receiver is located on a known station and the other one on an unknown station. The advantage of relative positioning is that some errors are the same at both stations since the observations are made simultaneously. They cancel out in single difference processing (between receivers or antennas). However, since two separate receivers are used, the clock biases are different and remain after the single difference operation. Therefore a differential receiver clock bias must be estimated at each epoch together with the 3D coordinates of the unknown station.

Based on simulations, *Santerre and Beutler* [1993] have shown that the vertical position accuracy drastically improves in the case where no differential receiver clock bias has to be estimated. In this case, the confidence ellipsoid becomes nearly spherical compared to the oblong shape in the conventional approach (Figure 2). In order to achieve this both antennas have to be connected to the same receiver, hence the measurements are referring to

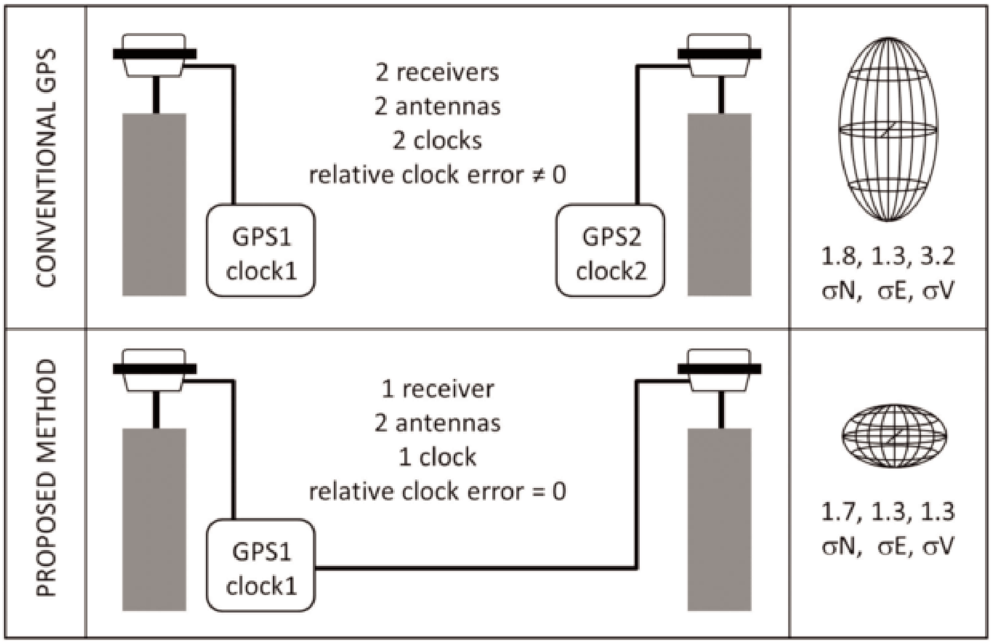

Figure 2: Comparison between conventional GPS and proposed method (adapted from *Santerre and Beutler*, 1993) / Comparaison entre le GPS conventionnel et la méthode proposée (adaptée de *Santerre et Beutler*, 1993)

Table 1: Positioning (vertical and horizontal) results for conventional GPS compared with the proposed method / Résultats du positionnement (vertical et horizontal) GPS conventionnel comparés à la méthode proposée

rms	148A: Without Movement		148R: With Movement	
	Conventional	Proposed	Conventional	Proposed
V	11.1 mm	4.4 mm	8.8 mm	4.1 mm
H	4.4 mm	4.2 mm	3.3 mm	3.2 mm

the same clock. However, the use of a single receiver (clock) does not completely solve the problem because of the varying hardware delays (mainly caused by temperature variations) in the different cables connecting the antennas to the receiver. In addition, a distance of at least several hundred meters between the two antennas should be considered in real life applications, like e.g. the deformation monitoring of a dam or a bridge.

This approach was designed, implemented, and tested in hardware by *Macias-Valadez* [2010]. Since the attenuation of the signal inside optical fiber is very low compared to the attenuation inside coaxial cable, optical fiber is the natural choice for the transmission of signals from the two antennas to the same receiver. In addition, an integrated and highly accurate calibration device was developed for monitoring the differential cable delays in real-time. This calibration device is the core component of the new system and allows for a complete elimination of the differential clock bias.

Table 1 and Figure 3 compare the results of two of the experimental sessions for the conventional and the proposed methods. The first session is 10 hours long with a solution calculated at each 30 seconds, without filtering or accumulation of the observations over time. The second session is 6 hours long in which a controlled vertical displacement up to 6 cm was applied to one of the antennas.

The rms value of the vertical component decreased from 11.1 to 4.4 mm in the first session and from 8.8 to 4.1 mm in the second session. This is the expected result; the proposed method improves the vertical component by a factor of 2 to 3 reaching the same accuracy as the horizontal component. This method's benefit is even more evident in Figure 3, especially for the session 148R, where the vertical movement of the antenna is better defined.

The periodicity of coordinate differences indicates the presence of multipath effects between the direct signal and secondary signals reflected by some surface around the antennas. The use of better multipath rejecting antennas and the implementation of algorithms to reduce multipath in the GPS software and in the monitoring software will reduce the multipath effects.

It is planned to rebuild a new multi-antenna system prototype with 4 to 8 antennas connected to the same receiver with better rugged-construction and to test it on real engineering structures. Other

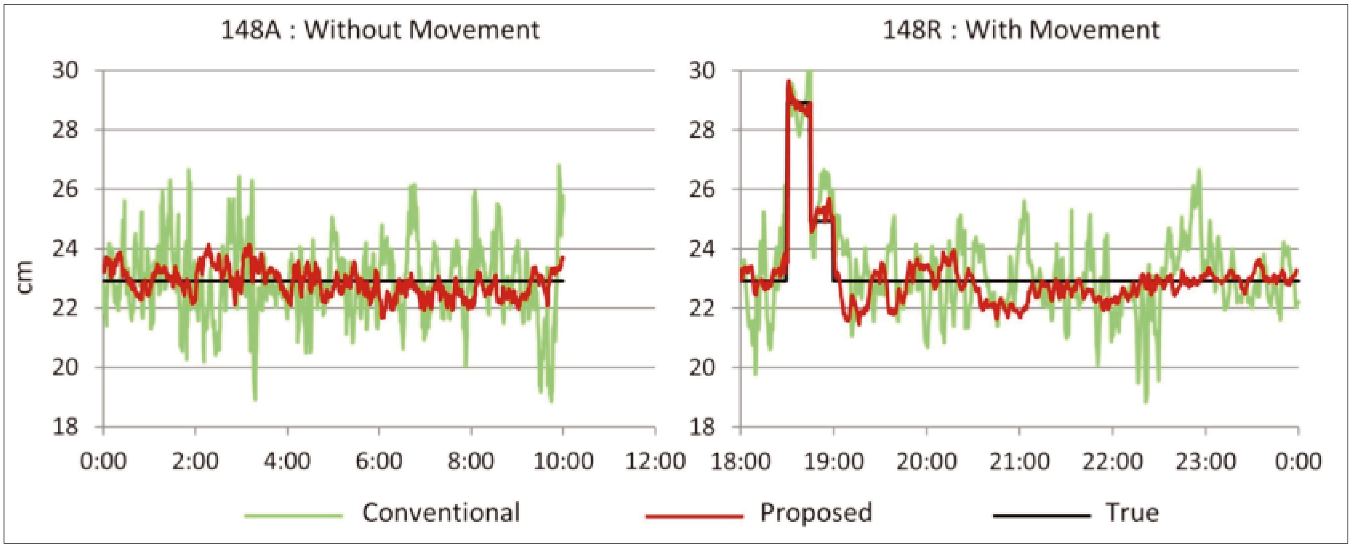

Figure 3: Vertical component for conventional GPS compared with the proposed method (adapted from *Macias-Valadez et al*., 2011) / Composante verticale du positionnement GPS conventionnel comparée à la méthode proposée (adaptée de *Macias-Valadez et al*., 2011)

applications where this technology could be used are: 1) GPS time transfer applications, by removing the unwanted effects of fiber cables relative time delay variations due to temperature changes; and 2) attitude measurements, by increasing the accuracy of roll and pitch angles to be as good as the yaw angle, especially for large separation between the antennas.

3. Crustal Deformation and Stability of Permanent GPS Networks

Among the tectonic plate monitoring techniques (i.e., satellite observations, sea-floor magnetization, etc.), GPS observations provide a cheap and accurate method of monitoring crustal deformation at a global scale. At plate boundaries, the relative horizontal and vertical velocities are typically between 5 and 50 mm/yr., which can be resolved with GPS campaign data acquired every year or two over a three to five year period. However, the relative velocities across tectonically less active intraplate regions, such as the Charlevoix seismic zone, are usually 1 mm/yr. or less, which is at the current limit of GPS resolution [*Henton et al*. 2006].

3.1 Postglacial Rebound in the Charlevoix Seismic Zone

The Charlevoix Seismic Zone (CSZ), in Quebec, has the highest recorded frequency of major earthquakes in eastern Canada. Since the 1600s, the region has had at least 5 earthquakes of magnitude 6 or higher on the moment magnitude scale. Unlike plate boundaries, where seismic activity is directly correlated with plate interactions, the driving mechanisms for intraplate earthquakes are more difficult to determine. Different reasons for the high intraplate tectonic activity in the CSZ have been proposed. The first possible explanation is the Devonian meteoric impact which occurred in this region 350 million years ago [*Rondot* 1968]. The second is related to the reactivation of Iapetan normal faults during the Jurassic rifting and opening of the North Atlantic Ocean [*Lemieux et al*. 2003]. A third explanation is related to the behaviour of the crust due to postglacial rebound (PGR), also termed glacial isostatic adjustment (GIA), which is a consequence of the last ice age in the late Pleistocene era 18000 years ago [*Mazzotti et al*. 2005].

Lamothe et al. [2010] quantified the PGR signal in the CSZ using two precise geodetic methods: levelling and high-precision GPS. The first geodetic method aims at the determination of vertical velocities from selected repeating levelling lines derived from the first order Canadian network in and around the CSZ. For vertical precision, geodetic levelling is unsurpassed with its millimetre accuracy. Measurements date back to 1909, but with very little spirit levelling done since 2001 because of the high manpower costs [*Véronneau et al*. 2006]. The levelling data is analyzed as a function of a temporal change in relative geopotential numbers, meaning that height markers in common from a levelling line are compared for different epochs. The changes over time in the geopotential numbers are then converted to height velocities.

The second geodetic method is relying on high-precision GPS observations from two campaigns, in 1991 and 2005, to determine horizontal and vertical velocities of geodetic markers in the CSZ. These GPS campaigns were carried out by Natural Resources Canada (NRCan) to study the geodynamic aspects of earthquake hazard in Eastern Canada. It must be mentioned that the 1991 data set is from before the International GNSS Service (IGS) era when the full GPS constellation was not yet available and when the number of IGS stations was significantly fewer. Fortunately, precise satellite orbits from SIO/SOPAC were available. The PGR signal was quantified by processing the observations with the specialized academic GPS software BERNESE v5.0 [*Hugentobler et al*. 2004]. The software allowed data processing at an accuracy of a few millimetres by taking into account the parameters that influence the precision of the coordinate solutions and also the use of IGS sites and products to tie the CSZ GPS network to the ITRF2000 [*IERS* 2011]. The site velocities were then calculated from the coordinates of common sites between 1991 and 2005. The horizontal velocities with respect to ITRF2000 were transformed to relative horizontal velocities with respect to the stable North American Plate by using a model of a constant plate rotation, in this case NUVEL-1A.

The results for the CSZ GPS campaign were then compared with those from a larger GPS survey conducted on the Canadian Base Network (CBN) pillars in eastern Canada, published in *Mazzotti et al*. [2005]. As illustrated in Figure 4, the CBN sites and the CSZ network sites were not using the same markers. The extension of the CSZ network was small enough to average the displacements over all sites. These average values were then compared to the three nearby sites in the CBN network in Table 2. There is good agreement between horizontal velocities with respect to the standard deviation of CBN

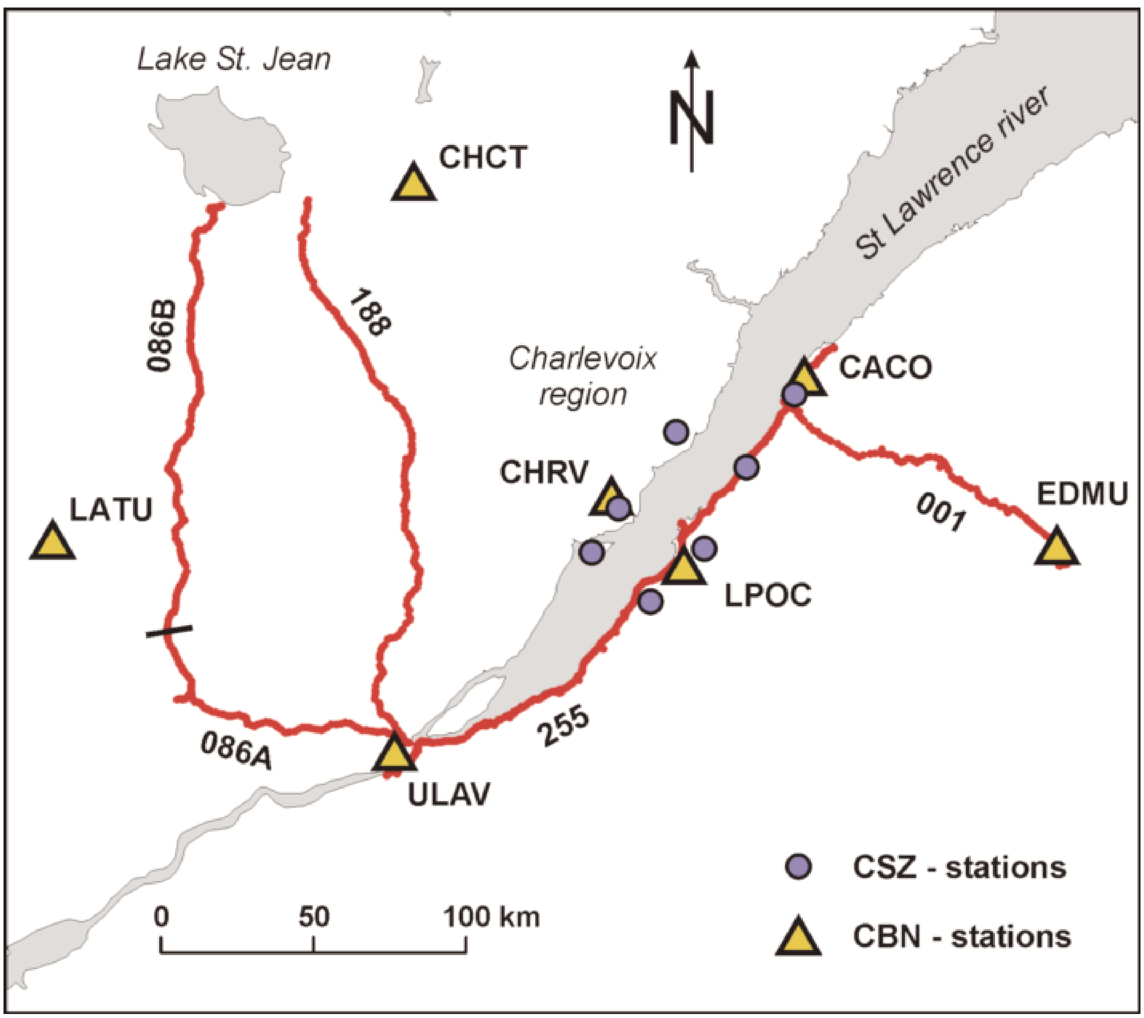

Figure 4: Global view of CSZ GPS campaign, levelling data and CBN stations / Vue d'ensemble de la campagne GPS dans la zone séismique de Charlevoix (CSZ), des mesures de nivellement et des stations du réseau de base canadien (CBN)

sites and CSZ network. It can be seen that the motion is in the southeast direction for the CBN sites and for the CSZ sites, the drift is in the east direction. There is also good agreement between the vertical velocities of CBN and CSZ network as both velocities show an absolute uplift signal. The CBN vertical velocities vary from 2.3 to 2.6 mm/yr. with a standard deviation of 1.0 mm/yr., which is comparable to the velocities of CSZ network at an average of 3.9 mm/yr with a standard deviation of around 1.4 mm/yr. Additionally, Table 2 presents the crustal motions predicted with the postglacial rebound model at the location of the CBN sites. The PGR horizontal velocities are approximately the same as the CBN velocities, except for the CACO site which has an irregular behaviour in CBN campaign sites with a southward drift of 0.9 mm/yr. The vertical velocities from the PGR model show a clear line between uplift (CHRV) and subsidence (LPOC, CACO) at the Saint Lawrence River, contrary to the results from the CBN and CSZ networks that show uplift on both shores of the Saint Lawrence River.

The height variations obtained by levelling are only relative since an arbitrary starting point has to be set to zero. As such, they are not directly comparable with GPS absolute values. What is comparable, however, is the difference in vertical velocity between two GPS points that are approximately at the beginning and at the end of the levelling lines. The levelling velocity differences are obtained from a linear regression fit on matching benchmarks. Details for some selected levelling lines and the comparison of their velocity differences with GPS CBN results and PGR model are presented in Table 3 and illustrated in Figure 4.

Overall, the lines outside the CSZ on the north shore (086A, 086B, 188) show the same trend of uplift gradient towards the northwest in Eastern Canada as the absolute velocities from CBN results and PGR prediction results. This means that the magnitude of uplift is much greater towards the Lake Saint-Jean area than closer towards the Saint Lawrence River with an approximate 2 mm/yr. variation in amplitude of the vertical velocities. The levelling lines 255 and the others in the CSZ (not presented) are parallel to the Saint Lawrence River and, therefore, are not optimal for detecting postglacial rebound effects; which also explain the fact that no relative uplift is evident. These results agree with the PGR model and the CBN results. The results for the line 001 show a greater uplift towards the Saint Lawrence River on the south shore than further inland, but the levelling velocity is much higher than the other values. It can be explained by the fact that it is the only one analyzed on the south shore and that it was measured recently with few years of data.

Table 2: Horizontal and vertical velocities for CSZ GPS campaign compared with CBN sites and PGR model / Vitesses horizontales et verticales de la campagne GPS dans la zone séismique de Charlevoix (CSZ) comparées à celles des stations du réseau de base canadien (CBN) et au modèle de rebond postglaciaire (PGR)

Velocity (mm/yr.)	Site	CSZ	CBN	PGR
N	LPOC	0.0 ± 0.3	-0.4 ± 0.4	-0.5
	CACO		-0.9 ± 0.3	-0.7
	CHRV		-0.6 ± 0.4	-0.6
E	LPOC	0.6 ± 0.3	1.1 ± 0.6	1.1
	CACO		0.0 ± 0.4	1.1
	CHRV		0.9 ± 0.6	1.1
V	LPOC	3.9 ± 1.4	2.6 ± 0.8	-0.2
	CACO		2.3 ± 0.6	-0.3
	CHRV		2.3 ± 1.4	0.3

Table 3: Results of velocity fit of levelling lines compared with CBN sites and PGR model / Vitesses obtenues des mesures de nivellement comparées à celles des stations du réseau de base canadien (CBN) et au modèle de rebond postglaciaire (PGR)

Line	Distance (km)	Direction	Year		# markers	Levelling (mm/yr.)	CBN (mm/yr.)	PGR (mm/yr.)	CBN Sites	
			Last	First					Last	First
001	120	SE-NW	1987	1979	88	7	1	2	CACO	EDMU
086A	120	SE-NW	1964	1919	14	2	2	2	LTUQ	ULAV
086B	135	SE-NW	1964	1925	18	2	2	2	LTUQ	ULAV
188	190	N-S	1992	1963	37	0	-2	-2	ULAV	CHCT
255	180	NE-SW	1987	1970	61	0	1	1	ULAV	CACO

The limited spatial coverage in intraplate environments plays as much of a role in the interpretation of the velocities as the resolution of the GPS observations themselves. The installation of permanent stations with continuously running GPS receivers would significantly decrease the uncertainties in both the horizontal and vertical velocities. A permanent GPS installation is projected in the CSZ north shore to complement the already existing permanent station LPOC on the south shore.

The Geological Survey of Canada, in cooperation with Natural Resources Canada (NRCan), has plans to measure the 2005 Charlevoix network again every couple of years for the next 10 years. This measurement was done in 2007, 2009, and 2011; additional measurements are planned for the summer of 2013. This will allow for a better time and spatial resolution. On-going observation processing results confirm horizontal and vertical velocities comparable to CSZ and CBN campaigns presented above.

3.2 GPS Networks in Eastern Canada

The GPS and Geodesy Research Group is archiving the observations of almost 50 permanent stations located in Eastern Canada and Eastern USA. The observations, some of which date back to 2001, come from the International GNSS Service (IGS), Natural Resources Canada (NRCan), the *Ministère des Ressources Naturelles et de la Faune du Québec* (MRNFQ), and Laval University (UL).

A first study was carried out by *Pinel* [2007] to analyze the temporal variability of the permanent stations and to verify if the MRNFQ and UL stations located on buildings were stable enough to properly detect crustal motions. The analysis of long data spans of daily solutions is encouraging and shows that the noise of the measurements for the stations installed on buildings is comparable to the noise for those on pillars. In addition to the tectonic signal, the influence of seasonal phenomena was noted in measurements. After removal of this periodic signal the linear motion of these stations is compatible with the models of crustal motion and these stations are available to be used for future geodynamic studies in the area.

This permanent GPS network is currently used in a Ph.D. research project to study the micro-plate tectonics of Eastern Canada. More specifically, the objectives of that research are to increase the accuracy, and perform a better analysis, of the GPS results; to determine the velocity, deformation and strain fields; and to compare and validate the results from GPS observations with geological and geophysical models and results.

4. Single GPS Receiver Positioning Techniques

Precise Point Positioning (PPP) and Time Relative Positioning (TRP) are recent single GPS receiver techniques that do not require a reference GPS (GNSS) receiver in the vicinity. The primary benefits of PPP and TRP are the simplification of the logistics and the reduction of costs for field surveys when compared to conventional GPS (GNSS) relative positioning.

4.1 Precise Point Positioning

PPP was developed in order to reach in absolute mode with a single GPS receiver, a similar level of accuracy to that of GPS conventional relative positioning. This implies that all effects and error sources which cancel out in differential mode, or are at least reduced, remain in a PPP-approach and have to be carefully and accurately modelled. The major drawback of PPP is that a long period of observations is necessary to reach accuracy at the centimetre level.

In Real Time Kinematic (RTK), the key feature to achieve a centimetre accuracy after a very short time period is a successful phase ambiguities resolution. GPS carrier phase measurements are very precise, but ambiguous. Hence, an unknown phase ambiguity has to be estimated for every observed satellite.

Hardware propagation delays affect the code and phase measurements after their generation in the satellites and receiver [*Blewitt* 1989]. In relative mode, these delays cancel and the double differenced phase ambiguities can be constrained to integer values.

In absolute mode, the presence of code and phase biases, as well as un-modelled errors, prevent the phase ambiguities resolution. Conventional relative positioning techniques for phase ambiguities resolution are difficult to apply to PPP. Therefore, the ambiguities are estimated as real values without forcing them to integers. This explains the much longer convergence time in order to reach a suitable accuracy. The PPP presently requires a period of observations of almost 30 minutes to obtain an accuracy of about ten centimetres for a static receiver and at least double the amount of this time in kinematic mode [*Héroux et al*. 2004]. An accuracy of one centimetre requires approximately 12 hours of observations [*NRCan* 2011].

An approach for phase ambiguities resolution in absolute mode consists of the estimation of phase delays in order to correct phase measure-

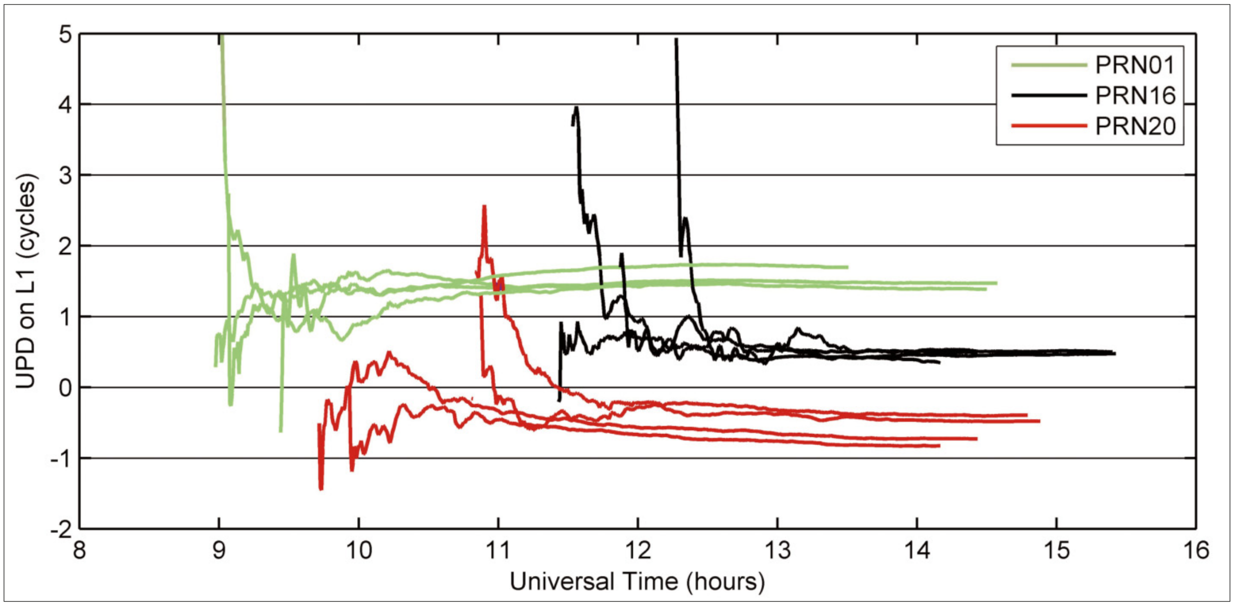

Figure 5: UPD on L1 for selected satellites calculated with four stations through Canada, October 17, 2007 / Biais de phase sur l'onde porteuse L1 calculés à partir de quatre stations à travers le Canada, 17 octobre 2007.

ments and retrieve their integer values. *Ge et al*. [2007] have shown that uncalibrated phase delays are rather stable in time and space, and can be estimated with high accuracy and reliability through a statistical analysis of the ambiguities estimated from a reference network. This reparameterization of un-differenced measurement models has led to better PPP performance achievements [*Laurichesse and Mercier* 2009; *Collins et al*. 2010].

The main objective of our PPP processing approach is to propose a reparameterized PPP model by making use of un-differenced measurements. Reparameterized PPP models lead to the determination of uncalibrated phase delays (UPD). Figure 5 presents the UPD on L1 for three selected satellites obtained from different IGS-stations ALGO, PRDS, VALD, and YELL. These stations provide a good spatial resolution through Canada. Each station estimated similar values of UPD for selected satellites. The UPD's temporal variation modelling might improve the single receiver ambiguity resolution and consequently, reduce the convergence time and enhance the coordinate accuracy. Further, reparameterized PPP model has the potential to estimate ionosphere delay per single receiver that leads to new additional by-product. In classical PPP model on the other hand, ionospheric delay is eliminated by combining measurements. Finally, an isolated receiver receiving satellites UPDs' values and their variations might be able to get shorter convergence time and better accuracy by means of ambiguity resolution.

4.2 Time Relative Positioning

Time Relative Positioning (TRP) is a method first developed by *Ulmer et al*. [1995] for processing GPS observations with a single GPS receiver. TRP is somewhat analogous to the conventional relative positioning, except that the difference of phase observations is taken between two different epochs while using the same receiver. The operational mode of TRP consists of moving a single receiver from a known station to one or more unknown stations, which keeps a high level of accuracy for a certain period of time. The advantage of TRP is that it requires only one receiver.

In TRP, carrier phase observations are preferred to pseudoranges since their resolution is superior and around a few millimetres. One of the advantages of TRP is the elimination of carrier phase ambiguities. Since phase observations are performed with the same receiver, the ambiguities remain constant over time, and thus cancel by using temporal difference. This assumption is only valid in the absence of cycle slips, which have to be detected and corrected when processing the data. The limitation of this method is the degradation over time of the positioning accuracy due to the temporal variation of different GPS errors varying between two epochs. These errors must be modeled in an appropriate way, especially in satellite clocks, ephemerides, and ionospheric delays.

TRP was the subject of several research projects carried out at Laval University, namely, *Michaud* *and Santerre* [2001], and *Balard et al*. [2006]. The method was refined by *Kirouac and Santerre* [2011], who applied GPS•C corrections available in real-time to a low cost mono-frequency receiver.

GPS•C corrections are generated from real-time positioning information collected by the Canadian Active Control System (CACS) of Natural Resources Canada (NRCan). The GPS•C corrections were broadcasted by the Canada-wide Differential GPS Service (CDGPS) until it was decommissioned on March 31, 2011 and were accessed by end-users using a GPS receiver with integrated CDGPS capability. NRCan is currently offering non-exclusive licenses for the distribution of GPS•C corrections.

The GPS•C correction data stream is described in *CDGPS ICD* [2003]. The grid of ionospheric delays has a resolution of 12.5 cm and a minimal update of 5 minutes (300 seconds). The satellite ephemeris and clock correction resolution correspond approximately to 4 mm. The fast corrections are refreshed every two seconds and the long-term corrections every two minutes (120 seconds). The TRP software, initially developed by *Michaud and Santerre* [2001], was modified to incorporate GPS•C corrections using software developed by Hyunho Rho under the supervision of professor Richard Langley at the Department of Geodesy and Geomatics Engineering, University of New Brunswick.

Table 4 presents the results obtained from two sessions. The first session of observations was carried out in static mode on a pillar with the known coordinates serving as reference values in the comparison. At least four satellites were visible throughout this 24-hour session which covers a large variety of DOP values. The second session was carried out in kinematic mode with the equipment installed on board a vehicle. To provide a reference for TRP quality, the trajectory was determined by a conventional GPS relative positioning using phase measurements from the permanent GPS receiver at Laval University and commercial software. The trajectory precision is estimated at 5 cm. During the second session, the average values of NDOP, EDOP and VDOP were 0.9, 0.6, and 1.4 respectively, indicating a good sky distribution of satellites during the 25-minute session.

Two different TRP solutions were calculated. The first one relies on broadcast clock correction and ephemerides only, while the second one applies the GPS•C corrections in addition to broadcast clock correction and ephemerides. By using a slid-

Table 4: Comparison of TRP results after 10 minutes and 20 minutes for solutions using broadcast clock correction and ephemerides only and using broadcast clock corrections and ephemerides with GPS•C corrections / Comparaison des résultats du positionnement relatif temporel (TRP) après un intervalle de 10 minutes et 20 minutes en utilisant les corrections d'horloges et les éphémérides diffusées seulement et en utilisant les corrections d'horloges et les éphémérides diffusées ainsi que les corrections GPS•C

Static	10 min (15 937 solutions)				20 min (14 881 solutions)			
	Broadcast		Broadcast + GPS•C		Broadcast		Broadcast + GPS•C	
(cm)	rms	mean	rms	mean	rms	mean	rms	mean
N	34.1	-2.0	7.4	0.1	55.1	-5.6	11.2	-0.6
E	25.5	9.1	5.3	-0.3	45.5	16.0	8.8	-0.5
V	57.5	2.8	14.4	0.9	101.6	-15.5	21.8	0.2
Kinematic	10 min (219 solutions)				20 min (99 solutions)			
	Broadcast		Broadcast + GPS•C		Broadcast		Broadcast + GPS•C	
(cm)	rms	mean	rms	mean	rms	mean	rms	mean
N	19.4	5.0	4.2	2.2	11.3	-0.6	4.7	2.8
E	18.9	15.3	2.5	-0.3	27.9	27.2	3.1	-0.9
V	36.7	-34.4	6.9	-5.3	37.7	-34.8	9.6	0.2

ing time window and comparing the differences between the last and the first epochs of the TRP solution to the corresponding known reference values, the degradation of the position after this time period is provided by the statistical rms and mean values. This analysis was applied to the two TRP solutions of both sessions for a window of 10 and 20 minutes respectively. The results are presented in Table 4.

For the static session, the rms values for N, E, V components are 11 cm, 9 cm and 22 cm respectively with the use of GPS•C corrections after 20 minutes. The rms values for the solution with broadcast ephemerides only reach half a meter in the horizontal components and one meter in the vertical component after the same period. The kinematic session confirms these results. The GPS•C solution provides rms values that do not exceed 10 cm for the three components for the same 20-minutes. In the alternative case (without using the GPS•C corrections), these values approach 40 cm. This shows the benefit of GPS•C corrections. For all intervals, the use of GPS•C corrections improve the quality of TRP positioning by a factor from 3 to nearly 6.

The first publication on time-relative positioning was related to the short vectors determination (namely highly accurate azimuth and pitch information for gun laying applications) where there are no or few geodetic points in the vicinity [*Ulmer et al*. 1995]. The TRP technique has also been applied to study parts of flight trajectory and operations such as takeoff and landing [*Traugott et al*. 2008]. Among the other potential applications of TRP, let us mention the determination of short length road profiles and road slopes, the set-up of short vector azimuths useful for backsight in total station survey operations and the determination of heading initialisation for inertial navigation systems (INS). Conversely, gyro-accelerometer measurements can be beneficial to TRP to detect and correct GPS cycle slips. A current M.Sc. research using high-rate gyro-accelerometer data is on-going at Laval University for this purpose.

It is also possible to use in parallel TRP and PPP positioning techniques. On one side, the PPP uses only one geodetic receiver but requires a time of convergence of several minutes before reaching decimetre or centimetre accuracy. On the other side, the TRP combines phase measurements collected at different epochs by the same receiver while decreasing positioning accuracy over time. The integration of these two single GPS receiver techniques would take advantage of the strengths and would reduce the weaknesses of each one taken individually. In other words, one user could rely on the TRP solution at the beginning of a single receiver survey until the PPP solution converges in time.

5. Conclusion: Future Perspectives for Precise Positioning

Precise positioning uses a rich assortment of high-accuracy measurement techniques. Some of them, such as total stations and digital levels are closely related to surveying. More recent ones such as global navigational satellite systems (GNSS) are nowadays also familiar techniques but involve geodetic infrastructures. Data or data products from global geodetic networks, as well as stable (3D) terrestrial and celestial reference frames, are required to achieve the highest accuracy. Fortunately, much of these infrastructures are getting more transparent to end-users. They allow for a large spectrum of phenomena to be monitored and studied by precise positioning techniques and at a wide range of spatial and temporal scales.

Continuous information provided by GPS (GNSS) makes the precise positioning a useful tool for the monitoring of structures and has a major benefit for public safety. With high temporal resolution, it is now possible to detect what was not observable before. Improved positioning observations also generate the capability of measuring the crustal deformation and contribute with other geophysical observations to gain a better understanding of the tectonic mechanisms between, across and inside tectonic plates. GNSS single receiver positioning techniques have an interesting potential and are in constant evolution. Further research to improve accuracy and user-friendliness will expand the use of these global techniques.

Over the next decade, the launch of more Galileo and Compass satellites and the modernisation of GPS and GLONASS will significantly improve the performance of the GNSS positioning systems. More satellites broadcasting stronger signals on more frequencies, in combination with the proliferation of geodetic network and telecommunication infrastructures, will facilitate precise positioning and will bring down some frontiers. The traditional distinction between static and kinematic positioning will vanish since an absolute instantaneous position with a centimetre level accuracy will become feasible thanks to an enhanced high-rate and real-time precise GNSS positioning. Furthermore the integration of other sensors such as precise MEMS gyro-accelerometers inside GNSS receiver, will allow seamless outdoor and indoor positioning. Finally, the proper combination of spatial and terrestrial techniques will make the traditional distinction between surveying and geodetic techniques obsolete.

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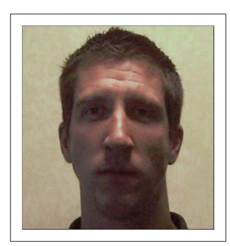

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