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C-GMS, The Canadian Ground Motion Service-Assessment and Correction of Thermal Effects on Bridges

VALENTIN PONCOS and DANIEL CUSSON

ABSTRACT

Many public infrastructure assets in Canada are old and deteriorating, with almost 40% of publicly-owned bridges rated as fair, poor, or very poor in terms of their condition. Structural health monitoring (SHM) is a method for ensuring the safety and integrity of structures, detecting damage progression, and estimating the performance of infrastructure assets over time. For this purpose, a new wide-area Canadian Ground Motion Service has been created to make radar satellite-measured ground motion data publicly available. In this paper, the methodology of the approach is described with a focus on the assessment and correction of thermal effects on bridges.

INTRODUCTION

According to Canada's Infrastructure Report Card [1], many public infrastructure assets in Canada are old and deteriorating, with almost 40% of publicly-owned bridges rated as fair, poor, or very poor in terms of their condition. For this reason, Kepler Space Inc. and its partners are creating a wide-area Canadian Ground Motion Service (C-GMS). The service is initially based on time series (every 6/12 days, between 2015 and 2022) of Sentinel-1 (S1) satellite radar data and a modified Persistent Scatterers Interferometry (PSInSAR [2]) approach to detect and map ground motion over time, with [mm/year] accuracy over wide areas (up to 700 km swaths). Presently C-GMS covers the Windsor-Quebec City corridor (roughly 1100 km in the East-West direction and around 250-500 km in the North-South direction and is publicly available for viewing and data download at: http://c-gms.com/.

C-GMS uses open access C-band S1 data (ensured to be acquired until 2038) and – depending on a successful launch – future S/L band NASA NISAR. The service can include data from additional SAR sensors, if available, produced by Kepler Space or by third parties. For this work, high-resolution RADARSAT-2 data acquired in Spotlight mode (SLA12; 1x3 m^2 resolution) from a descending orbit with an incidence angle of 39° was used. The acquisition period started in May 2016 and ended in Sept. 2018.

C-GMS facilitates:

- Integration with ground-based measurements from differential GNSS networks;
- Predictive modelling using artificial intelligence (AI); and
- Result dissemination using open-access online platform running on mobile devices.

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The main value of such service consists in detecting areas of strong ground motion dynamics, identifying the source of the observed motion, modelling, 2D decomposition, and deciding whether to issue an alert if the motion exceeds some pre-defined thresholds.

METHODOLOGY

The dataset, which is openly accessible, was implemented to follow the general format of the European Ground Motion Service E-GMS, defined in [3], and is identified as layer Level 2.b raw (i.e., measurements in the slant-range direction of the radar) in the C-GMS platform. Additional to the open-access measurement layer Level 2.b raw, Kepler is producing layers of information that may be of interest to specific end users, including:

- **Level 2.b sm – seasonal motion**: relates to variations in temperature and differences in gravitational tides. This motion is of interest when monitoring thermal dilation in man-made structures (like bridges). To detect non-linear motion, sudden/discontinuous motion, subtle changes in motion patterns, and target backscattering characteristics, the seasonal motion must be removed from the raw data.
- **Level 2.b cb – coherent before date**: contains the point targets monitored on the ground chosen based on temporal persistency. Sometimes, such targets are degraded or removed (e.g., house being demolished, occurrence of landslide, or infrastructure breakdown). This layer contains all persistent targets that degraded at various dates during the monitoring period, indicating events that occurred on the ground in certain areas and for different causes that might be of interest for subsequent correlation (e.g., input for an AI-based event prediction module).
- **Level 2.b ca – coherent after date**: contains all the new targets appearing during the monitoring interval. This information is useful when the length of the monitoring period is important, especially when long-term/wide-area motion is of interest (e.g., geodynamic processes, tectonic plate motion [4]).
- **Level 2.b cd – changes in displacement rates**: indicates areas with unstable motion, such as the settlement of recently built infrastructure or an accelerated motion that could be an indication of an eventual disaster. Areas with accelerated motion could be included in an alert map.
- **Level 2.b gb – break events without loss of coherence**: indicates areas of mostly local targets that suffer a sudden displacement (such as a bridge structure that gets displaced a few millimetres or centimetres without changing its shape and orientation). This information could be of interest in predicting a larger and possibly catastrophic collapse of that infrastructure.

The millimeter accuracy [2] of the linear deformation rate measurements from the PSInSAR technique can be compromised by the presence of strong seasonal motion of certain types of infrastructure, such as bridges, tall buildings, and other man-made targets in general. Also, a short-term monitoring period may lead to exaggerated linear motion estimates, especially when extrapolated to the long term. Figure 1 illustrates a simple displacement model with a zero linear displacement rate but with a strong periodic motion of different durations simulating the thermal component from seasonal variations.

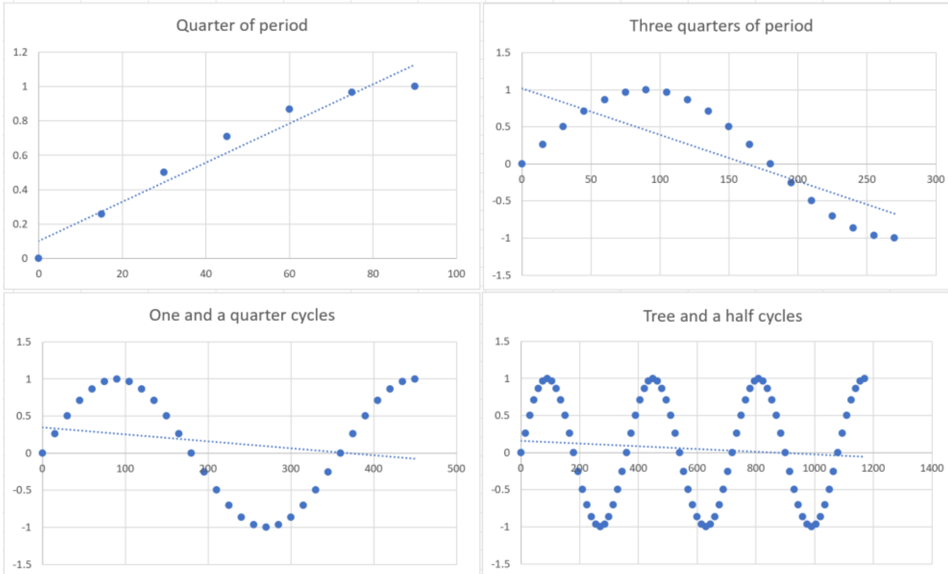


Figure 1. Examples of false displacement trends induced by strong seasonal displacements.

It can be seen that the estimated linear displacement rates are far from zero and also vary largely as a function of the length of the sinusoids. Trying to extrapolate the seasonal/thermal motion to an integer number of cycles in order to remove the bias effects on linear displacement rates has the problem that the weather doesn't repeat itself exactly, thus extrapolating the thermal cycle to an integer cycle might induce additional noise in the data.

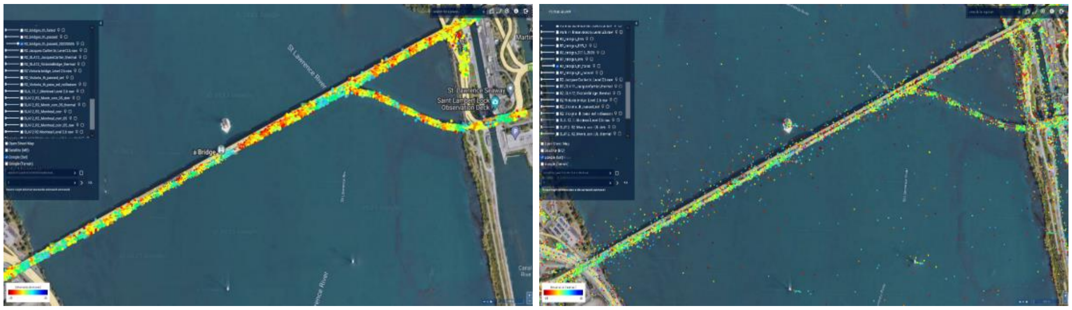
Thus, before estimating the actual linear displacement rates and detecting eventual critical dynamics, the seasonal motion needs to be identified and removed from the data. Additionally, the seasonal motion can be used as input to a thermal analysis, which is useful for bridge health monitoring.

The following methodology, based on **thermal consistency,** was used to separate and model the thermal component of measured temporal displacement: A general detection criterion testing for consistency of thermal motion is applied: Assuming that any summer in Canada is warmer than any winter, it is expected that a target on a bridge would be moving in the same general direction every summer (or every winter) unless a non-negligible non-thermal movement starts developing. Details on similar methods to determine thermal displacements from raw displacement data can be found in [5] and [6].

CASE STUDIES

Victoria Bridge in Montreal, Canada (45°29'30"N, 73°31'46"W)

Figure 2 illustrates the maps of radar targets monitored on the Victoria Bridge, separated by the thermal consistency criterion. The colour scale is proportional to the oscillating amplitude [mm] due to seasonal motion; the linear displacement rate was removed. The targets that passed the criterion are illustrated in Figure 2(a), where one can observe that the dataset is less noisy, and the colour alternations related to the dilation/contraction of the different bridge spans are well delimited.



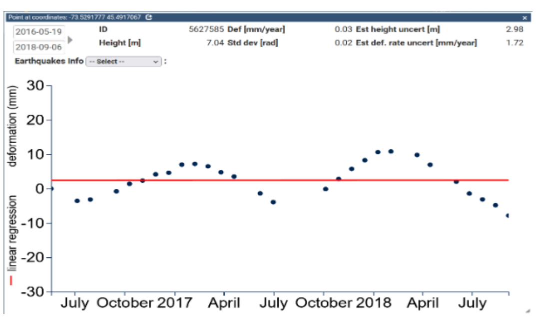
(a) Thermally consistent scatterers (b) Thermally inconsistent scatterers

Figure 2. Victoria bridge – separation of scatterers based on thermal consistency.

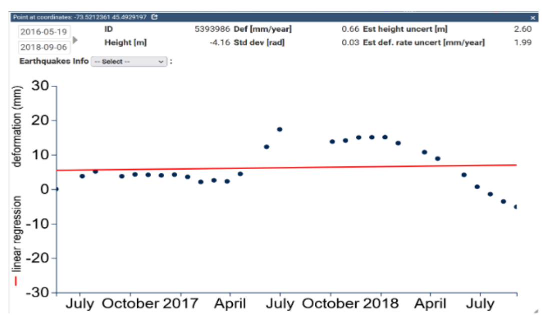
Figure 2(b) illustrates the map of targets that failed thermal consistency. The colour alternation is less evident; thus, the motion of the targets is not directly related to thermal effects, at least not the way they were assumed. It is possible that some targets exhibit a complex motion due to multiple motion vectors or other factors.

Figure 3 illustrates some examples of temporal profiles extracted from the red areas (top) and blue areas (bottom) in Fig. 2(a). In Figs. 3(a) and 3(c), profiles that passed the thermal consistency criterion resemble expected typical temperature variations. In Figs. 3(b) and 3(d), profiles that failed the thermal consistency criterion do not correlate very well with the expected typical temperature profile.

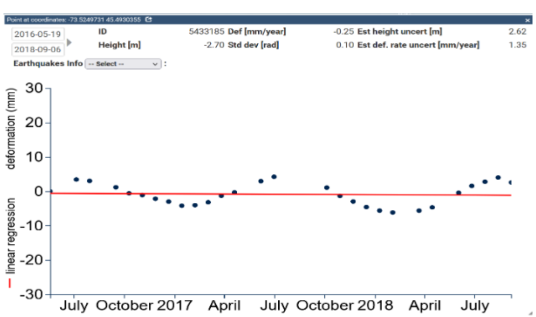
In Figure 3(a), the red areas are moving away from the radar in the summer periods (at the maximum dilation period). Similarly, in Figure 3(c), the blue areas are moving toward the radar in the summer periods (dilation). The opposite motion is observed in the wintertime. Figures 3(b) and 3(d) illustrate inconsistent profiles.



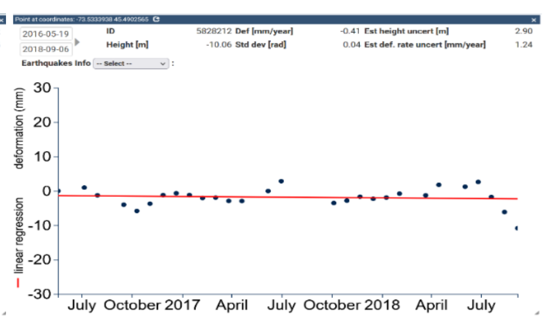
(a) Thermally consistent profile - red areas



(b) Thermally inconsistent profile - red areas



(c) Thermally consistent profile - blue areas

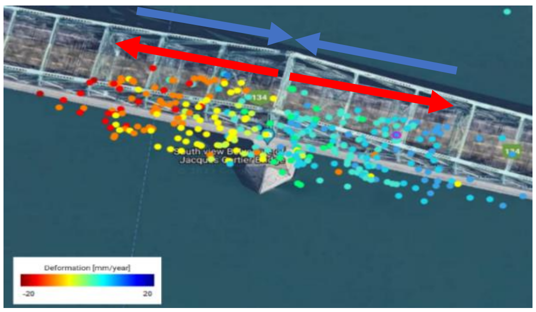


(d) Thermally inconsistent profile - blue areas

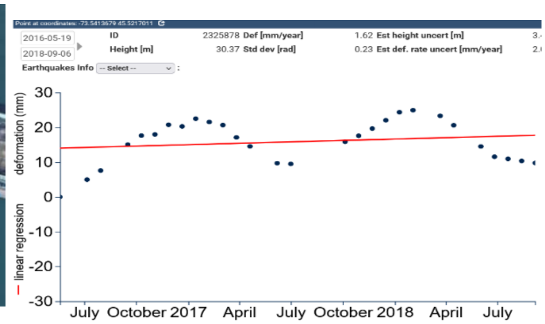
Figure 3. Victoria Bridge – Examples of temporal profiles that passed and failed the thermal consistency criterion.

Jacques Cartier Bridge in Montreal, Canada (45°31'19"N, 73°32'30"W)

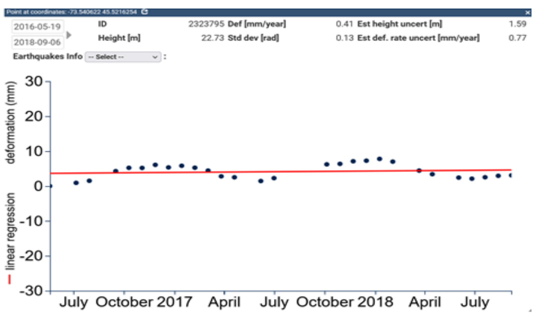
The same type of information is also presented in Figure 4 for the Jacques-Cartier Bridge. Figure 4(a) illustrates the junction between two bridge spans on each side of a pier. The motion in the area is threefold: yellow area – relatively stable (Figure 4(c)); red area – moving away from the radar satellite in the summer (Figure 4(b)); and blue area – moving towards the radar satellite in the summer (Figure 4(d)). The red arrows in Figure 4(a) illustrate the direction of motion in the summer, and the blue arrows the direction of motion in the winter.



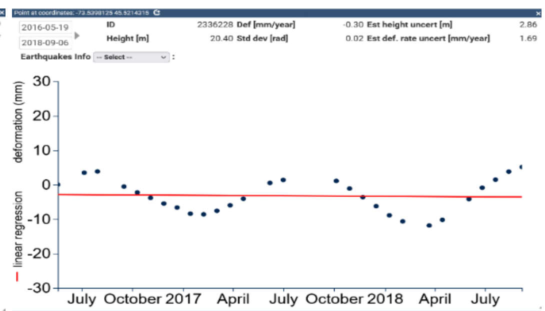
(a) Targets map



(b) Thermally consistent profile - red areas



(c) Thermally consistent profile - yellow areas



(d) Thermally consistent profile - blue areas

Figure 4. Jacques-Cartier Bridge – thermal effects.

Samuel de Champlain Bridge in Montreal, Canada (45°28'12"N, 73°31'14"W)

Figures 5 and 6 illustrate the same type of information (i.e., thermally consistent targets and examples of profiles from the red and blue areas) for the Samuel de Champlain Bridge. The same comments mentioned above also apply here.

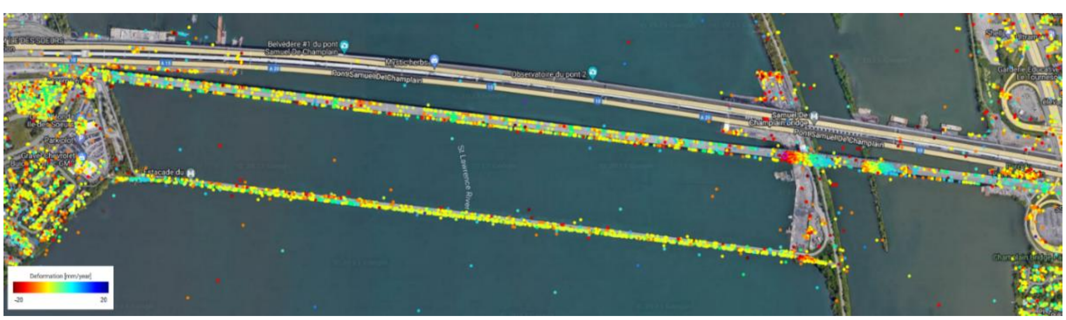
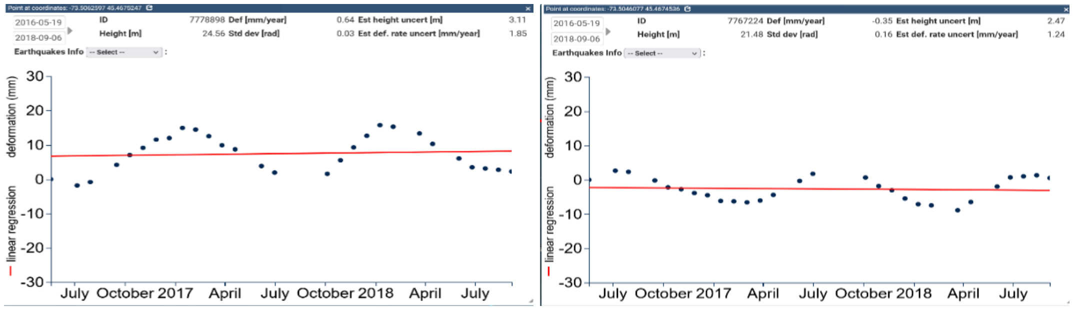


Figure 5. Samuel de Champlain Bridge - map of persistent scatterers that passed the thermal consistency criterion.



(a) Thermally consistent profile - red areas (b) Thermally consistent profile - blue areas

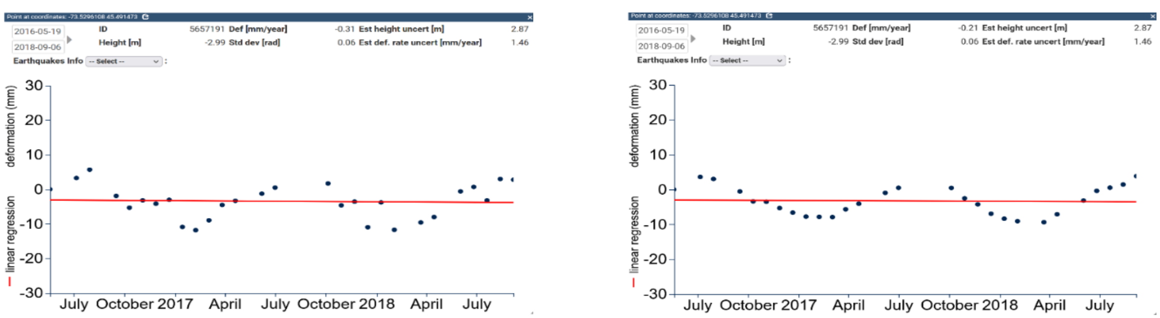
Figure 6. Samuel de Champlain Bridge – temporal profiles that passed the thermal consistency criterion.

THERMAL MODELING AND CORRECTION

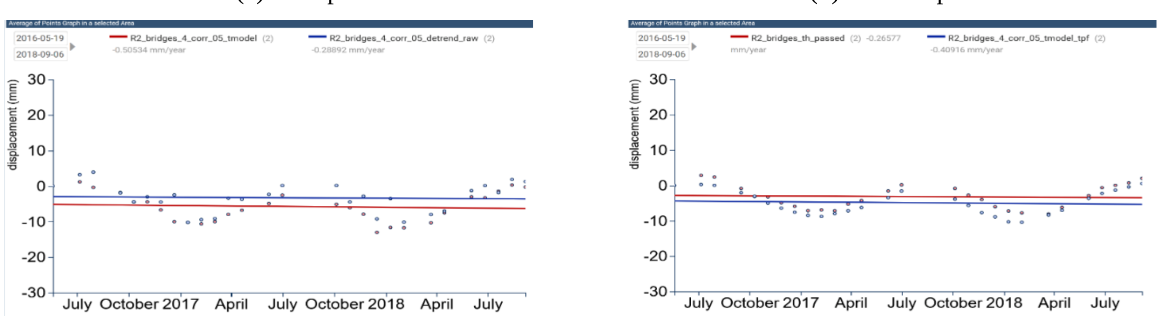
Two datasets were created, one containing the original (raw) displacement profiles and another containing the profiles after a least square smoothing filter was applied on a 140 days window (2 samples before and 2 after the filtered value). The thermal analysis was conducted on both datasets for comparison.

The temporal profile of every target on the three bridges was correlated with the ambient temperature, assuming a linear correlation between the temperature and the dilation amplitude.

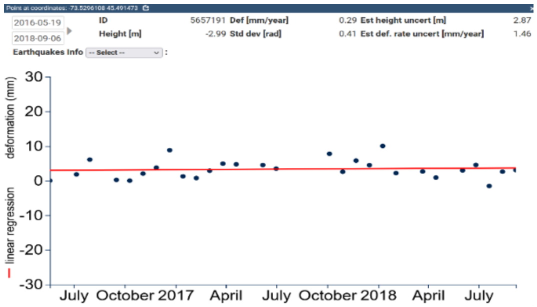
Once the thermal models were estimated for all targets, they were removed from the displacement profiles. For the Champlain Bridge, Figures 7 and 8 give an example of the estimation and removal of the thermal profiles from raw displacement data and temporarily filtered profiles for the blue and red areas, respectively. The resulting residual profiles are now ready for further analysis (e.g., estimation of linear displacement rates and rate changes).



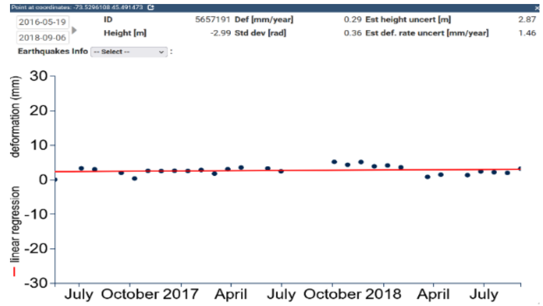
(a) Raw profile (b) Filtered profile



(c) Thermal model (red) from raw profile (blue) (d) Thermal model (blue) from filtered profile (red)

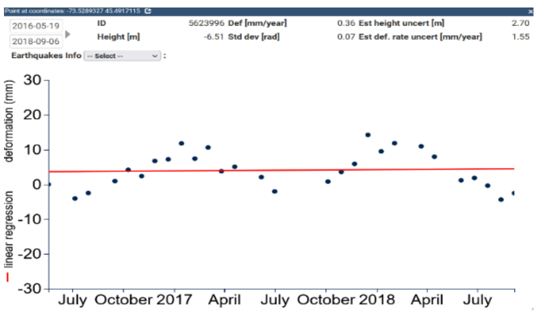


(e) Residual raw profile (thermal model removed)

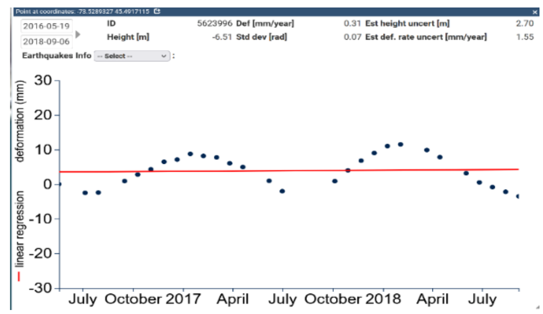


(f) Residual filtered profile (thermal model removed)

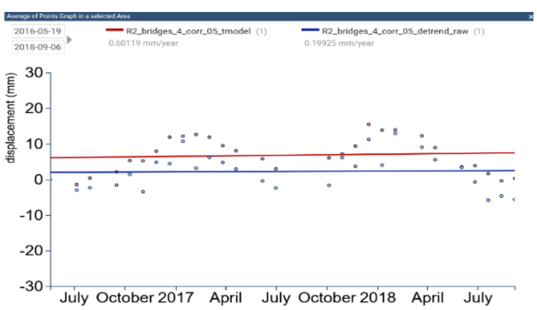
Figure 7. Champlain Bridge – Removal of thermal models from displacement measurements (blue areas).



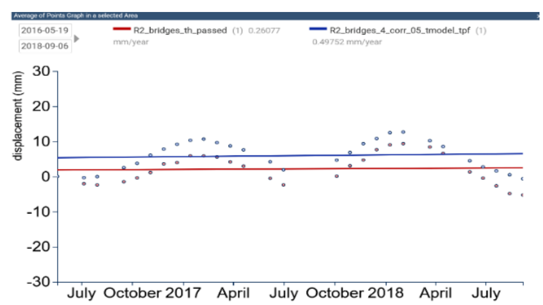
(a) Raw profile



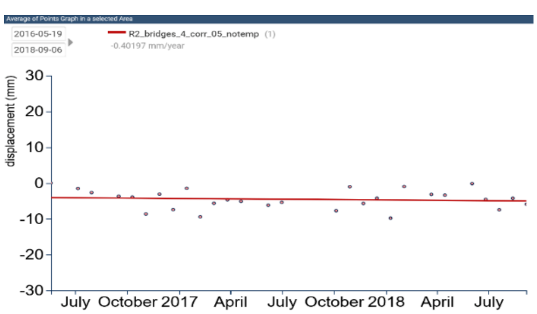
(b) Filtered profile



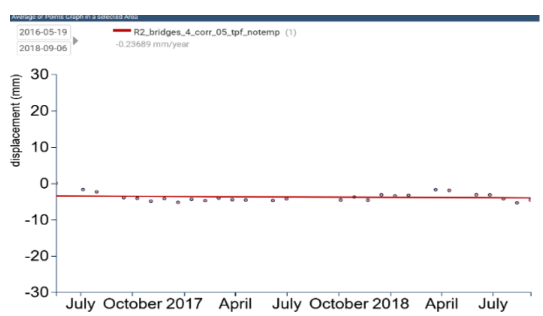
(c) Thermal model (red) from raw profile (blue)



(d) Thermal model (blue) from filtered profile (red)



(e) Residual raw profile (thermal model removed)



(f) Residual filtered profile (thermal model removed)

Figure 8. Champlain Bridge – Removal of thermal models from displacement measurements (red areas).

SUMMARY AND CONCLUSIONS

The modelling of thermal effects is useful for assessing the structural health of a bridge, both as an analysis of the thermal response of the structure and to detect eventual deformations that accumulate in time and could lead to the structure's collapse. It was demonstrated that seasonal motion can affect the accuracy of the measured linear deformation rates; thus, it must first be estimated and removed from the measurements before any other analysis on the bridge stability is carried on. This work addressed the creation of the C-GMS seasonal motion layer of data, which made possible subsequent analyses leading to the creation of the next data layers, as described earlier in the methodology. It is hoped that this dataset will be useful for ensuring the safety and integrity of structures, detecting damage progression, and estimating the performance of infrastructure assets over time.

ACKNOWLEDGMENT

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