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Le pont de Québec, qui enjambre le fleuve Saint-Laurent à l’ouest de la ville de Québec, est le pont cantilever ayant la plus longue portée libre au monde, avec 548,6 mètres entre ses deux principaux piliers. La construction du pont de Québec a été complétée il y a 100 ans, en 1917, après deux échecs tragiques—en 1907 et en 1916—and the loss of 89 lives. The impressive road, rail and pedestrian bridge was largely designed and built by Canadian engineers using an innovative K-truss design and was the first bridge in North America to use nickel steel as a structural material. Universally recognized as a symbol of engineering excellence, the Canadian (now the Engineering Institute of Canada) and American Society of Civil Engineers declared the Quebec Bridge a historic monument in 1987, and, on January 24, 1996, the bridge was declared a National Historic Site of Canada.

The Quebec Bridge is the subject of a paper entitled: "Movements of the Quebec Bridge’s suspended span measured by GNSS-technology," published in this Geomatica issue (see p. 298).

Photographic credit: R. Santerre, CRG, Laval University, Quebec City

The Quebec Bridge, stretching across the St. Lawrence River west of Quebec City, is the world’s longest span cantilever bridge at 548.6 metres between the main piers. Construction on the Quebec Bridge was completed 100 years ago in 1917, following two tragic failures—in 1907 and 1916—and the loss of 89 lives. The impressive road, rail and pedestrian bridge was largely designed and built by Canadian engineers using an innovative K-truss design and was the first bridge in North America to use nickel steel as a structural material. Universally recognized as a symbol of engineering excellence, the Canadian (now the Engineering Institute of Canada) and American Society of Civil Engineers declared the Quebec Bridge a historic monument in 1987, and, on January 24, 1996, the bridge was declared a National Historic Site of Canada.

The Quebec Bridge is the subject of a paper entitled: "Movements of the Quebec Bridge's suspended span measured by GNSS-technology," published in this Geomatica issue (see p. 298).
Introduction

The origin of this project was to better establish the actual clearance of the Quebec Bridge, which crosses the St. Lawrence River near Quebec City, and to potentially increase the number of tall ships that can securely pass under the bridge and reach the Port of Montreal. For this purpose, the Montreal Port Authority installed a radar instrument under the structure of the Quebec Bridge to monitor the St. Lawrence River water level. This project was done in collaboration with the Canadian Coast Guard (CCG) and the Canadian Hydrographic Service (CHS), with the agreement of the Canadian National (CN) Railway Company, the owner of the Quebec Bridge. Furthermore, in order to take into account the movement of the installed radar, a GNSS antenna (Global Navigation Satellite Systems including the American GPS and the Russian GLONASS systems) connected to a GNSS receiver, was installed on top of the central suspended span of the bridge 34 m above the radar.

Although the original goal of the experiment was not dedicated to monitoring the 3D deformation of the Quebec Bridge, we asked to have access to the GNSS data collected on top of the Quebec Bridge’s suspended span for analysis. This was an opportunity to monitor one of the most famous engineering structures in Canada built a century ago.

This paper contains the analysis of the 3D deformation of the Quebec Bridge’s suspended span as measured by GNSS technology as functions of train and wind loads, along with the effects of temperature, including solar radiation. The next sections present a short description and the history of the Quebec Bridge and the equipment and data used to perform this analysis.

The Quebec Bridge

The Quebec Bridge (46° 45’ N, 71° 17’ W) is the first bridge over the St. Lawrence River encountered by ships travelling upstream from the Gulf of St. Lawrence and the Atlantic Ocean.

The Quebec Bridge was completed in 1917 and it is still the longest cantilever bridge in the world. Overall, the actual movements of its suspended span, as detected by GNSS (between 2012 and 2013), are in fair agreement with the original design calculations: for the train loading effect on the vertical movement (17 cm for one freight train); the transversal wind load effect on the transversal movement (32 cm for a wind speed of 170 km/h); and the temperature loading effect on the vertical movement of the suspended span (3.2 cm for a 50°C temperature variation). Further movements have been detected by GNSS technology, namely: the transversal and longitudinal movements of the suspended bridge span due to train passages (11 cm transversally, at the top of the suspended span, and 1 cm longitudinally); the transversal movement of the bridge caused by solar radiation (differential) conditions on both sides of the bridge (5 cm for high solar radiation values); and the longitudinal movement of the suspended span of the Quebec Bridge at temperatures lower than 6°C (7 cm to −25°C).

La construction du pont de Québec a été achevée en 1917 et il est toujours le plus long pont cantilever au monde. Dans l’ensemble, les mouvements actuels de sa travée suspendue détectés par GNSS (entre 2012 et 2013) correspondent bien avec les calculs d’origine : pour l’effet de charge des trains sur le mouvement vertical (17 cm pour un train de fret); l’effet de charge du vent transversal sur le mouvement transversal (32 cm pour une vitesse de vent de 170 km/h); et l’effet de charge de la température sur le mouvement vertical de la travée suspendue (3,2 cm pour une variation de température de 50°C). D’autres mouvements ont été détectés par la technologie GNSS, à savoir : les mouvements transversaux et longitudinaux de la travée suspendue du pont en raison du passage de trains (11 cm transversalement, au sommet de la travée suspendue et 1 cm longitudinalement); le déplacement transversal du pont provoqué par les conditions du rayonnement solaire (différentiel) sur les deux côtés du pont (5 cm pour les valeurs élevées de rayonnement solaire); et le déplacement longitudinal de la travée suspendue à une température inférieure à 6°C (7 cm à −25°C).
This bridge is located about 10 km upstream from Quebec City and about 250 km downstream from Montreal in Quebec, Canada.

As indicated on the actual chart of CHS, the clearance of the Quebec Bridge with respect to the High Water, Large Tide (HWLT) is 46 m. In Quebec City, the tide can reach up to 5–6 m depending on the time of the year. In fact, there are some ships that can pass under the Quebec Bridge only when the tide is falling. This shows the importance of establishing the actual (and the predicted) bridge clearance along with the tide level measured by nearby tide gauges.

To give a short history, it is worth mentioning that the central suspended span was successfully lifted and installed on September 20, 1917 (the first attempt failed on September 11, 1916). It is also interesting to note that the ends of the cantilever arms dropped by 19.4 cm (7 5/8 in) once the suspended span was lifted. The first transit of a train over the bridge occurred on October 17, 1917, and it was officially inaugurated on August 22, 1919. Let us also remember that the southern part of the first Quebec Bridge, under construction, collapsed on August 1907 because of a structural design problem.

The Quebec Bridge is still the longest cantilever bridge in the world and it was the longest bridge (of all types) between 1917 and 1929. It was recorded as a Canadian national historic site in 1996 by the Government of Canada and it was recognised as an international historic civil engineering landmark in 1987 by the American Society of Civil Engineers and the Canadian Society for Civil Engineering.

In 1917, the bridge had two railways and two sidewalks. A car lane was added between the two railways in 1929. Later on in 1948, one of the railways (to the downstream side) and one of the sidewalks (to the upstream side) were removed, and the second railway was slightly shifted (to the upstream side) in order to widen the car lane.

Currently, three traffic lanes for cars are present: two lanes in the north direction and one lane in the south direction in the morning, and vice versa in the evening. The central car lane is

---

**Table 1: Technical specifications of the Quebec Bridge.**

<table>
<thead>
<tr>
<th>Length, Width, Height</th>
<th>Feet</th>
<th>Metres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of suspended span</td>
<td>640</td>
<td>195.1</td>
</tr>
<tr>
<td>Length of cantilever arms</td>
<td>580</td>
<td>176.8</td>
</tr>
<tr>
<td>Length of anchor arms</td>
<td>515</td>
<td>157.0</td>
</tr>
<tr>
<td>Total length of steel work</td>
<td>3,239</td>
<td>987.2</td>
</tr>
<tr>
<td>Distance between main piers*</td>
<td>1,800</td>
<td>548.6</td>
</tr>
<tr>
<td>Width (external) of the bridge</td>
<td>100</td>
<td>30.5</td>
</tr>
<tr>
<td>Height of main posts</td>
<td>310</td>
<td>94.5</td>
</tr>
<tr>
<td>Height of suspended span (at the center)</td>
<td>110</td>
<td>33.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weight</th>
<th>imperial tons</th>
<th>metric tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total weight of steel** superstructure</td>
<td>66,480</td>
<td>60,310</td>
</tr>
<tr>
<td>Weight of the suspended span</td>
<td>5,510</td>
<td>4,999</td>
</tr>
</tbody>
</table>

* World record for a cantilever bridge; ** 75% carbon steel and 25% nickel steel

---

Figure 1: The Quebec Bridge, left—in summer from the south shore; right—in winter from the north shore.
closed at noon and during nights and weekends. Every week day (but less often during the weekend), around 35 000 cars (500 cars per 15 minutes during rush hours), 4 freight trains (with about 30 wagons) and 8 passenger trains transit the bridge (there is no passenger train service between 10 p.m. and 5 a.m.). The maximum train speed is regulated to 64 km/h and the maximum car speed is limited to 70 km/h. Since 1991, the transit of large trucks has been forbidden.

Figure 2 (left) also depicts the view of the train track, the three car lanes and the sidewalk as seen from the GNSS antenna location.

**GNSS Equipment and the Auxiliary Data**

A chokering (Antcom) antenna (see Figure 2, left) connected to a multi-frequency geodetic Ashtech (Profilex 500) GNSS (GPS-GLONASS) receiver was installed on top of the central suspended span of the bridge on the upstream side (the side of the railway). The data set was available from the beginning of July 2012 up to mid-July 2013, with observations recorded at 1 s intervals. Altogether, almost 18 million observation epochs were recorded and processed for a total of 140 GB of GNSS data (including the GNSS reference station files) in the ASCII RINEX format.

The distance between the Quebec Bridge and the nearest permanent GNSS reference station (QBC2) was about 7 km with a height difference of about 70 m. This might be a proper setup for the original objective of the project, which was to measure (at an accuracy of 0.1 m) the bridge clearance for safe ship navigation, but this is not optimal for bridge deformation monitoring because of the long distance and large height difference between these two GNSS antennas. Even though it would have been preferable to have a closer GNSS reference station to mitigate GNSS errors (especially the tropospheric error which mainly affects GNSS height determination), one can expect that for a short period of time (such as a train passage of a few minutes) the tropospheric modelling error will stay almost constant and will not significantly deteriorate the detection of the vertical displacement of the GNSS antenna located on the top of the bridge’s suspended span. Let’s also recall that tropospheric delay mismodelling has almost no effect on the horizontal GNSS coordinates [Santerre 1991].

The reference station was equipped with a multi-frequency GNSS Trimble NetR5 receiver and a geodetic Trimble Zephyr antenna. The GPS-GLONASS ambiguity fixed ionospheric free (L1 and L2) solutions with a 10° elevation mask angles were produced using the Trimble Business Center (TBC) post-processing software [Trimble 2012].

Due to the large amount of GNSS data, the TBC software was used for several features: efficient data screening, reliable ambiguity-fixing algorithms, automated cycle-slip detection and correction engine, and its user-friendly interface. The observation files in the RINEX format were processed in the kinematic mode. Therefore a new set of 3D coordinates was estimated at every epoch. Altogether, it took 15 days to post-process this volume of GNSS data (140 GB) on 10 personal computers. All the results are reported in Smadi [2015].

The instantaneously estimated precision (epoch by epoch) of the horizontal components at 95% probability level was typically 1.5–2.5 cm for the horizontal and vertical components, respectively [Smadi 2015]. Let us keep in mind that the precision of the displacement (the coordinate variation in
time) is much better, especially for a short time duration where the GNSS errors are highly correlated. From the analysis of this large GNSS data set, a realistic precision of 5 and 8 mm for the horizontal and vertical displacements, respectively, can be stated. Moreover, the moving average filtering helps to significantly reduce the noise associated with the GNSS observations, as will be shown in the next sections.

Several auxiliary data sensors were available, such as an ultrasonic anemometer (Young Model 81000), to collect wind velocity in N-S, E-W and U-D directions, averaged every 10 min along with the air temperature. This anemometer is located on top of a light pole just south of the north tower on the upstream side of the Pierre-Laporte suspension bridge, which is located 200 m upstream of the Quebec Bridge (see Figure 2, left). Unfortunately, no anemometer is installed over the Quebec Bridge. The solar radiation values were recorded by the MeteoLaval station located about 4 km from the Quebec Bridge. The traffic loops operated by Quebec Department of Transportation (MTQ) were used to provide the total number of cars for the 15 min intervals. The arrival and departure times of passengers and freight trains were provided by the CN Railway Company for the two nearby train stations, namely Ste-Foy and Charny, respectively. These are located 1.5 km north and 4 km south from the center of the Quebec Bridge. Table 2 shows the summary of the auxiliary sensor values during the observation period.

A Miros microwave radar remote sensor for the ocean surface radar, model SM-094, was used to measure the clearance (instantaneous vertical distance at 1 s intervals) between the bottom of the suspended span of the Quebec Bridge and the water level of the St. Lawrence River (Figure 2, right). According to the manufacturer, the accuracy of an individual measurement is 1 cm. As one will see later, the measurements not only contain information about tides, but they are also affected by waves. During the winter season, the radar pulses bounce back from ice blocks that are floating on the river. Thus the radar data obtained in this season were not used for the analysis.

The variations in the coordinates of the antenna are with respect to the average 3D coordinate values obtained from a 24 h static solution for the day March 3, 2013. This day was selected because the average air temperature value was close to zero (0.7°C) and the wind velocity was as low as 4 km/h in the transversal direction. The results presented in the next sections are, in fact, the coordinate variations (displacement) of the GNSS antenna (located on top center of the suspended span) expressed in the bridge local reference frame (L, T, V), where the longitudinal (L) component has a positive value toward the river’s north shore direction, the transversal (T) component has a positive value toward the river’s downstream direction and the vertical component has a positive value in the up (zenith) direction. This transformation was done using the known bearing of the longitudinal axis of the Quebec Bridge, which is 340°.

To analyze the Quebec Bridge deformations, let us remember that the GPS system has been used for decades for deformation monitoring of large engineering structures such as bridges [Hyzak et al. 1995; Xu et al. 2010], Dams [DeLoach 1989], towers and buildings [Lovse et al. 1995; Yi et al. 2012] are also monitored using GPS (GNSS) technique. Some of the recently constructed mega structures are permanently equipped with GPS (GNSS) receivers along with other sensors such as accelerometers, tilt sensors and so on. GPS (GNSS) technology is now part of structural health monitoring toolboxes [USACE 2002; Santerre 2011].

### Movement Analysis Caused by Train and Car Load

#### Vertical and Transversal Displacements

Figure 3 (top) shows typical effects of freight train transits on the vertical (V, green lines) and transversal (T, blue lines) components as detected by the GNSS receiver every second for a period of 6 min. Radar measurements (vertical distances at every s) are represented by dark lines and are intentionally shifted by 5 cm to avoid masking the two other lines. In fact, the radar values are the measurement residuals after the main tidal constituents have been removed (by the CHS). Remember that the tide height can reach 5–6 m in Quebec City. The superimposed lines are the results of applying a 10 s window moving average filtering. This technique helps to significantly reduce the data noise, especially for the radar measurements affected by the roughness of the river.

### Table 2: Summary of the auxiliary sensor values from July 2012 to mid-July 2013.

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>North car traffic flow (/15 min.)</td>
<td>0</td>
<td>509</td>
<td>118</td>
</tr>
<tr>
<td>South car traffic flow (/15 min.)</td>
<td>0</td>
<td>503</td>
<td>103</td>
</tr>
<tr>
<td>Trains (/week)</td>
<td>45</td>
<td>71</td>
<td>61</td>
</tr>
<tr>
<td>Ambient air temperature (°C)</td>
<td>−28</td>
<td>33</td>
<td>7.3</td>
</tr>
<tr>
<td>Solar radiation (W/m²)</td>
<td>5</td>
<td>1397</td>
<td>299</td>
</tr>
<tr>
<td>Longitudinal wind speed (km/h)</td>
<td>−41</td>
<td>30</td>
<td>−2.4</td>
</tr>
<tr>
<td>Transversal wind speed (km/h)</td>
<td>−71</td>
<td>98</td>
<td>3.4</td>
</tr>
</tbody>
</table>
There is indeed a good agreement between the radar measurements and the vertical variation of the GNSS antenna coordinates. One can notice that the less noisy GNSS antenna coordinate variations are related to the transversal components and the vertical coordinate variations are noisier. This is because GNSS (GPS) is less precise in the vertical direction [Santerre 1991] and that the bridge movements induced by car and train transits are mainly in the vertical direction. Transversal values were not always centered at zero because when the wind blows transversally, the suspended span moves in the transversal direction. The effect of the wind load is discussed later.

The shape and the size of the detected movements certainly depend on the weight and the length of the train. The duration of the transit probably depends also on the speed of the train. Unfortunately, no such information was available from the CN train file provided to us. For the freight train transits, the largest subsidence value reached 17 cm and the maximum transit duration was 3 min. The asymmetric shape of the graphs is attributed to change in the train speed or different weights of wagons. This asymmetric shape happens more often for freight trains going toward the north direction probably because they have to reduce their speed to enter the curve travelling westward before approaching the nearby Ste-Foy train station.

The vertical variations of the GNSS antenna were in fair agreement with the calculated values [DRC 1908a,b], which state that the deflection at middle of channel (suspended) span caused by a live load consisting of 2 Cooper’s Class E60 locomotives (60 000 pounds or 27 273 kg), followed by 5000 pounds/linear foot (7456 kg/m) on each track, should be 33.7 cm (13.25 in). As mentioned before, there is currently only one railway track and the bridge was originally designed with two railway tracks.

The transversal displacement of the antenna can be explained by a lever arm (tilt) effect. Remember that the train track and the GNSS antenna were located on the upstream side of the bridge (not in the middle point of the transversal section of the bridge, which is 31 m wide), and the GNSS antenna is about 34 m above the railway. The ratio of the peak values between the transversal and the vertical displacement (T/V) is 0.66 ±0.08 (for all types of freight or passenger train).

Figure 3: Vertical (V) and transversal (T) displacements during the transit of a freight train (top) and during the transit of a passenger train (bottom).
The maximum value of the transversal displacement was about 11 cm. This means that the train load seems also to produce a tilt effect on the suspended span along with a subsidence effect. The transversal movement correlates perfectly with the vertical displacement. In this configuration, it is even easier to detect train transit with the transversal GNSS component because it has a greater precision than the vertical component.

Figure 3 (bottom) shows typical effect of passenger train transits. The passenger trains, which are typically smaller and travel at higher speed than freight trains, produce smaller peaks. The maximum measured vertical subsidence value was about 2.5 cm, while the minimum subsidence was as low as 1.0 cm. The longest duration of the load effect of the passenger trains was about 1 min. For comparison, the weight by unit of length of a passenger wagon is less than 2500 kg/m vs about 6000 kg/m for a tank wagon.

The vertical coordinate variations of the GNSS antenna caused by the car load were not visually perceptible even during traffic rush hours. In fact, the car load is considerably smaller than the train load (for comparison, the weight by unit of length of a car is less than 400 kg/m versus about 6000 kg/m for a tank wagon). To confirm the visual inspection, FFT analysis was performed during the night (0:00–1:15 a.m., with an average of 300 passing cars), during the morning rush hour (6:45–8:00 a.m., with up to 6000 passing cars) and during the evening rush hour (4:00–5:15 p.m. with up to 6000 passing cars). In fact, no significant difference in FFT amplitude or period values between the night period (with the lowest number of car transits) and the two rush hours was noticed.

**Longitudinal Displacements**

The train load effect on the longitudinal coordinate variation of the antenna (located at the middle of the suspended span) was also investigated. Figure 4 presents graphs where longitudinal displacement of the GNSS antenna (maximum value of 1 cm) due to freight trains has been noted. The longitudinal coordinate variations are in magenta and the transversal variation is in blue. The latter was superimposed to clearly identify the train transits. In fact, the

![Figure 4: Longitudinal (L) and transversal (T) displacements during freight train transits.](image-url)
longitudinal coordinate variation was detected for 45% of the freight train transits and for only 10% of the passenger train transits.

The slope of the longitudinal variation at the time corresponding to the transversal peak value is positive (displacement in northward direction) for the northbound trains and negative (displacement in southward direction) for the southbound trains. This relatively small coordinate variation demonstrates the great capability of GNSS results to monitor engineering infrastructures. This behaviour might be explained by the kinetic energy transferring from the train to the suspended span. In fact, the suspended span is hinged on by the cantilever arms and the suspended span movement is also attenuated by shock absorbers (traction brakes) installed between the cantilever arms and the suspended span.

Xia et al. [2000] reported train load effects on a suspension bridge as measured by GPS receivers. They also presented a suspension bridge dynamic response model to explain this phenomenon. However, this model would have to be adapted for a structure such as the cantilever Quebec Bridge.

### Movement Analysis Caused by Wind Load

#### Transversal Displacements

Figure 5 presents examples for six windy days, showing the transversal coordinate variations (blue line in cm) of the GNSS antenna atop the suspended span at 10 min intervals, filtered using a 10 min moving average and the averaged transversal wind speed as recorded by the anemometer every 10 min (green line in km/h). In order to distinguish and study just the effect of the wind loading, the days with high solar radiation (from 500 up to 1400 W/m²) were discarded and the periods of train transits were removed. The impact of solar radiation will be discussed in the next section. Furthermore, to have a minimal number of values for the calculation of the daily cross correlation value (also reported on the lower left of each graph in Figure 5), only the days that had at least 25% of common epochs between GNSS and wind data values were retained. Altogether, 54 days meet these criteria and 12 days had wind speed values larger than 60 km/h (the maximum value recorded was 98 km/h). To better distinguish the two time series, two different origins for the vertical axes have been selected.

The cross-correlation coefficients range from 0.80 to 0.97, as indicated in the lower left corner of the graphs. This indicates that the bridge reacts quite instantaneously to the transversal wind load. The high correlation between both time series is clearly visible from the graphs, especially when the wind speed is high. The largest reported winds were 98 km/h from the west (day: 13-01-31) with a displacement of 10 cm in the eastward direction and almost 60 km/h from the east (day: 13-01-20) with a displacement of 6 cm in the westward direction. The largest

![Figure 5: Transversal displacement of the central suspended span versus transversal wind speed for six different days.](image-url)
Diurnal wind speed variation also occurred in day 13-01-20; about 130 km/h wind change for total transversal displacement of 14 cm during that day. It is worth mentioning that the time of wind zero crossings (green line) coincides with the transversal displacement zero crossings (blue line).

To see the complete behavior of the transversal wind effect on the transversal coordinate variation, all the data sets have been displayed together in Figure 6. The total number of values (sampled every 10 min) was 7161. In this graph, the transversal displacements associated with the east transversal wind (in green) have been changed of sign. The blue dots are associated with the west winds. Altogether, there were 10 days where the west wind blew above 60 km/h (up to 98 km/h) and two days with maximum east wind at 60 km/h. The best fit parabola (in magenta) has been estimated by least-square and their coefficients and their precisions are reported in Table 3.

Using the parabola coefficient, the value for a 170 km/h wind speed was extrapolated and a value of 34.6 cm was obtained. The red parabola was interpolated from the 1908 prediction for a transversal wind speed of 170 km/h (see below). The third parabola (in brown) was obtained from the best fit to the west wind speed only (for a total of 2938 measurements). The $R^2$ value of 0.79, associated with the parabola fits, successfully passed the Fisher test.

It can be seen in Figure 6 that the transversal effect of the wind from the east direction (green dots) seems to be greater than the east wind (blue dots).

<table>
<thead>
<tr>
<th></th>
<th>$a \pm \sigma_a$ (m h$^2$/km$^2$)</th>
<th>$b \pm \sigma_b$ (m h/km)</th>
<th>$c \pm \sigma_c$ (m)</th>
<th>$R^2$</th>
<th>$y(\text{at } 170 \text{ km/h})$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>East and west winds (7161 values)</td>
<td>0.000 007 3 ± 0.000 000 3</td>
<td>0.000 82 ± 0.000 02</td>
<td>-0.005 4 ± 0.000 3</td>
<td>0.79</td>
<td>0.346</td>
</tr>
<tr>
<td>West wind only (2938 values)</td>
<td>0.000 008 2 ± 0.000 000 4</td>
<td>0.000 49 ± 0.000 03</td>
<td>-0.000 9 ± 0.000 4</td>
<td>0.79</td>
<td>0.320</td>
</tr>
</tbody>
</table>

Figure 6: Distributions of the transversal displacement of the central suspended span as a function of the transversal wind speed.
The transversal wind speed must be strong enough to be detected by the measured GNSS vertical coordinate variations, since GNSS is less precise in the vertical component compared with the horizontal direction [Santerre 1991]. In fact, for the day with the highest wind speed recorded (100 km/h), a vertical displacement of 2.8 cm was measured by GNSS, a value larger than the predicted one of 1.9 cm.

Table 4: Comparison of transversal displacements for different transversal wind speed values.

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>170</th>
<th>150</th>
<th>100</th>
<th>60</th>
<th>30</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (m/s)</td>
<td>47.2</td>
<td>41.7</td>
<td>27.8</td>
<td>16.7</td>
<td>8.3</td>
<td>2.8</td>
</tr>
<tr>
<td>1908 Prediction (cm)</td>
<td>34.3</td>
<td>26.8</td>
<td>11.9</td>
<td>4.3</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Best fit (all) (cm)</td>
<td>34.6 ± 0.9</td>
<td>28.2 ± 0.7</td>
<td>15.0 ± 0.4</td>
<td>7.0 ± 0.2</td>
<td>2.6 ± 0.07</td>
<td>0.4 ± 0.04</td>
</tr>
<tr>
<td>Best fit (west wind) (cm)</td>
<td>32.0 ± 1.2</td>
<td>25.7 ± 1.0</td>
<td>13.0 ± 0.5</td>
<td>5.8 ± 0.2</td>
<td>2.1 ± 0.09</td>
<td>0.5 ± 0.04</td>
</tr>
</tbody>
</table>
**Movement Analysis Caused by Temperature and Solar Radiation**

Table 5 (last line) shows the length and height of the bridge steel variations (in inches) due to a temperature variation of -30°F to 120°F (for a total variation of 150°F, or 83.3°C) as reported in DRC [1908a,b]. The value of the steel thermal coefficient was assumed to be 0.000 006 1/°F. This corresponds to 11.0 ppm/°C. With this value, the displacements in mm for a 10°C temperature variation have been calculated; see Table 5 (line 3). The dimensions given in line 2 of Table 5 are also shown in Figure 1.

**Vertical Displacements**

The first effect of temperature investigated was the vertical variation of the GNSS antenna with respect to the air temperature (Figure 7). Unfortunately, no steel bridge temperature was available. In the time series, the train transit effect, which can be as large as 15 cm (see first section above), was removed in order to only keep the effect of temperature on the vertical coordinate variations. In Figure 7, the pale blue dots represent the 10-min moving average vertical coordinate variations of the GNSS antenna; the dark blue dots are the mean values for a complete day associated with their corresponding daily mean air temperature. In this time

<table>
<thead>
<tr>
<th>L. arm cantilever</th>
<th>½ L. central span</th>
<th>H. main tower</th>
<th>H. total central span</th>
<th>H. central span</th>
<th>½ bridge width</th>
</tr>
</thead>
<tbody>
<tr>
<td>177.0 m</td>
<td>97.5 m</td>
<td>94.5 m</td>
<td>69.5 m</td>
<td>33.5 m</td>
<td>15.3 m</td>
</tr>
<tr>
<td>19.5 mm</td>
<td>10.7 mm</td>
<td>10.4 mm</td>
<td>7.6 mm</td>
<td>3.7 mm</td>
<td>1.7 mm</td>
</tr>
</tbody>
</table>

* 6.34 in 3.50 in 3.40 in 2.52 in N/A N/A

* Equivalent values in inches for a 150°F temperature variation (from DRC [1908a,b]).

![Figure 7: Vertical coordinate variation as a function of the (ambient) air temperature.](image-url)
series, the daily mean temperature ranged from —23.6°C to 25.9°C, 49.5°C temperature variation.

In general and as expected, when the temperature is above 0°C, the vertical variation is positive and vice versa. A linear regression was estimated (the purple line in Figure 7) using the daily values. This provided a corresponding thermal coefficient of 9.3 ±1.5 ppm/°C (instead of the theoretical value of 11.0 ppm/°C) with a R² value of 0.50 (although a small value, the Fisher test was passed). The red line in Figure 7 represents the predicted values calculated with the 11.0 ppm/°C thermal coefficient using the total height of the suspended span (69.5 m). For the 49.5°C total daily temperature variation during the year, the measured vertical variation was then 3.2 cm versus 3.8 cm for the predicted value (for a discrepancy of 6 mm).

To explain this discrepancy (6 mm), one might suspect remaining errors in the relative wet tropospheric delay model, especially during summer where the relative humidity (partial water vapor pressure) is high (in comparison with the winter season), and this effect is not totally cancelled in relative (differential) positioning, especially because the (closest) GNSS reference station was located 7 km away with a height difference of 70 m with respect to the Quebec Bridge GNSS receiver. Residual tropospheric errors mainly affect the GNSS height determination [Santerre 1991]. Moreover, no steel temperature data were available, as previously noted.

**Longitudinal Displacements**

Since the GNSS receiver was located at the middle of the suspended span, one might not expect any variation in the longitudinal coordinate. But some departures were noticed, as illustrated in Figure 8, representing two separate weeks during the summer season (bottom) and the winter season (top). During the summer, the longitudinal variations remained very close to 0, regardless of the positive temperature value, but as soon as the temperature dropped below 0°C (roughly) during winter, the variations became negative (displacements toward the south shore). This is an indication that the suspended span was blocked and pulled by the south cantilever arm once the (air) temperature was below about 0°C. The cross-correlation values at zero time lag, indicated in the lower left corner of the graphs, were indeed very large (0.93) for the weeks with negative temperature and smaller for positive temperature (as low as 0.36 during the week in summer).

For studying this phenomenon further, a graph of the longitudinal coordinate variation as a function of the air temperature is presented in Figure 8.
Figure 9. The large dots represent the daily mean values and the small dots represent the 10-min moving average longitudinal variation of the GNSS antenna. This figure shows that the longitudinal displacement occurred at 6°C instead of around 0°C. Then the data time series were divided into two parts: below (green dots) and above (blue dots) 6°C. The linear regressions for both parts are also plotted in Figure 9 (solid lines).

By dividing the slope of the linear regressions by the length of the cantilever arm plus half the length of the suspended span (275 m), a thermal dilatation value of 0.2 ± 0.2 ppm/°C was obtained with R² value of only 0.01 when the temperature was above 6°C. In this case, there was no significant correlation with temperature (as indicated by the Fisher test). However, when the air temperature was below 6°C, the corresponding thermal dilatation was 8.3 ± 0.3 ppm/°C with R² value of 0.92 (in this case, the Fisher test was passed successfully). With respect to the theoretical thermal coefficient of 11.0 ppm/°C and for a temperature of −30°C (from 6°C to –24°C), one should obtain a transversal variation of −9.0 cm instead of −7.2 cm (see Figure 9). It seems some part of the longitudinal displacement was absorbed by the damping mechanisms (shock absorbers) and the supports between the suspended span and the anchor arms. It is worth recalling that the tropospheric error (mentioned in the previous section) does not affect GNSS horizontal (longitudinal and transversal) components.

Interesting to note that L’Hébreux [2001] reported that eight pins used for linking the suspended span and the cantilever arms were replaced in 1985 because the bridge expansion did not behave adequately. According to the Canadian National’s engineers (personal communication), the dampers (shock absorbers) between the suspended span and the cantilever arms were also replaced more than 10 years ago (around 2005). From Figure 8 and 9, it seems that an unusual displacement in the longitudinal direction of the suspended span of the bridge still exists.

Transversal Displacements

Particularly during sunny summer days, an important transversal variation in the GNSS antenna coordinates was noticed. Some examples are given in Figure 10. In this figure, to avoid superposition of the different plots, the range of the solar radiations (right side scale) was set between 0 and 4 kW/m² even when the maximum recorded value was 1.4 kW/m². The temperature values (brown line), to be read with the left scale, have to be multiplied by 3 to obtain the real air temperature in °C. The time is indicated in hours in local time (LT), that is,
Eastern Time zone. In order to isolate the effect of solar radiation, only the days with low transversal wind (less than 30 km/h) were selected, which also affects transversal coordinate variations (see previous section).

The transversal displacements could easily reach up to ~5 cm before noon and a bit less (about 3 cm) in the afternoon during summer sunny days, in which solar radiation values were as high as 1 kW/m², as in the examples presented in Figure 10. The rapid variation in the solar radiation during the day indicates the presence of clouds. In fact, during cloudy days the transversal displacements were significantly reduced (and of course at night there is no solar radiation). During the winter season, the sun’s elevation angle is always low (maximum 21° during the winter solstice), and therefore the transversal displacement was always close to 0. Indeed, the transversal displacement due to solar radiation is also related to the sun orientation with respect to the bridge structure (which creates a temperature difference between both sides of the bridge) and the thermal inertia of steel.

Let us mention that solar radiation effects have been reported for bridge towers and telecommunication towers. For example, Schenewerk et al. [2006] have shown a tower lateral variation of 9 cm due to differential temperature for the Sunshine Skyway bridge (with towers 132 m in height), located in Tampa (Florida). Breuer et al. [2008] studied the daily and seasonal drift of the Stuttgart TV Tower caused by the daily solar radiation and air temperature variation. During a sunny day, the surface of the tower concrete shaft that was exposed to sunlight was subjected to the thermal expansion provoked by non-symmetrical warming. The side exposed to the sun would extend, and the tower and its top would incline away from the sun.

Summary, Conclusions and Recommendations

Table 6 compiles the movements of the suspended span of the Quebec Bridge measured by GNSS, as reported in the previous sections, along with the calculations (larger expected deformations) made by the Quebec Bridge engineers who designed it more than a century ago.

The freight train load causes the centre of the suspended span to subside by up to 17 cm. This measured value is in fair agreement with the value assumed by engineers during the design and the construction of the Quebec Bridge. The subsidence value is smaller for passenger trains (ranging between 1.0 and 2.5 cm). The train transits also provoke a tilt to the suspended span since the railway is located on the upstream side of the bridge. The
maximal transversal displacement of the GNSS receiver, located 34 m above the railway, was 11 cm. The longitudinal displacement (of about 1 cm) of the suspended span was also detected for freight train transits, but not for passenger trains. Car loading effect was not detected by the GNSS antenna that was located on top of the suspended span of the Quebec Bridge.

It was also shown that the center of the suspended span reacts instantaneously to transversal wind load and the transversal displacement is proportional to wind speed squared. The measured values can reach 13 cm for wind speed of 100 km/h. The extrapolated value fits very well with the predicted value made during the stage of the bridge design.

The relationship between vertical displacements of the suspended span and the transversal wind speed has not been demonstrated. To detect this effect using the GNSS technique, the authors recommend the installation of a reference GNSS station closer to the bridge and another GNSS antenna on the other side of the suspended span of the Quebec Bridge. In this last configuration, for such a short baseline of 31 m (equal to the bridge width), GNSS will be able to measure the inclination of the suspended span even if GNSS height accuracy is less than the horizontal accuracy. Another possibility is to install digital inclinometers (tilt sensors) on the suspended span at the top and at the deck level. Longitudinal wind load does not affect the suspended span of the Quebec Bridge.

The impact of the temperature variation on the vertical movement of the GNSS antenna located at the centre of the suspended span of the Quebec Bridge was measured at a slightly smaller value (3.2 cm versus 3.8 cm, a 6-mm discrepancy) compared with the predicted one. One can suspect the GNSS height determination to be affected by errors in the wet delay modelling during the summer time because the nearest GNSS reference station is located 7 km away with a 70 m height difference. A blockage of the suspended span with the south cantilever arm was measured when the temperature drops below 6°C. The magnitude of this longitudinal displacement reached 7 cm for a temperature variation of 31°C. Transversal displacement of the GNSS antenna easily reached up to 5 cm because of the high solar radiation values (up to 1 kW/m²) during summer days. This phenomenon can be explained by the differential temperature values between the two sides of the Quebec Bridge.

For a complete geodetic deformation monitoring of the Quebec Bridge, the addition of GNSS receivers on each side of the suspended span and on top of the main towers is recommended, along with the installation of inclinometers. In order to improve the GNSS determination, especially in the vertical component, the authors suggest installing closer reference GNSS stations. To study the natural frequencies of the bridge, the authors suggest recording GNSS data with a higher data rate (some receiver models can measure at a rate of 100 Hz). Since GNSS signals are blocked by metallic structures, the authors also recommend complementing GNSS measurements with other sensors, such as accelerometers and total station reflective prisms, installed at the deck level. Finally, an anemometer should be installed directly on the Quebec Bridge to measure the real parameters of wind (speed and direction) acting on the bridge as well as the installation of steel temperature sensors at strategic points of the bridge.

**Acknowledgements**

Firstly, we want to gratefully thank the Port of Montreal for giving us the access to the GNSS receiver data as well as their partners in this project, the Canadian Coast Guard, the Canadian Hydrographic Service and CN (Canadian National Railway Company). The authors were also offered free access to the complementary data described in this paper by the Quebec Department of Transportation, MeteoLaval and Cansel. We are very thankful for their collaboration. Finally, NSERC (Natural Science and Engineering Research Council of Canada) is acknowledged for its research grant that was used to partially fund this research.

<table>
<thead>
<tr>
<th>Load</th>
<th>Direction</th>
<th>1908 design calculation</th>
<th>GNSS measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train</td>
<td>Vertical</td>
<td>34 cm (two trains)</td>
<td>17 cm (one freight train)</td>
</tr>
<tr>
<td></td>
<td>Transversal</td>
<td>N/A</td>
<td>11 cm (at the top of the span)</td>
</tr>
<tr>
<td></td>
<td>Longitudinal</td>
<td>N/A</td>
<td>1 cm</td>
</tr>
<tr>
<td>Car</td>
<td>Vertical</td>
<td>N/A</td>
<td>Not significant (not detected)</td>
</tr>
<tr>
<td>Wind</td>
<td>Vertical</td>
<td>2 cm (at 100 km/h)</td>
<td>3 cm (at 100 km/h)</td>
</tr>
<tr>
<td></td>
<td>Transversal</td>
<td>34 cm (at 170 km/h)</td>
<td>32 cm (extrapolated at 170 km/h)</td>
</tr>
<tr>
<td>Temperature and solar radiation</td>
<td>Vertical</td>
<td>3.8 cm (for 50°C variation)</td>
<td>3.2 cm (for 50°C variation)</td>
</tr>
<tr>
<td></td>
<td>Transversal</td>
<td>N/A</td>
<td>5 cm (for high solar radiation)</td>
</tr>
<tr>
<td></td>
<td>Longitudinal</td>
<td>N/A</td>
<td>7 cm (at –25°C)</td>
</tr>
</tbody>
</table>
References


