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Remote Monitoring of Bridges From Space

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Abstract

The widespread deterioration and some recent collapses of highway bridges have highlighted the importance of developing effective bridge monitoring strategies that can help identify structural problems before they become critical and endanger public safety. A typical major urban centre may possess several hundreds of bridges, which makes it difficult to upgrade all these bridges with surface-mounted sensors to monitor their structural performance due to practical and economic reasons. A two-step approach may be used, in which potentially critical bridges are first identified through a screening process by remote satellite-based monitoring, and then further investigated with in-situ monitoring and detailed inspection. The capability of Canada's RADARSAT-2 advanced Synthetic Aperture Radar (SAR) satellite is being investigated for use in the first step of the proposed approach, which can help prioritize in-situ monitoring and maintenance of critical bridges. Interferometric SAR (InSAR) is an advanced processing technique applied to radar images of the Earth's surface that can detect very small movements from ground features such as infrastructure systems, including roadway and railway bridges and their major components. By applying InSAR processing techniques to a series of radar images over the same region, it is possible to detect vertical movements of infrastructure systems on the ground in the millimetre range, and therefore identify abnormal or excessive movement indicating potential problems requiring detailed ground investigation. A major advantage of this technology is that a single radar image, which can be obtained in darkness and in any weather, can cover a major urban area of up to 100 km by 100 km, and therefore all bridges in the area could be monitored cost effectively. Preliminary results from the application of this technology to transportation infrastructure assets in selected major Canadian urban centres like Vancouver and Montreal are presented and discussed.

Keywords: Bridges; Infrastructure; Remote monitoring; RADARSAT-2 satellite

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1. **Introduction**

1.1 State of Health of Canadian Bridges

Canadian provinces, municipalities, and regions have substantial and diverse transportation infrastructure assets, including bridges, roads, and railways, supporting our economy and quality of life. Most of this infrastructure was built in the 1950s through the 1970s and has gradually deteriorated over the decades due to limited investment in timely maintenance and repair. The inadequate upkeep of these public assets has accelerated the growing costs of repairs and replacements, which was estimated five years ago at $22 billion for municipalities only (MIRZA 2007). These inflating costs are directly associated with the rehabilitation of deteriorating bridges and roads all over Canada. Aside from fiscal pressures, aging infrastructure like bridges poses significant risks to public safety and quality of life. Although the wearing of public roads and consequent hazards are a source of disturbance to commuter traffic, fast-deteriorating highway bridges could present a threat to human life in the event of a collapse. Approximately 25% of today's bridges are considered deficient in terms of structural capacity and functionality (U.S. DOT *et al*. 2007). Assuming this percentage applies to Canada, between 15,000 and 20,000 Canadian bridges could require major upgrading, rehabilitation, or replacement.

Bridges in Canada are subject to intense freeze/thaw cycles and serious corrosion-induced damage due to de-icing salt use on roads for safe winter travel (ZAKI and MAILHOT 2003). Since many of these structures were built several decades ago, a number of them do not comply with modern bridge design codes. Design flaws, poor construction, materials degradation, traffic increase, environmental stresses, and heavier truckloads further accelerate deterioration and render these ageing bridges structurally and functionally deficient. Deteriorating bridges have become ubiquitous across Canada in several major urban centres.

Unfortunately, it sometimes takes a disastrous structural failure to draw attention to severity of the problem. In September 2006, a 20-meter section of the Concorde Blvd Overpass collapsed onto Highway 19 in Laval, Canada, killing 5 people and seriously injuring 6 others. Because of that, Quebec's Transportation Ministry slated 28 similar bridges for demolition and replacement, and another 25 for major rehabilitation (JOHNSON *et al*. 2007). In USA, the recent dramatic failure of the Mississippi River Bridge in Minneapolis has raised public and government awareness of the risk of relying only on periodic bridge inspections (e.g. every two years) to detect deficiencies that are continuously developing over time (DRAKE 2008). However, bridge structures are designed to display ductile failure modes in case of collapse, and consequently most of them will display early warnings when the structure is under extreme loads, providing enough time for remedial actions. With this in mind, structural health monitoring (SHM) is ideal for detecting early warnings of possible failures or need for rehabilitation and strengthening.

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1.2 Need for Remote Monitoring

The growing concern over civil infrastructure safety has spawned increased research to develop suitable monitoring technologies and strategies. The broad objectives of SHM are to measure bridge condition, evaluate in-service performance, detect deterioration, determine required maintenance, and estimate remaining service life. The judicious use of SHM on critical bridges can contribute to addressing some of today's challenges and improving inspection, repair, and rehabilitation methods and reducing traffic disruption. For instance, a more accurate knowledge of the life cycle performance of a bridge network through SHM can provide more complete and timely information to decision makers for an improved management of highway bridges regarding their maintenance and rehabilitation. SHM can also help re-assess and update traffic and environmental loads and associated safety factors used in bridge design, including the effects of climate change. Reliability-based service-life prediction models, such as the one developed by LOUNIS and DAIGLE (2008), can be calibrated and regularly updated with selected SHM data to improve the accuracy and validity of service life predictions (CUSSON *et al*. 2011). Consequently, the safety, structural performance, and durability of major bridges can be optimized, and their risks of failure and life cycle costs can be minimized.

Even as in-situ monitoring technologies evolve and get integrated into modern sensor-packed "smart bridges", thousands of other bridges throughout the nation will remain inspected using conventional methods to the minimum required frequency. Current bridge inspection programs include some laborious and subjective methods for quantifying deterioration of various bridge elements. In-situ sensors are appropriate for targeted monitoring of selected structures, but cannot be readily deployed on a large scale, due to the already limited budgets for bridge maintenance and rehabilitation. Little attention, however, has been given to remote sensing technologies, as reported by Ahlborn *et al.* 2010. Satellite-based monitoring data generated using radar imagery may offer a viable source of independent information products that may be used to remotely monitor the structural health of bridges, confirm conclusions drawn from in-situ sensor data, and feed decision-support models and tools for pre-emptive bridge rehabilitation. Moreover, remote monitoring technologies can eliminate the need for bridge lane closure and traffic disruption or the preparation of the structure before the acquisition, since these technologies do not come in direct contact with the structure.

For these reasons, a collaborative project entitled RADARSAT-2 Structural Health Monitoring (R2SHM) was recently initiated to apply a mature remote sensing technology towards the large-scale monitoring of bridges in urban areas. R2SHM will supply bridge information products, combined with in-situ data, which can be used by bridge owners to help identify safety-critical structures and quantify the risk they pose to their users. Improved assessments allow limited resources to be allocated towards repair and maintenance activities, thereby extending the service life and minimizing life cycle cost of bridge networks.

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1.3 Previous Applications of Airborne Remote Monitoring in Civil Engineering

Remote sensing may be defined as the collection and measurement of spatial information about an object, area, or phenomenon at a distance from the data source without direct contact (FALKNER 1995). Remote sensing includes a wide number of technologies that may be valuable to bridge condition assessment, such as ground-penetrating radar, spectra, 3D optics, optical satellite and airborne imagery, optical interferometry, light detection and ranging (Lidar), thermal infrared, remote acoustics, digital image correlation, radar, interferometric synthetic aperture radar (inSAR), and high-resolution digital photography. A detailed comparative evaluation of these commercially available technologies can be found in a Michigan Tech report by AHLBORN et al. (2010).

In the following, the discussions will focus on a smaller set of remote sensing technologies that are used onboard of aircrafts or satellites. With these technologies, spatial resolution is an important concept, and refers to the dimension of the ground surface covered by an image’s pixel. High spatial resolution means that smaller areas on the ground surface can be observed compared to images acquired with low spatial resolution sensors. Another important concept is temporal resolution, which refers to the frequency at which a site or ground feature can be sensed by an instrument. The viewing angle is another important consideration. Due to high flight altitudes ranging from 300 meters for small-format aerial photography to 800 km for the RADARSAT-2 satellite, airborne- and more specifically space-borne technologies are most suitable for the monitoring of top horizontal surfaces of bridge decks. For the monitoring of side girders, for example, highly oblique imagery would be required, which are best obtained by ground-based monitoring technologies. Finally, the cost of acquiring airborne and satellite-borne imagery for infrastructure monitoring is not insubstantial, but can be offset by encompassing a large number of bridges in the network within a single satellite scene, or a series of aerial photographs.

1.3.1 Electro-Optical Imagery

Electro-optical sensors are electronic detectors that convert light, or a change in light, detected in the visual and/or infrared spectra, into an electronic signal. A report by HAUSER and CHEN (2009) indicated an image resolution of 13 mm using small-format aerial photography (i.e. altitudes from 300 m to 1500 m), which could be sufficient for identifying defects at the surface of bridge decks such as concrete spalling, large structural cracks, or a change in bridge length. Image analysis techniques can be used however to improve the measurement accuracy in the sub-pixel range. For example, KANT and BADARINATH (2002) confirmed that ground features less than 2% of pixel dimension could be detected. Space-borne electro-optical image resolution is even coarser according to ALHBORN *et al*. (2010) who reported image resolutions of 41 mm for the GeoEye-1 satellite and 46 mm for the WorldView-2 satellite.

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1.3.2 Light Detection and Ranging (LiDAR)

LiDAR is an optical remote sensing technology that can measure the distance to a target by illuminating it with light, often using pulses from a laser. LiDAR instruments fitted to aircraft and satellites are used for land surveying and mapping. LIDAR has been identified by NASA as a key technology for enabling autonomous precision safe landing of future robotic and crewed lunar landing vehicles (AMZAJERDIAN *et al*. 2011).

Figure 1 (left) illustrates the LiDAR detection process by measuring the amount of time it takes for the laser pulse to travel from and reflect back to the aircraft, in order to map elevations of features both on land and in shallow water, as shown in Figure 1 (right). Global Positioning Systems (GPS) on board the aircraft and on the ground near the survey area provide sub-meter accurate positioning of the laser pulse. NASA has developed the Experimental Advanced Airborne Research LiDAR with unique capabilities (WRIGHT and BROCK 2002). With a weight of 112 kg, this LiDAR system can easily be installed onboard an aircraft. At an altitude of 300 m and a speed of 50 m/s, the system can survey 43 km^2 of area per hour, with a 2-m resolution and nominal ranging accuracy of 30 mm to 50 mm.

In Canada, a recent application of LiDAR was reported by LOCAT *et al*. (2010), in which a railway line in the Gaspé Peninsula was monitored because it was threatened by an active 0.5 Mm^3 rockslide. Due to the economic importance of the railway for this region, a monitoring system, including LiDAR and various ground-based sensors, was put in place to understand the movement types and extents, and to develop warning criteria and a risk assessment scenario to be part of the risk management plan for the site.

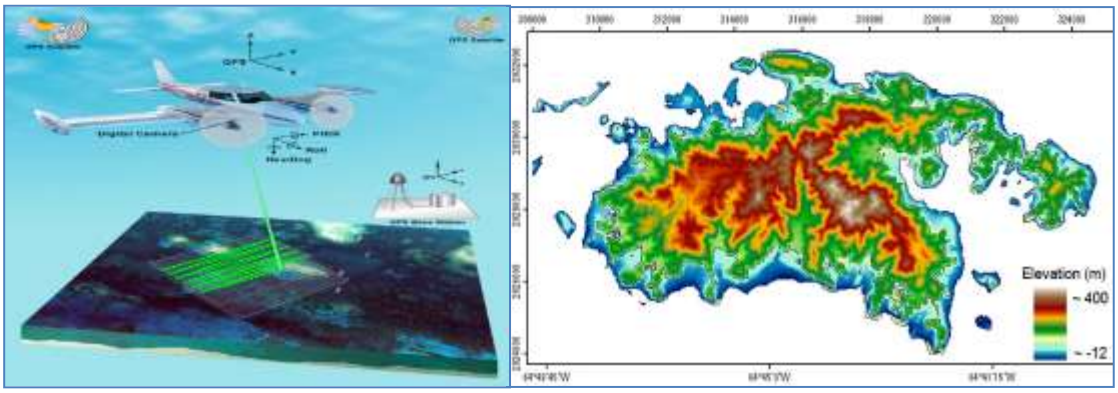

Figure 1 – LiDAR Process (left); USGS Elevation Results in St-Johns, U.S. Virgin Islands (right) (SCHREPPEL and CIMITILE 2011)

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1.3.3 SAR Interferometry for Elevation Mapping of Earth's Surface

The creation of interference images (or interferograms) from pairs of finely co-registered synthetic aperture radar (SAR) images acquired using nearly identical viewing geometry spawned a host of applications that characterize the earth's surface and its atmosphere. SAR is fundamentally a ranging measurement that generates images by bouncing microwaves off the Earth's surface. Each pixel in an interferogram comprises a phase difference (from 0 to 2π radians) between two distinct SAR snapshots of a given horizontal resolution. The interferogram phase is cumulatively sensitive to all geometric and physical variables that affect the return path length of the microwaves from the satellite sensor to the Earth's surface during each of the two satellite passes. Hence, the phase is proportional to surface topography, ground displacement along the satellite line-of-sight, atmospheric pressure and water vapour, and soil moisture.

As illustrated in Figure 2, the radar instrument measures along its line-of-sight (range direction), which can be projected along a different direction depending on the application (vertical in this case). There are several commercial vendors and government owners whose products can be used to create interferometric SAR (InSAR) images. They include MacDonald, Dettwiler and Associate Ltd. with Canada's RADARSAT-1 and RADARSAT-2 satellites (launched in 1995 and 2007, respectively), the Jet Propulsion Laboratory in the U.S. with AirSAR and UAVSAR sensors (onboard of aircrafts), and the European Space Agency with ERS and ENVISAT satellites (launched in 1991 and 2002, respectively).

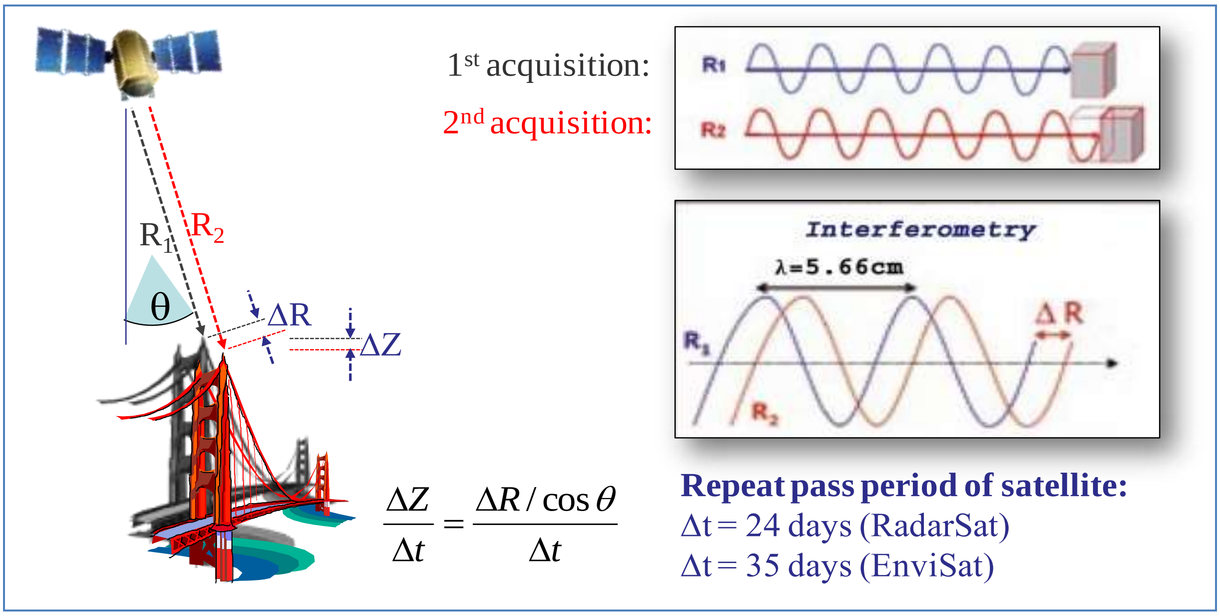

Figure 2 – SAR interferometry for remote monitoring of urban structures

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Although the horizontal resolution of typical space-borne InSAR images is in the meter range (ALHBORN *et al*. 2010), the accuracy of the vertical displacement measurement is in the millimetre range. MARINKOVIC (2007) compared satellite-based InSAR vertical displacement measurements to known imposed vertical displacements of corner reflectors installed on stable ground over a period of 5 years. Their data analysis indicated an accuracy of 1.6 mm for ENVISAT and 2.8 mm for ERS-2. Given that Canada's RADARSAT-2 satellite has newer sensor technology than the ENVISAT and ERS-2 satellites, it is expected to achieve similar if not better measurement accuracies. A study has been recently initiated to determine the exact accuracy of InSAR evaluation measurements from the RADARSAT-2 satellite.

SAR interferometry used to measure surface displacement was first demonstrated by GABRIEL *et al*. (1989). Since then, InSAR has been successfully used to measure displacements from landslides (FRUNEAU *et al*. 1996), earthquakes (MASSONNET *et al*. 1993), volcanoes (BRIOLE *et al*. 1997), glaciers (GOLDSTEIN *et al. 1993*), metal mining (RABUS *et al*. 2009), oil/gas fields (FIELDING *et al*. 1998), groundwater extraction (MCCARDLE *et al*. 2009), urban infrastructure (RABUS and GHUMAN 2009), and buildings (SHINOZUKA *et al*. 2000).

In the previously cited publications, SAR interferometry has been applied to diverse applications such as generating elevation maps of the earth, mapping of expansive and localized motion phenomena, and characterization of atmospheric water vapour. This is because SAR sensors capture path images that can be co-registered and interfered to yield a path difference that is sensitive to the imaging geometry and variations in physical parameters such as elevation, displacement, atmosphere and soil moisture. Each pixel of an interferogram contains phase contributions from these physical variables, and the contrasting spatio-temporal statistical properties of the constituent signals can be utilized to isolate the desired component.

1.3.4 Examples of previous InSAR applications from satellites

InSAR for displacement mapping of the earth's surface has been applied to diverse applications. Figure 3 illustrates differential uplift on the airstrip at Iqaluit Airport. Iqaluit is the largest community in Nunavut, Canada, located in the Everett Mountains. Ice rich permafrost has been identified within the municipality, which can affect structural integrity as it thaws and re-freezes. The goal was to identify localized displacement basins that can cause cracking and tilting of the infrastructure. In addition, displacement basins identified outside the built-up area can assist urban planners in screening future expansion of the community. Analysis of the archive data stack (3 m resolution) comprising 17 RADARSAT-2 images shows seasonal uplift at the Iqaluit Airport. Such locally inhomogeneous movement causes cracking and bending of the runway, which requires regular maintenance.

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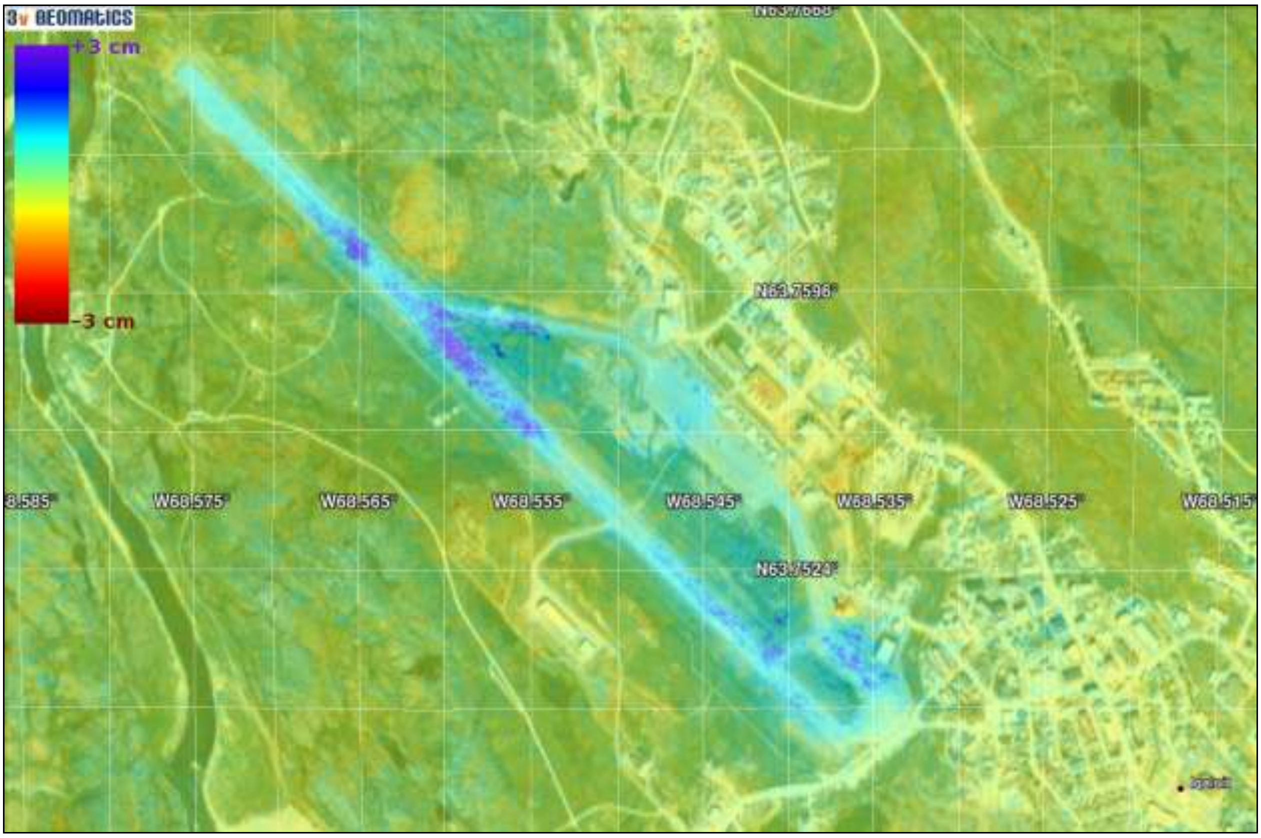

Figure 3 – Infrastructure monitoring, Iqaluit Airport

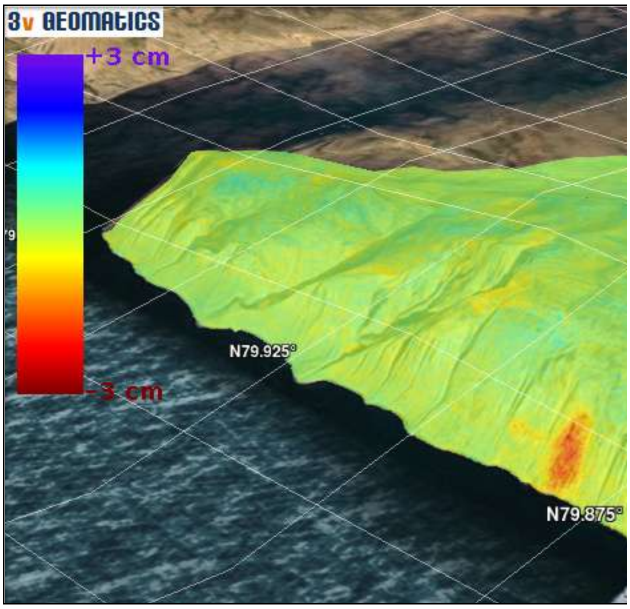

Figure 4 – Slope creep, Ellesmere Island

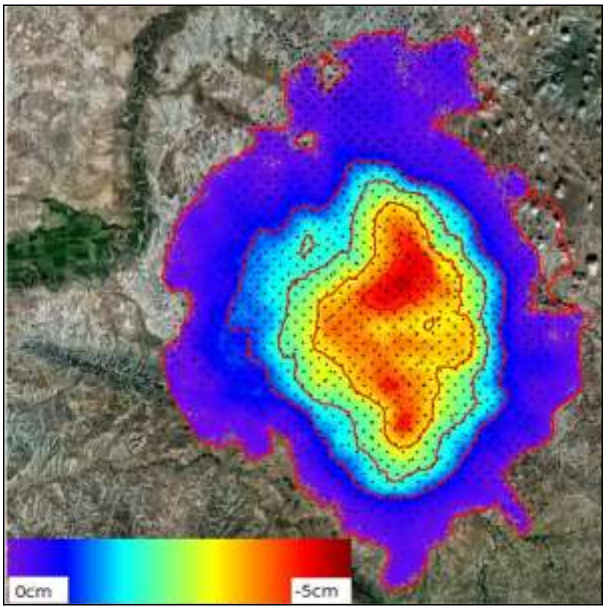

Figure 5 – Resource extraction, Wyoming

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Figure 4 illustrates a creeping slope problem that can pose a geohazard if it is close to a community or transportation corridor. The illustrated area represents Ellesmere Island, which is located in the Canadian Arctic Archipelago, and is mostly covered by the Arctic Cordillera mountain system. Mountainsides are expected to creep due to high slope gradients and melting/re-freezing of permafrost. The goal was to spatially map and quantify geohazards using InSAR. Analysis of the archive data stack (10 m resolution) comprising 27 RADARSAT-2 images shows gradual creeping of a slope facing the ocean. The measured component of the motion along the satellite line-of-sight increases monotonically with time, and indicates even more severe downhill motion. Failure of this specific slope would not pose an immediate threat to people and property in this specific location, but nevertheless demonstrates a geohazard monitoring application using InSAR.

Figure 5 illustrates the ground subsidence induced by oil/gas extraction in Wyoming, USA. The objective was to spatially and temporally map ground subsidence resulting from oil and gas extraction in Wyoming to help decide on the pre-emptive action to take in order to mitigate the impact on people, property, or business operations. The site is very suitable for InSAR monitoring due to dry atmospheric conditions and lack of vegetation. An EnviSAT data stack (25 m resolution, 100 km x 100 km coverage area) comprising 19 consecutive images was analyzed to identify displacement basins, and generate a series of displacement maps. The main displacement basin was a dynamic sinkhole that was expanding spatially as well as sinking vertically as oil and gas were being extracted. A qualitative assessment of publicly available well extraction data revealed that ground subsidence was correlated with resource extraction. All displacement maps were interpolated at well locations to generate a motion time-series for each well.

2. Space-borne SAR Interferometry for Remote Monitoring of Bridges

The expected accuracy of elevation measurements being in the millimetre range, as indicated above, makes this technology very attractive to displacement monitoring of bridges and other infrastructures. Space-borne InSAR, compared to other non-destructive evaluation techniques, offers the potential of rapid assessment of numerous bridges in a single scene from high standoff distance without requiring calibration or preparation of the structure and without interfering with traffic, which is a considerable benefit for busy highway bridges. This technology is best suited for the monitoring of the global metrics of a bridge, including bridge differential settlement, bridge deformed shape and, to a lesser extent, changes in bridge length and bridge deck transverse displacement by extracting the horizontal components of the measured satellite light-of-sight displacement.

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The side looking nature of SAR satellites (i.e. incidence angles typically from 20 to 50 degrees) introduces some geometric distortions such as layover and foreshortening in all imagery. For instance, bridge features over water have specific requirements for interpretation. Bridges that are aligned along the satellite flight direction can produce unique double or triple-bounce echoes as illustrated in Figure 6: first, the direct return from the bridge, then double-bounce reflection between the bridge and water, and finally a triple-bounce reflection (water, bridge under-body, then water again) (CADARIO *et al.* 2008). The direct bridge echo appears closest to the sensor because it is the shortest travel time and is received by the satellite first. High-resolution SAR images are advantageous in monitoring such bridges because the finer spatial sampling produces three distinctly segregated returns, as illustrated using the Spotlight (1.6 m horizontal resolution) RADARSAT-2 beam mode in Figure 6.

In-situ sensors are commonly deployed on important bridges to monitor their health. Two limitations of in-situ monitoring – the lack of spatial detail on a given bridge and the inability to instrument all bridge structures in a major urban centre – can be supplemented by satellite-based remote monitoring through regular radar imaging. Although radar-monitoring technology is mature and capable of measuring millimetre-level target displacements, its temporal resolution is limited by the repeat pass period of the satellite, which is 24 days in the case of RADARSAT-2. Consequently, there is a natural synergy between the high temporal resolution of in-situ sensors and high spatial resolution and coverage of satellite-based radar images.

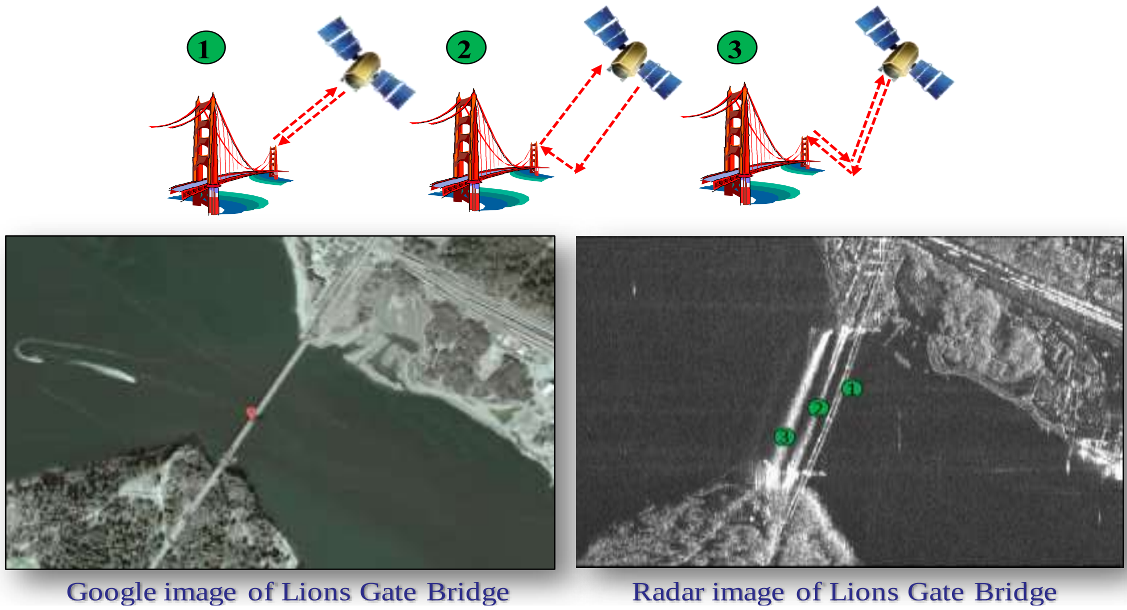

Figure 6 – Multi-bounce signal reflections in water near Lions Gate Bridge
(1: direct return; 2: double-bounce reflection; 3: triple-bounce reflection)

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The RADARSAT-2 satellite sensor has several advanced beam modes that are suitable for regular displacement monitoring of specific targets on bridges (e.g. slabs, trusses, towers, abutments, joints, barriers, posts). Targets that are dominant in their immediate neighbourhood, and reflect a stable echo to the satellite over time are known as Point Targets (PT). PT identification techniques use some pixel property − such as stability of the spectrum, amplitude, or phase − as a scoring function. The measurability of a point target is a function of its phase stability; and since directly evaluating phase stability is difficult and time-intensive, spectral or amplitude stability are often used as proxies for phase stability. Figure 7 illustrates point targets identified near the Vancouver Airport using spectral (top), amplitude (middle) and phase (bottom) stability. Spectral stability identifies the fewest targets, and numerous phase-stable targets are missed. Amplitude stability identifies the most targets, but many false targets over vegetated terrain are chosen. The analysis presented in this paper utilizes phase stability to select PTs, as it strikes the right balance between including the majority of phase stable targets and excluding false targets that contribute noise during data processing.

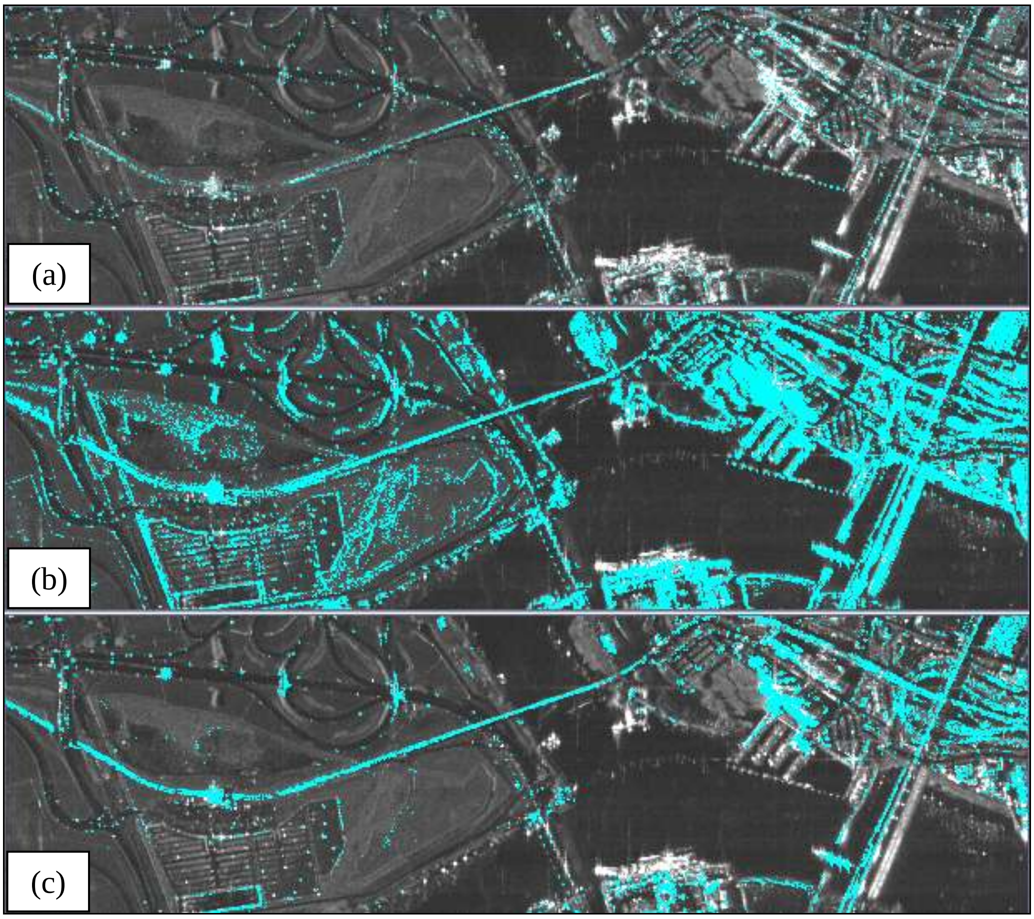

Figure 7 – Point Target Identification over Richmond, BC, Canada
(PTs identified using (a) spectral stability; (b) amplitude stability; and (c) phase stability)

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The displacement history at each PT can be measured through the process of Point Target Interferometry (PTI), also known as Persistent Scatterer Interferometry (PSI). In order to identify PTs and accurately apply PTI, a data stack comprising more than 15 overlapping SAR images is required. As InSAR phase is an aggregate of several different signals, it must be unravelled to isolate the target signal. Phase decontamination is the process of segregating the target signal by modeling and removing all other phase contributions (i.e. contaminants). For the purpose of bridge monitoring, displacement is the target signal and the main contaminants are atmosphere and elevation errors. Local and expansive variations in atmospheric water vapour get imprinted on interferograms because microwaves travel through the atmosphere during imaging. Elevation errors occur because accurate vertical positions of bridge targets are unknown during the processing of SAR images. Phase denoising techniques are also applied, whereby multiple redundant measurements are generated, each with independent noise characteristics, and this over-defined set of observations is mathematically solved to suppress noise and emphasize the target displacement signal.

A stepwise point target analysis is described below and illustrated in Figure 8 showing radar images taken over of a portion of the city of Montreal, QC, Canada:

A) A redundant network of point interferograms is generated. Long-scale phase variations due to atmosphere and short-scale phase fringes due to height error on tall buildings and thermal displacement on bridges are evident.

B) A long-scale Atmospheric Phase Screen (APS) is generated for each interferogram and removed. Short-scale phase variations remain.

C) The network of PT interferograms is spatio-temporally (3D) unwrapped. The background phase colour can change due to an ambiguity of 2π radians or a multiple thereof.

D) Each interferogram is spatially referenced to a stable neighbourhood, and the network is inverted using singular value decomposition (SVD) to derive a point interferogram for each acquisition. The local phase fringe density changes because the reference date corresponds to the temporal mean of the stack.

E) Phase decontamination including height error removal and static atmosphere correction is applied. Dense fringes over skyscrapers disappear.

F) The first interferogram is chosen as the temporal reference. This is directly converted to a displacement map.

Generally, temporal low-pass filtering is applied to remove residual atmospheric phase, which is random in time. However, it is not applied here to preserve the temporally random thermal displacement phase manifesting at bridges. This dataset of radar images over Montreal, with a spatial resolution of 10 metres, does not adequately sample the thermal phase gradients on bridges. Higher resolution images are more conducive for bridge applications, as they yield more PTs per unit area and prevent phase aliasing over bridge superstructures. The advantage of using lower resolution images in some applications is that they can cover larger ground areas than higher resolution images.

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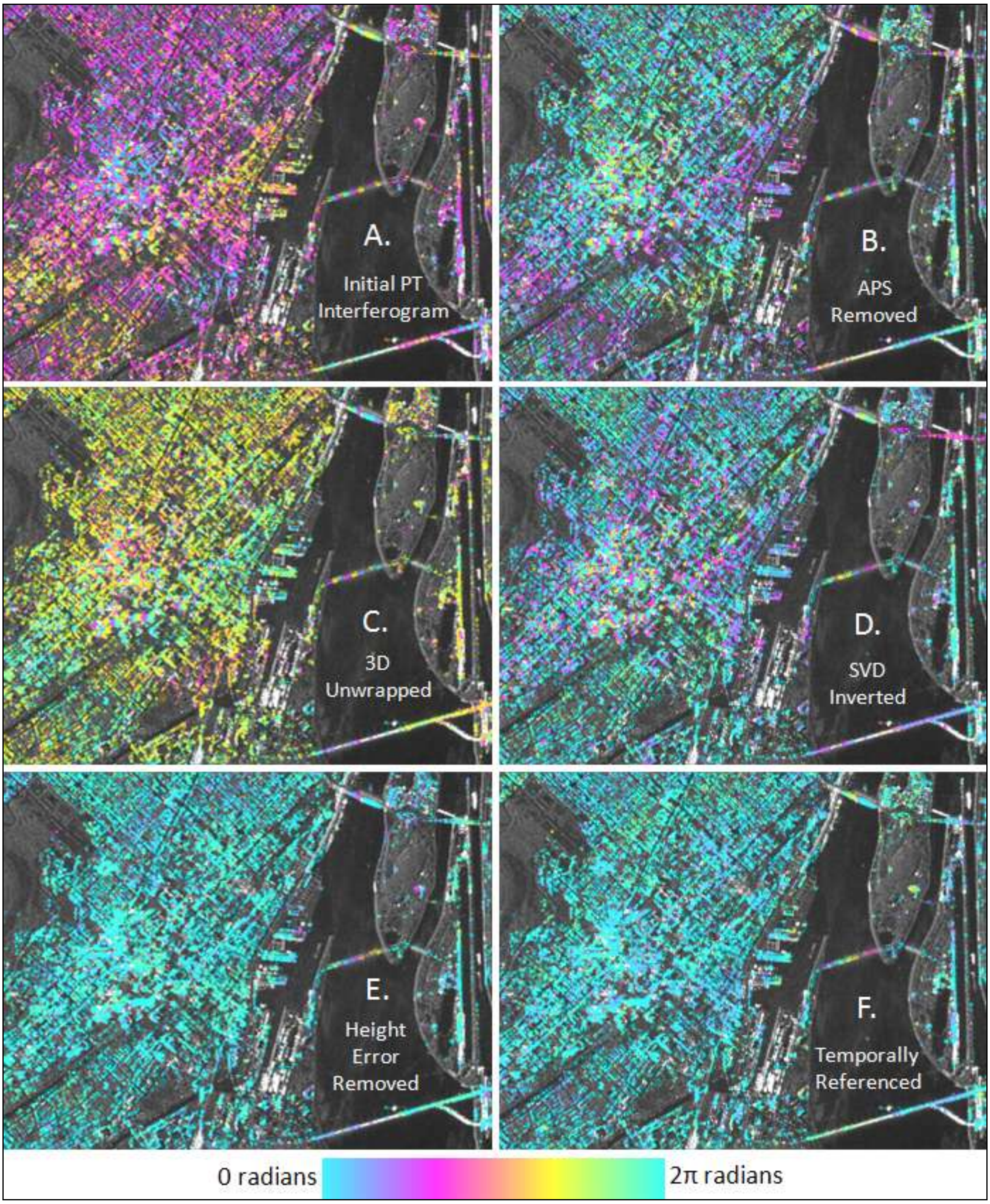

Figure 8 – Interferometric processing of a dataset over Montreal, QC
representing signal phase change (2π = -28 mm) from Jan 28, 2011 to March 17, 2011
and showing Jacques-Cartier br. (top); de la Concorde br. (middle); and Victoria br. (bottom)

3. Early Results of Satellite-Based Monitoring of Civil Infrastructure Assets in Vancouver, Canada

The current focus of the R2SHM project is on deriving reliable displacement histories for PTs occurring over bridge structures in urban centres. This project uses radar image data from Canada's RADARSAT-2 satellite launched in 2007, which is one of the world's most advanced commercially available Earth observation radar image providers. The sensors installed on the satellite – orbiting at an altitude of 800 km – provide various beam modes that offer different spatial resolution and area coverage. The FQ2 (8 m horizontal resolution), MF21N (5 m res) and U18 (3 m res) stacks were used over the city of Vancouver to identify PTs on urban infrastructure assets, including bridges. The overall urban point densities obtained are 1,827 points/km^2 for the FQ2 stack, 2,626 points/km^2 for the MF21N stack, and 15,444 points/km^2 for the U18 stack. For example, the total number of PTs identified over five selected bridges in Vancouver (Granville, Burrard, Cambie, Lions Gate, and Ironworkers Memorial bridges) was 678 for the FQ2 stack, 3,624 for the MF21N stack, and 11,165 for the U18 stack. The much higher density of point distribution achieved with the U18 stack over the two other stacks is advantageous for measuring bridge vertical displacements with greater spatial detail. Moreover, it enhances measurement accuracy because signal processing algorithms benefit from an increased density of PTs. Table 1 provides information on the five selected Vancouver bridges and compares the number of PTs identified on each bridge with the three different datasets.

Table 1 – Information on selected satellite-monitored bridges in Vancouver, Canada

Bridge Name (year opened)	Granville (1954)	Burrard (1932)	Cambie (1985)	Lions Gate (1938)	Ironworkers (1960)
Location	49.272°N, 123.133°W	49.275°N, 123.137°W	49.272°N, 123.115°W	49.315°N, 123.138°W	49.296°N, 123.026°W
Water crossing	False Creek	False Creek	False Creek	Burrard Inlet	Burrard Inlet
Type	Cantilever/truss	Steel truss	Box girder	Suspension	Cantilever/truss
Length	732 m	850 m	1,100 m	1,517 m	1,292 m
Number of lanes	8 traffic lanes	6 traffic lanes + 2 sidewalks	6 traffic lanes + 1 sidewalk	3 traffic lanes + 1 sidewalk	6 traffic lanes + 1 sidewalk
Peak height (GPS)	48 m	38 m	19 m	69 m	59 m
FQ2 Nb. of PTs	246	60	131	158	83
MF21N Nb. of PTs	902	264	660	985	813
U18 Nb. of PTs	2,265	726	1,578	4,256	2,340

InSAR is capable of generating wide-area displacement maps that identify and quantify displacement basins occurring in the entire imaged region. Figure 9 illustrates the cumulative displacement map generated over the Greater Vancouver area using a Multi-Fine RADARSAT-2 dataset (5-metre resolution) over a period of 2 years. The coloured displacement basins are quantified with respect to the legend. Subsidence basins are evident in North Vancouver, Mitchell Island, South Burnaby, New Westminster, Port Coquitlam, Vancouver International Airport (Richmond), South Richmond, Annacis Island, and North Surrey. Many basins are proximal to bridge approaches and exits.

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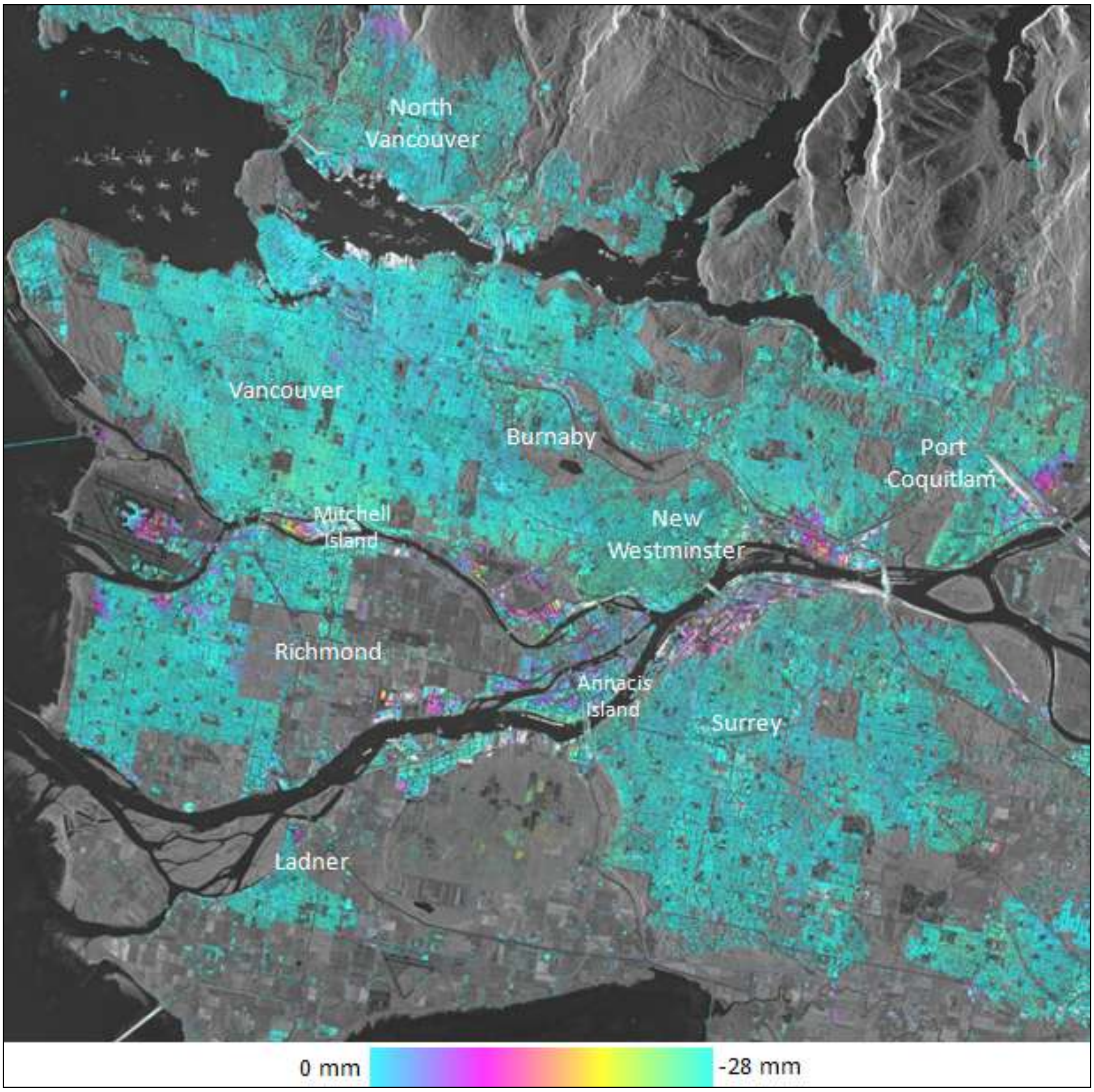

Figure 9 – Cumulative Displacement map over Greater Vancouver, Jan 2010 – Feb 2012

The Ultra-fine RADARSAT-2 dataset is more conducive for measuring signal on bridges due to its higher resolution (3 metres). Figure 10 illustrates displacement measurements on and around selected bridges in Vancouver and Richmond. The Lions Gate Bridge and the Skytrain (Canada Line) exhibit conspicuous thermal displacement, manifesting as cyclic displacement fringes along the length of the structure.

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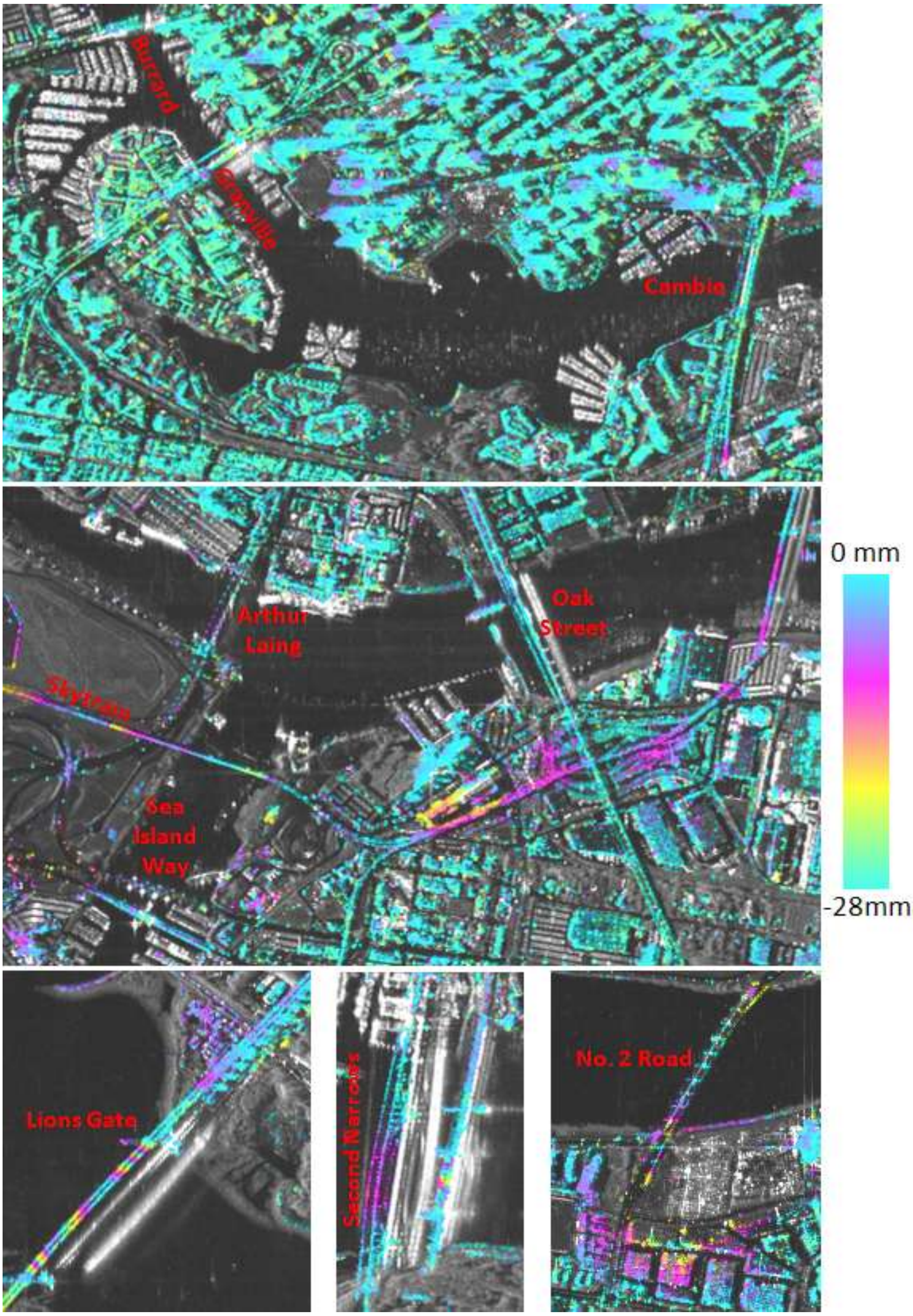

Figure 10 – Bridge Proximal Displacement Measurements of selected Vancouver bridges

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In addition to spatial displacement mapping, PTI was also used to extract displacement histories at discrete point targets on infrastructure installations such as buildings (Fig. 11), and bridges (Fig. 12). Although some seasonal effects may be observed, the general trends show steadily increasing ground sinking down to 20 mm over two years. A detailed analysis of surrounding PTs can then be conducted to assess whether the whole infrastructure asset is sinking uniformly or only at some locations, which could be worrisome.

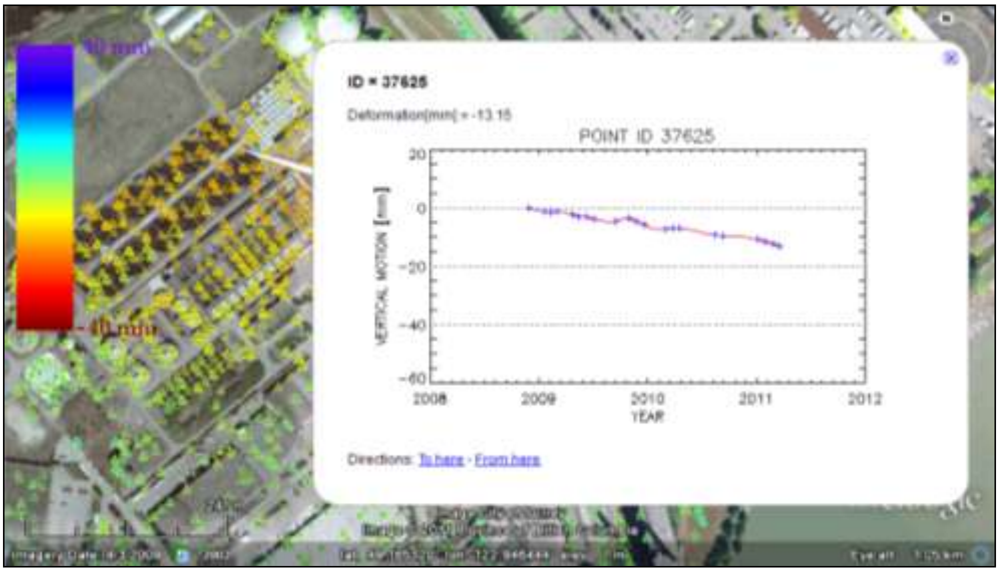

Figure 11 – Displacement over two years of a point target on a wastewater treatment plant

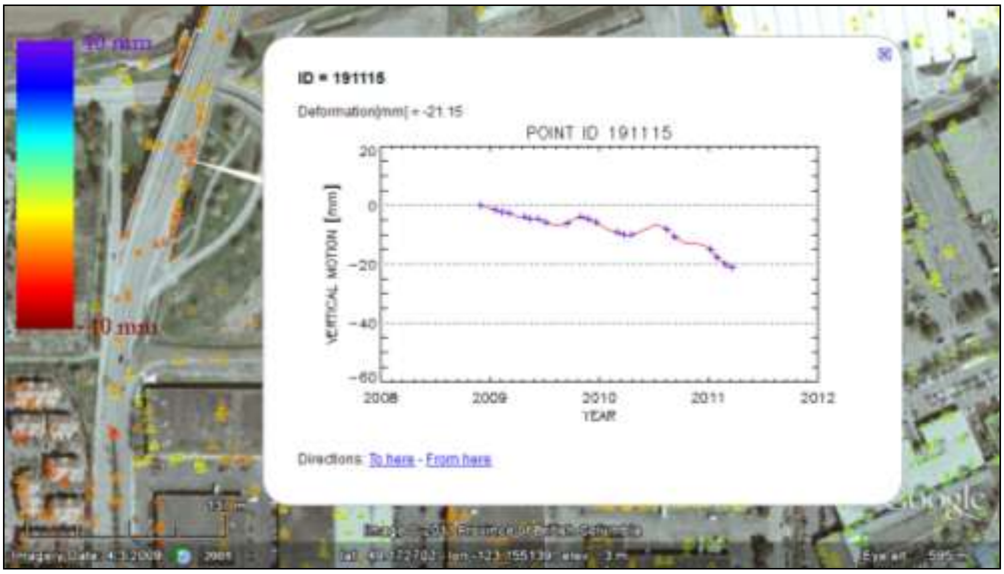

Figure 12 – Displacement over two years of a point target on a bridge approach slab

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4. Case Study: Thermal Displacement Analysis of Lions Gate Bridge

The Lions Gate suspension bridge in Vancouver, Canada crosses the First Narrows of Burrard Inlet, and connects the City of Vancouver to other municipalities on the north shore. The bridge was built in 1938 with a main span of 473 m and two approach spans of 187 m each. Among the number of bridges being monitored in the R2SHM project, measuring vertical displacements of the Lions Gate Bridge is the most challenging, as the interferogram pixels over the bridge comprise two uncorrelated signals: elevation error and strong displacement due to environmental factors. Figure 13(a) illustrates an interferogram of the Lions Gate Bridge, in which the numerous coloured fringes are indicative of large displacements occurring over the bridge.

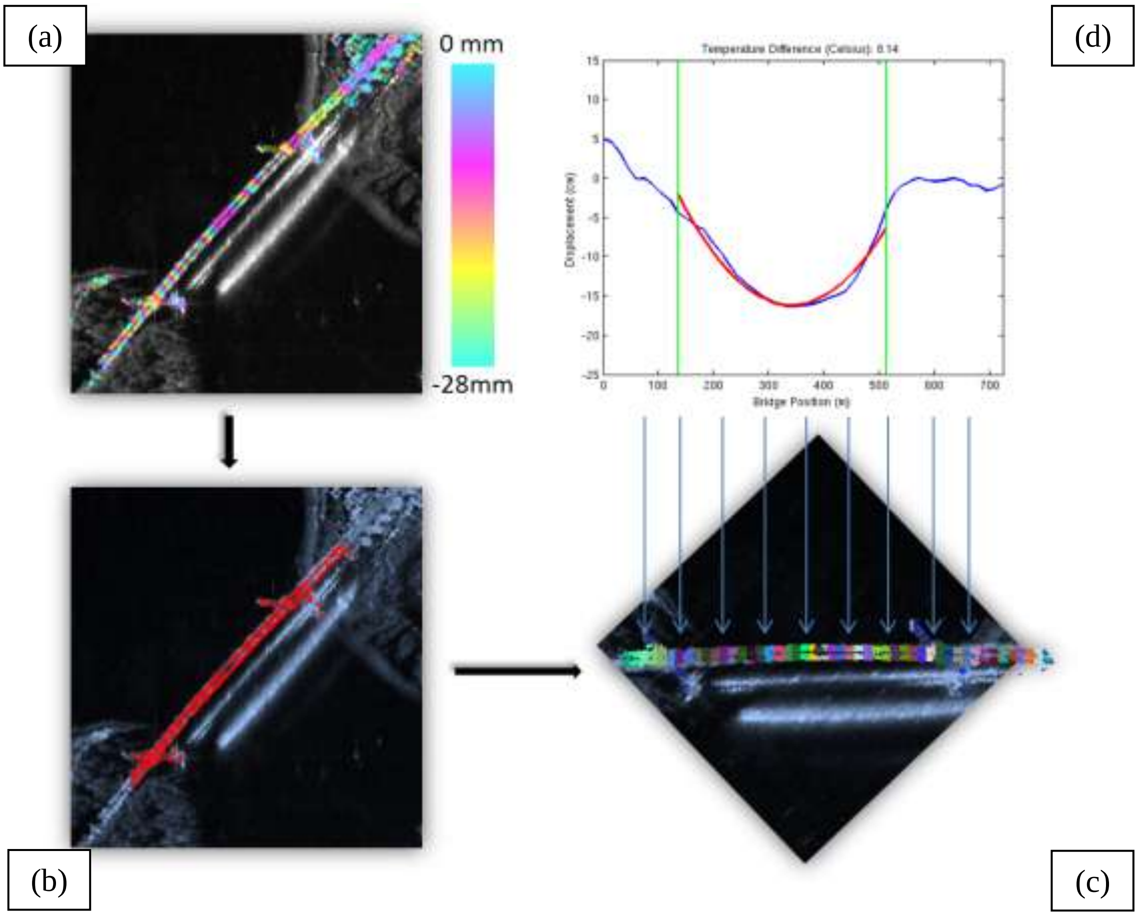

Figure 13 – Thermal deformation analysis of the Lions Gate Bridge

(a): Interferogram of the Lions Gate Bridge, with many coloured fringes indicating large displacement;
(b): Pixel selection over Lions Gate bridge; only pixels for which realistic measurements can be made are included;
(c): Bottom right: *Binning* of neighbouring pixels along bridge yields 50 bins used as abscissa for further analysis;
(d): Displacement results for InSAR pair plotted in cyan; quadratic profile fitted over mid-span of the bridge plotted in red, (estimated) bridge pier locations are shown as blue lines.

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Deformation due to changes in ambient temperature between pairs of interferograms is of interest for satellite-based SHM of bridges in two regards. Firstly, it is an expected displacement component and thus must be modeled and removed in order to reveal suspect mechanical displacements, if any. Secondly, it is used as a means of validating any vertical displacement measurements taken from space: two independent data sets are compared (i.e. temperature records and InSAR-derivate displacements) and the strength of the correlation indicates the degree of confidence in the measurements.

The Lions Gate Bridge presents an important case study for the R2SHM project. In a another case study by WESTGATE *et al.* (2011), a similar long-span suspension bridge (over the Tamar River in UK) was monitored using in-situ sensors, and its structural response to environmental variables was analysed using a calibrated finite element model of the bridge. The effects of temperature on vertical displacements of the bridge were found to be dominant among all other variables. For example, the sag in the suspension cables due to a temperature increase caused the main span of the bridge to sag along a parabolic profile, and vice versa. In the displacement results of the Lions Gate Bridge in Figure 13(d), a similar trend is observed.

Analysis of the thermal vertical displacement along the Lions Gate Bridge was done by first selecting bridge pixels for which reasonable measurements could be made. The chosen pixels are shown in Figure 13(b). Following pixel selection, bins were formed along the bridge by grouping neighbouring pixels into one sample through averaging (Fig. 13(c)), in order to reduce the effect of noise and outliers in the ensuing analysis.

Approximately fifty displacement measurements were generated along the bridge between pairs of InSAR images taken over a period of approximately two years and temporally referenced to the first SAR acquisition (2008-11-28). A least squares quadratic polynomial was fit to these displacement measurements corresponding to the main suspended span of the bridge. The displacement measurement profiles and quadratic polynomials are illustrated in Figure 14. Ambient temperature records for each SAR acquisition date were obtained from an Environment Canada weather station, located approximately 2 km away from the bridge. Temperature changes from the first acquisition were correlated with the set of quadratic coefficients and yielded a strong correlation coefficient of 0.93, as shown in Figure 15.

In their analysis, WESTGATE *et al.* (2011) obtained an almost identical (absolute) correlation coefficient of 0.92 for the correlation of temperature changes and the in-situ vertical displacements measured on the Tamar River suspension bridge. The strong correlation of the regression analysis provides high confidence in the InSAR-derived displacement results at the Lions Gate Bridge, and indicates that the thermal component of the displacements can be accurately modeled and removed.

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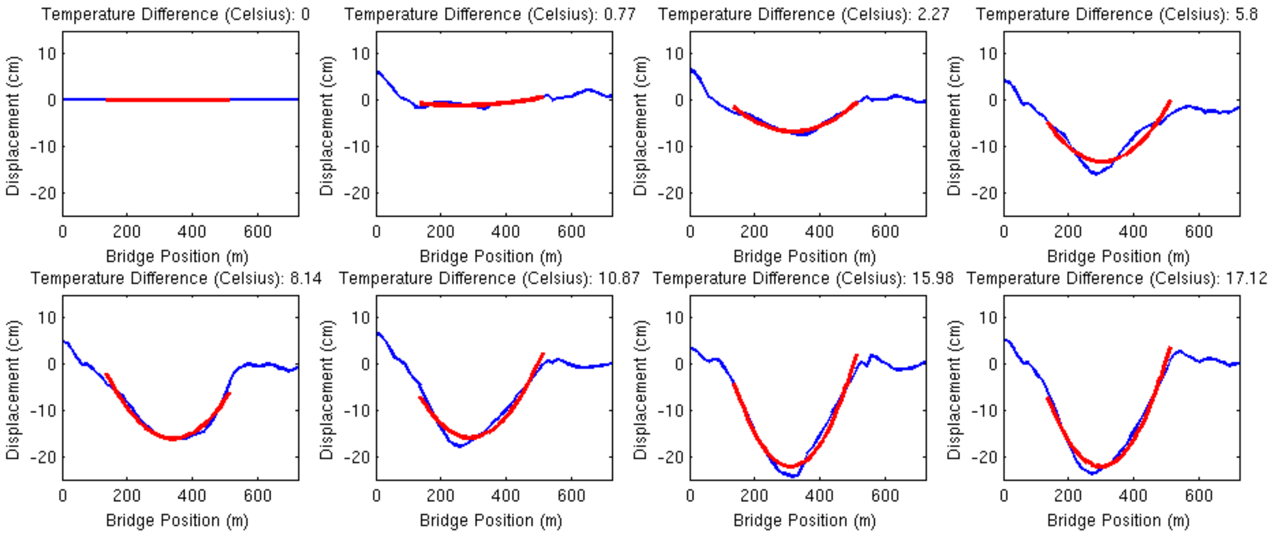

Figure 14 – InSAR-derived vertical displacement (blue) and quadratic fits (red) of the main span of the Lions Gate Bridge. Several profiles are shown with increasing temperature differences (left to right, top to bottom).

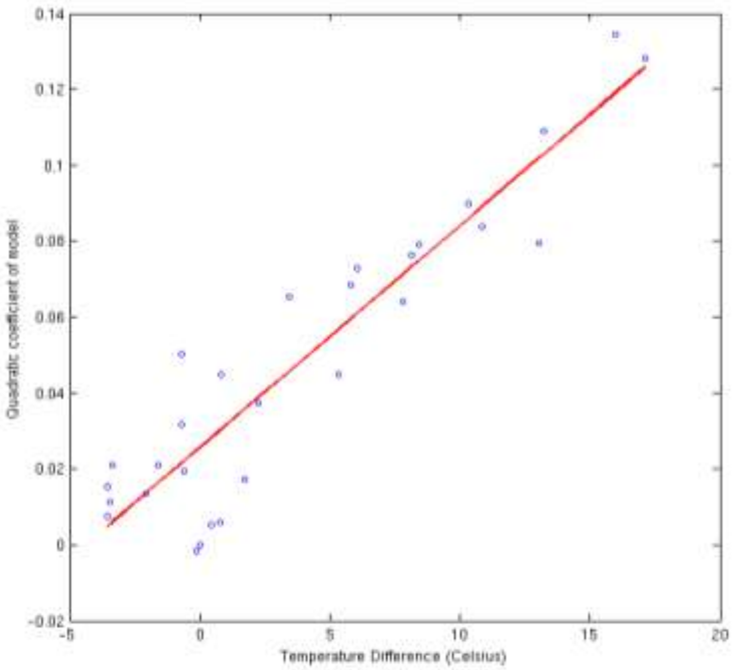

Figure 15 – Correlation between quadratic coefficients and temperature changes from the first interferogram (correlation coefficient is 0.93)

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5. Foreseen Benefits of Satellite-Based Structural Health Monitoring of Transportation Infrastructure

SHM is the practice of monitoring a structure to ensure that its structural integrity and safety remain satisfactory. The ability of apply remote sensing technologies to bridge inspection and monitoring has considerable value, given the sheer number of bridges in the public transportation infrastructure and the limited funds currently available at all government levels for bridge inspection, maintenance and rehabilitation.

5.1 Applicability of Space-Borne InSAR to Bridge Monitoring

In order to appreciate the benefits of this technology, one should known about its areas of application, as no single monitoring technology will satisfy all requirements of bridge inspection and monitoring. Should satellite-based InSAR be selected for a bridge monitoring project, it must be used in parallel to standard bridge inspection methods and in-situ sensor monitoring technologies.

Table 2 presents the areas of applicability of space-borne InSAR to bridge monitoring. Due to its relatively high mm-scale accuracy but low m-scale spatial resolution, the types of bridge features that are best monitored with this technology belong to global metrics, as detailed in the table. Global metrics of a bridge may not be observable during a routine inspection, but their influence on the system behavior has the potential to affect the performance of the bridge sub-systems.

Table 2 – Applicability of remote InSAR to bridge monitoring

Criteria	**Applicability**
Primary bridge component	Bridge deck, superstructure (above deck), approach slab, foundations (beside bridge) – Not suitable for substructure monitoring
Type of measurable quantity	Vertical displacement (mainly) with mm accuracy – May be suitable for horizontal displacement – Not suitable for strain and other variables
Frequency of measurement	Period of 24 days, ideal for long-term static displacement monitoring – Not suitable for vibration or dynamic monitoring
Type of bridge defects	Global metrics limited to bridge settlement, differential settlement, thermal deformation, deformed shape for long-span bridges, and river water/ice level – May be suitable for transverse deck displacement due to damaged bearings, and bridge length change for long bridges – Not suitable for deck cracking, delamination, spalling, and subsurface defects
Type of observable material	All types, including concrete, steel, wood and fiber-reinforced plastic, since the strength of radar signals depend mainly on bridge geometry
Land area coverage and horizontal resolution	-Ultra-fine beam mode: 10-30 km at 3-m horizontal resolution (ideal for bridge SHM) -Fine beam mode: 50 km at 10-m horizontal resolution (acceptable for long bridges) -Five intermediate beam modes (details at http://www.asc-csa.gc.ca/eng/satellites/radarsat2) -ScanSAR wide mode: 500 km at 100-m horizontal resolution
Cost of technology	Image acquisition may be costly; however, very competitive unit cost per bridge

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5.2 Increased Bridge Inspection/Monitoring Frequency

Typically, bridges are periodically monitored with different levels of scrutiny, including initial, routine, hands-on, fracture-critical, underwater, in-depth, and damage inspections (NCHRP 2007). Routine inspections, which serve as the primary mechanism for long-term condition and performance assessment of bridges, are known to be highly subjective, rely on experienced bridge inspectors, and rarely involve specialised sensor technology.

The City of Ottawa, for example, conducts three levels of inspections on their bridge inventory: (i) monthly routine visual inspections (conducted to identify obvious concerns such as vehicle impacts); (ii) annual general inspections; and (iii) mandatory biennial thorough inspections. Displacement monitoring is only available for the very few bridges that are instrumented with surface-mounted or embedded sensors. One main advantage of remote InSAR monitoring is that displacement information could become available between major bridge inspections. Specific point targets on bridges could be monitored to identify and investigate suspicious displacements on a monthly time-scale (after filtering out thermal effects as shown earlier in the case study). As a result, timely identification of potential problems can help mitigate their impact on structural health and reduce bridge rehabilitation costs.

5.3 Improved Bridge Integrity and Serviceability

The goal of periodic InSAR displacement measurements is to establish a correlation with bridge serviceability and integrity issues. Bridge engineers are interested in monitoring subtle displacements that can be indicative of unexpected events. Motion can be detected along each of the three dimensions, for example: (i) vertical bridge displacement from the settlement of a newly constructed bridge; (ii) longitudinal bridge displacement from daily or seasonal thermal expansion/contraction; and (iii) transverse deck displacement from damaged bearings, as indicated in Table 2. The sensitivity of InSAR to horizontal displacements, however, depends on the relative angles between the satellite line-of-sight and the bridge longitudinal direction.

As indicated in Table 1, hundreds and even thousands of point targets can be obtained on the same bridge structure; however their locations cannot be predetermined, unless corner reflectors are installed at strategic locations on the bridge. Hence, the large number of PTs measured on a bridge deck allows the evaluation of differential vertical displacements along the bridge, which may result in excessive expansion joint opening or stress in the deck. In addition, a sudden change (acceleration/deceleration) in the temporal evolution of a point target on a bridge is of greater concern than steady displacement, which information may be used to prompt urgent inspection and/or corrective action.

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5.4 Overcoming Bridge Accessibility Issues

5.4.1 Traffic disruption

Monitoring the condition of a bridge using remote technologies can eliminate the need for lane closure and traffic disruption, as these technologies do not come in direct contact with the structure. Lane closure can cost from $2,000 to $3,000 per day (AHLBORN *et al*. 2010). Another benefit from remote technologies is that the structure does not have to be prepared prior to monitoring, contrary to some other technologies (e.g. spectral imaging requiring cleaned surfaces; digital image correlation requiring painted surface patterns, or other methods requiring installation and calibration of instruments on the structure). Installing in-situ sensors during the construction of a bridge also requires good coordination with construction crew and may cause some construction delays.

5.4.2 Remote bridge locations

Satellite-based monitoring has significant economic and logistical value towards monitoring of hazards in remote areas that often do not receive the required attention due to accessibility issues. Remote InSAR could be useful to monitor the watercourse around bridges in remote areas. For example, meandering rivers that change course along the Alaska Highway can overwhelm bridges and threatens their foundations. Another benefit in this case is the monitoring of bridges in remote areas with difficult access, severe weather conditions, and possibly resulting in infrequent onsite inspections. The use of R2SHM would complement and validate the limited onsite inspection data, while optimizing the inspection travels and related budget.

6. Conclusions

Based on the preliminary results of this on-going R2SHM project, the following conclusions are drawn regarding the use of satellite-based InSAR for bridge monitoring:

- Can remotely monitor hundreds of bridges simultaneously in a single radar image, through clouds and at night with a satellite pass period of 24 days.
- Can identify and measure mm-scale vertical displacement of up to thousands of point targets over a single bridge, depending on deck area and image resolution.
- Can evaluate global metrics such as bridge settlement, deck deflection, thermal deformation, foundation settlement, and critical river water/ice level.
- Can help identify and prioritize bridges requiring field inspection and in-situ SHM.
- Can complement in-situ monitoring that has low spatial density/high temporal density data with high spatial density/low temporal density data for validation of SHM data.
- Can offer benefits such as monthly bridge displacement monitoring, improved bridge integrity and serviceability, and fewer bridge accessibility and traffic disruption issues.

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