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Satellite Sensing Technology to Monitor Displacement of Bridges and Other Civil Infrastructures

D. Cusson, Ph.D., P.Eng., Senior Research Officer, NRC, Ottawa
and
P. Ghuman, M. Gara, A. McCardle, 3v Geomatics, Vancouver

Presentation outline

- Introduction
  - Condition state of bridges in North America
  - Need for advanced bridge monitoring
- Proposed application – Satellite-based monitoring of bridges
- Previous applications of satellite-based monitoring
- Experimental program
- Early results obtained
- Case study – Thermal displacement analysis of a suspension bridge
- Summary of benefits and limitations of satelite-based bridge monitoring

Introduction

→ State of health of N. American bridges

- **There are 600,000 bridges in USA, and about 75,000 bridges in Canada.**
- **25% of these bridges are structurally deficient or functionally obsolete.**
- **Most of them built in the 1950s−1970s, reaching the end of their design life.**
- **Bridges have deteriorated due to severe mechanical & environmental loads:**
  - Increased traffic volume and heavier truckloads;
  - Repeated exposure to freezing and thawing, and to de-icing chemicals;
  - Insufficient inspection and maintenance due to limited funds.

Introduction

→ State of health of N. American bridges

- **Investments of $50B/yr on rehabilitation and new construction.**
- **Cost of required upgrades and repairs estimated at $65 billion in N. A., and could grow ten-fold in 20 years (based on current investment rate).**
- **Considerable impact on society:**
  - Reduced safety of structures;
  - Increasing costs (direct, social, and environmental);
  - Reduced quality of life.

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Introduction
→ Issues and challenges

- **Inadequate materials and structural systems**
- **Increasing demand for higher levels of service**
- **Higher requirements of sustainability and security**
- **Limited budgets for maintenance and difficulty to prioritize allocation**

Introduction

→ Need for remote monitoring of bridges

- **Judicious use of in-situ SHM of critical bridges can help address some of today's challenges by providing:**
  - More accurate knowledge of bridge life-cycle performance;
  - Improved prioritization and planning of bridge maintenance;
  - Optimized structural safety and minimized life-cycle cost.
- **Even as sensors get integrated into modern smart bridges, thousands of other bridges throughout the nation will remain insufficiently inspected and inadequately serviced due to limited budgets.**

Introduction

→ Need for remote monitoring of bridges

- **As a complement to in-situ SHM and conventional inspection methods, radar satellites can be used to:**
  - Monitor numerous bridges simultaneously, through clouds, in darkness, in major urban centers or in hardly-accessible remote locations;
  - Identify critical bridges requiring in-situ monitoring or urgent inspection.
- **Scope of remote monitoring with radar satellites:**
  - Elevation measurements within satellite line-of-sight (mm accuracy);
  - Low temporal density of measurements (monthly basis).

Introduction

→ Remote monitoring

- **May be defined as: The collection and measurement of spatial information about an object at a distance from the source of data (i.e. no direct contact).**
- **Includes a wide range of technologies:**
  - Spectra
  - 3D optics
  - remote acoustics
  - thermal infrared
  - optical interferometry
  - digital image correlation
  - ground-penetrating radar
  - high-resolution digital photography
  - light detection and ranging (LiDAR)
  - optical satellite and airborne imagery
  - interferometric synthetic aperture radar (inSAR) ← Focus of presentation

(LiDAR and optical satellite and airborne imagery: Briefly introduced)

Introduction

→ Air/Space-borne technologies

For airborne technologies, four factors play a major role in the selection of a given technology for bridge monitoring:

- **Spatial resolution –** Refers to dimension of ground surface covered by pixel (e.g. high resolution means smaller area of ground observed, see picture)

- **Temporal resolution –** Refers to frequency at which a target can be sensed

- **Viewing angle** (e.g. space-born technologies limited to observation of top surfaces)

- **Cost of acquiring imagery** (e.g. space-born image acquisition may be costly, but may be offset by the large number of observations that can be made in a single image)

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Introduction
→ Air/space-borne remote monitoring

Electro-Optical Imagery

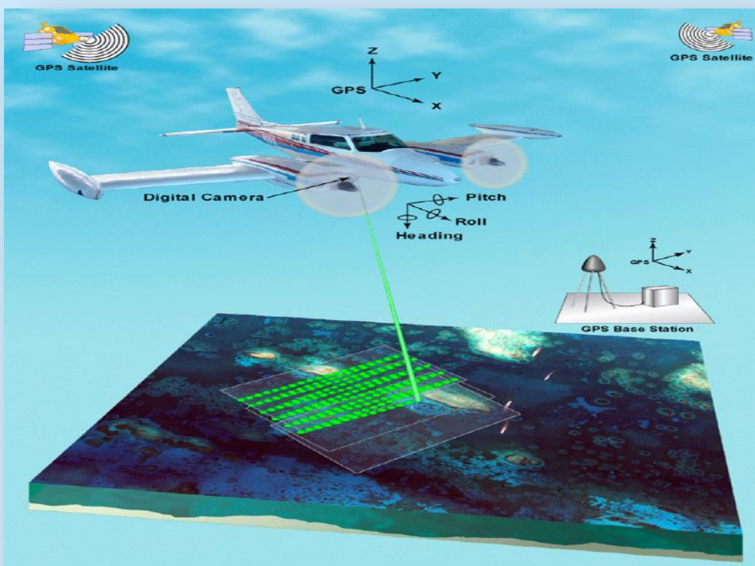
- Uses sensor that converts light, or a change in light, detected in the visual or infrared spectra, into an electronic signal.
- Image resolution of 13 mm when using low areal photography (300-1500 m altitude).
  - May be sufficient to identify defects like concrete spalling, large cracks, change in bridge length.
- Image resolution of 41-46 mm when using satellites like GeoEye-1 or WorldView-2.

Introduction

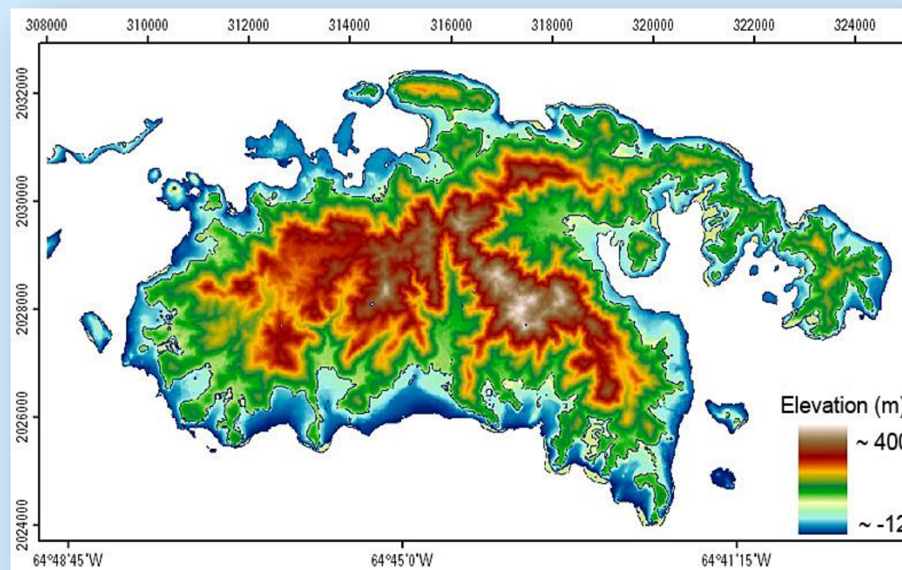
→ Air/space-borne remote monitoring

Light Detection and Ranging (LiDAR)

- Determines distance to target by measuring the time a laser pulse takes to travel between the source and its target (back and forth).
- Used for land surveying & mapping when mounted on aircrafts or satellites.
- At altitute of 300 m and speed of 50 m/s, aircraft can survey 43 km^2 of area per hour, with a 2-m horizontal resolution and ranging acuracy of 30-50 mm.



LiDAR process (combined with GPS)

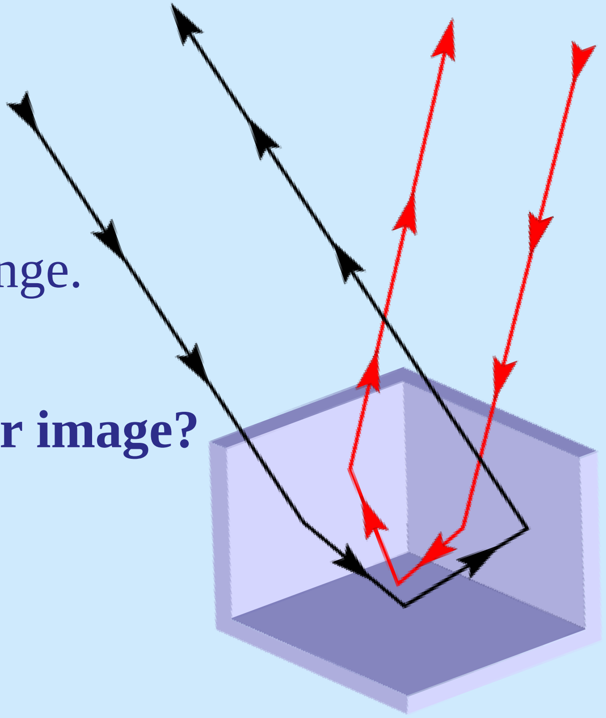


USGS elevation data, US Virgin Islands

Introduction

→ Air/space-borne remote monitoring

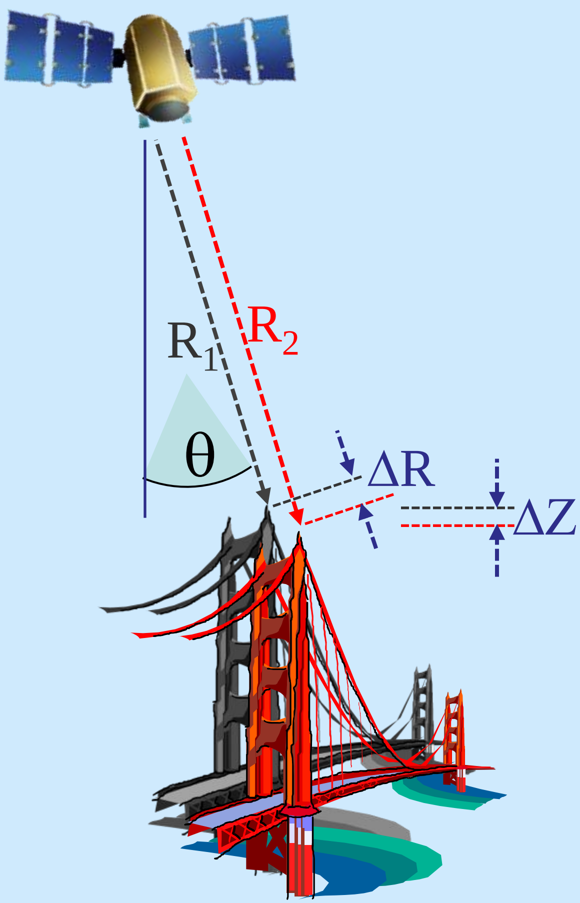
- **Synthetic aperture radar (SAR) interferometry**
  - Ranging measurement that generates radar images by bouncing microwaves off the Earth's surface.
  - Compares pairs of radar images acquired using similar viewing geometry (i.e. from same position and angle).
  - Determines distance to a point target (PT) along the line-of-sight of satellite.
  - Horizontal resolution is in the meter range.
  - Displacement acuracy can be in the millimeter range.



- **What constitutes a strong signal for a PT in a radar image?**
  - A sharp edge!
  - Bridges and buildings display many sharp edges.

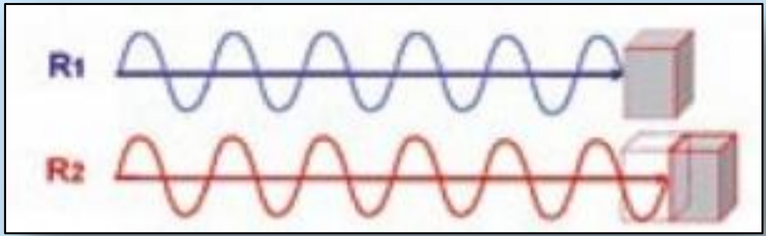
Proposed application

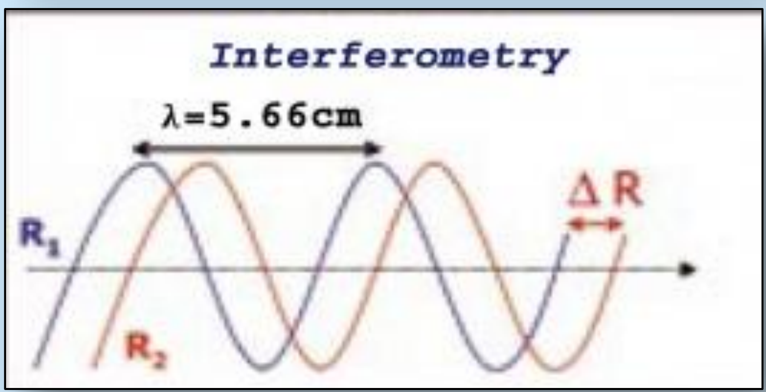
→ SAR Interferometry for remote SHM



1^{st} acquisition:

2^{nd} acquisition:





Repeat pass period of satellite:
Δt = 24 days (RadarSat)

Received signals can be affected by: surface topography, ground displacement, atmospheric pressure and water vapour. Denoising techniques can be applied.

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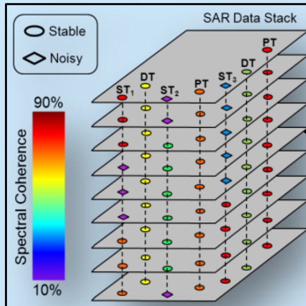
Proposed application

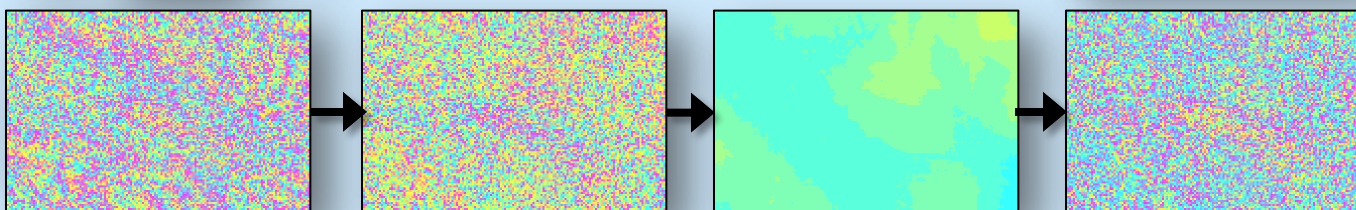
→ SAR Interferometry for remote SHM



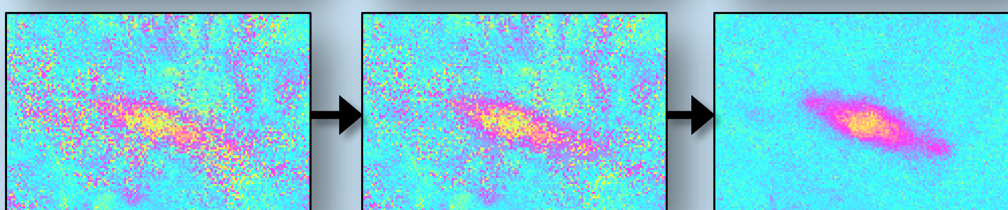
Data Import

Stacking

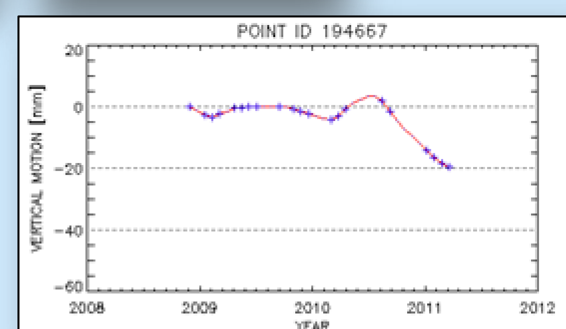
InSAR Processing



Decontamination & Denoising



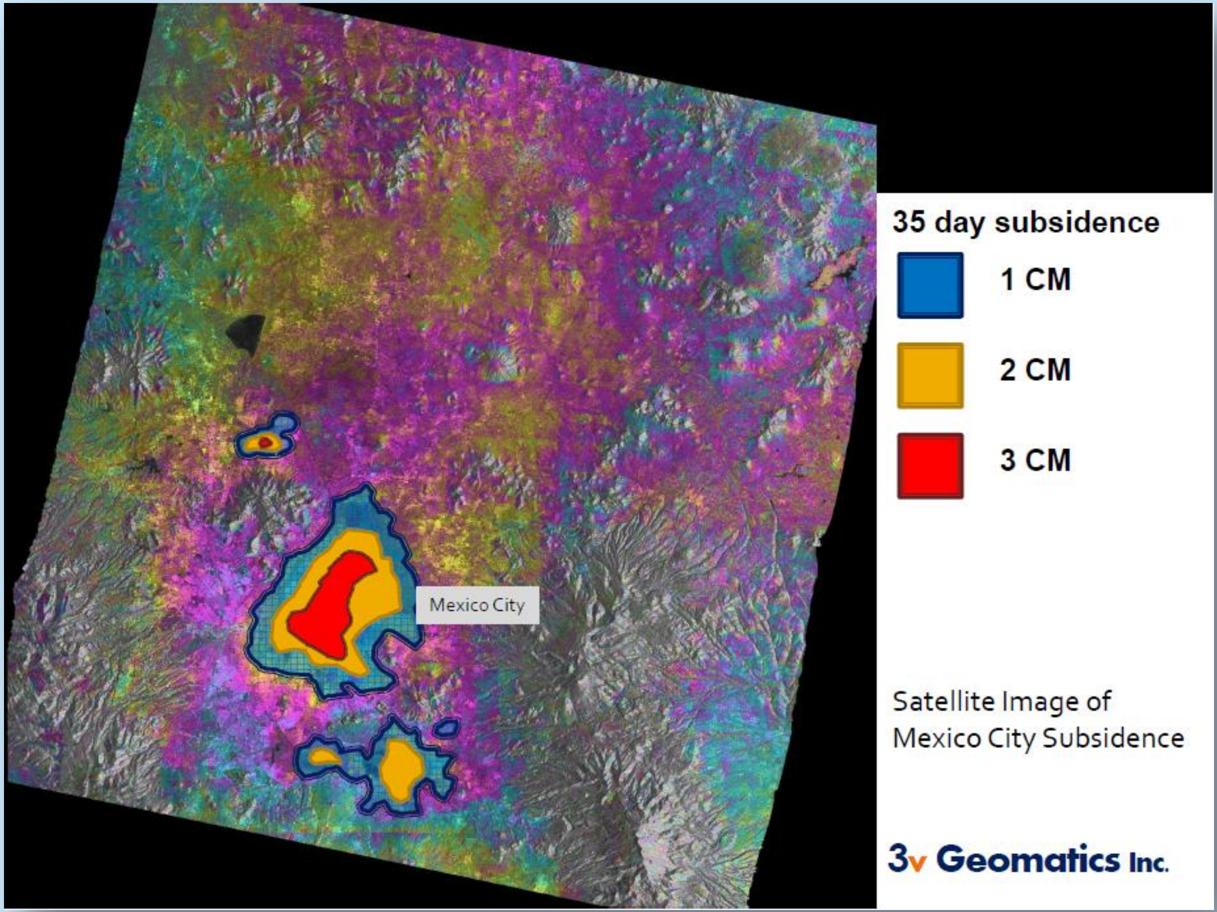
Visualization & Interpretation



Previous applications

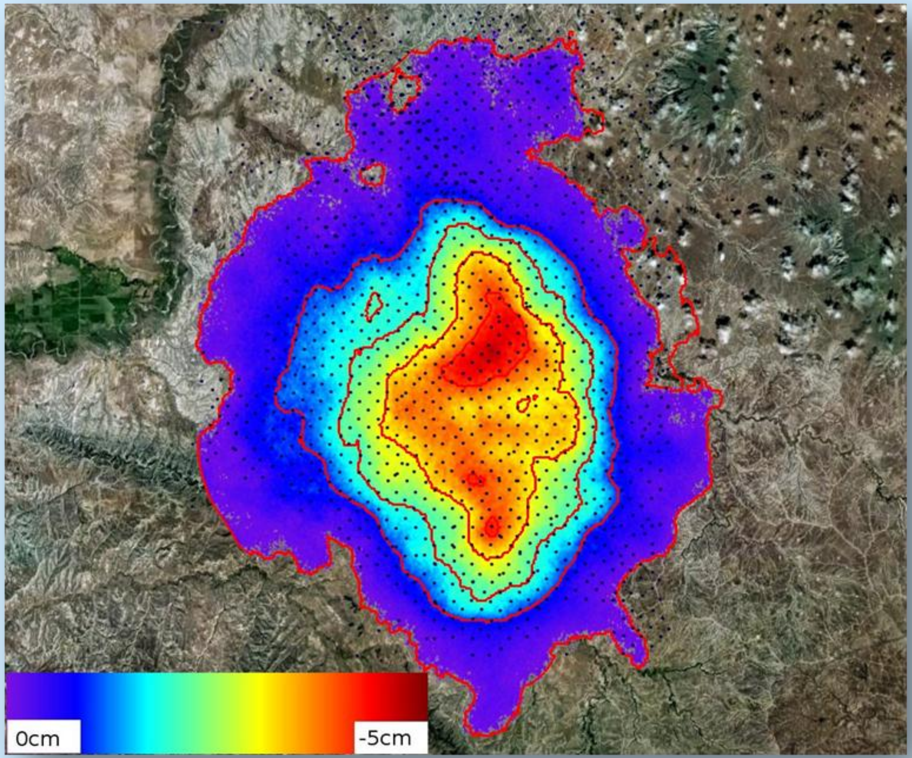
→ Subsidence monitoring in Mexico City

- Massive subsidence observed due to groundwater extraction.
- Residents exposed to increasing risks of flooding.
- Large-scale problem hard to monitor with existing technology.



Previous applications
→ Monitoring of oil wells in Wyoming

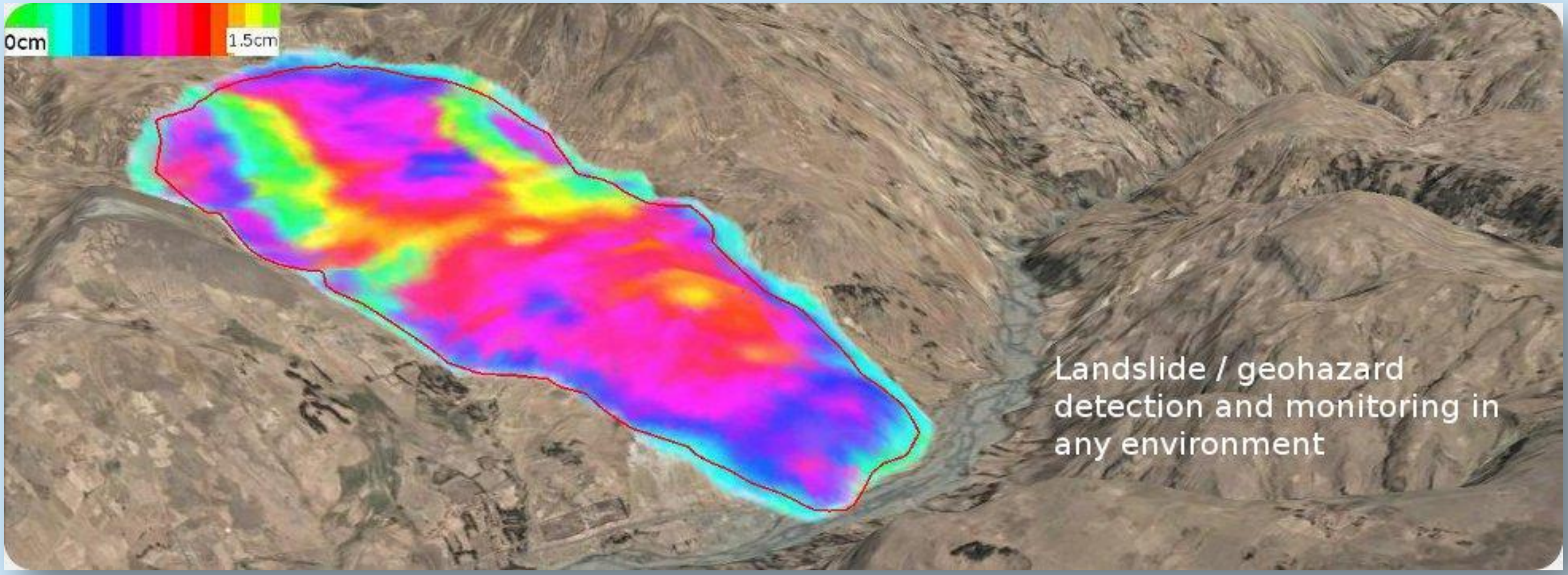
- Enhanced oil recovery injection and extraction techniques were being applied to a mature oil field.
- Degree and extent of uplift were unknown to reservoir engineers.
- Analysis of satellite images taken at times of CO_2 injections confirmed strong correlation between injections and ground uplift.



Previous applications

→ Landslide detection/monitoring in Chile

- InSAR analysis was used to identify and quantify landslides and ice heave near a mine site where a pipeline corridor was being planned.
- Numerous landslides were observed and measured that had potential impact on mining operations (15 mm displacements observed in one month).

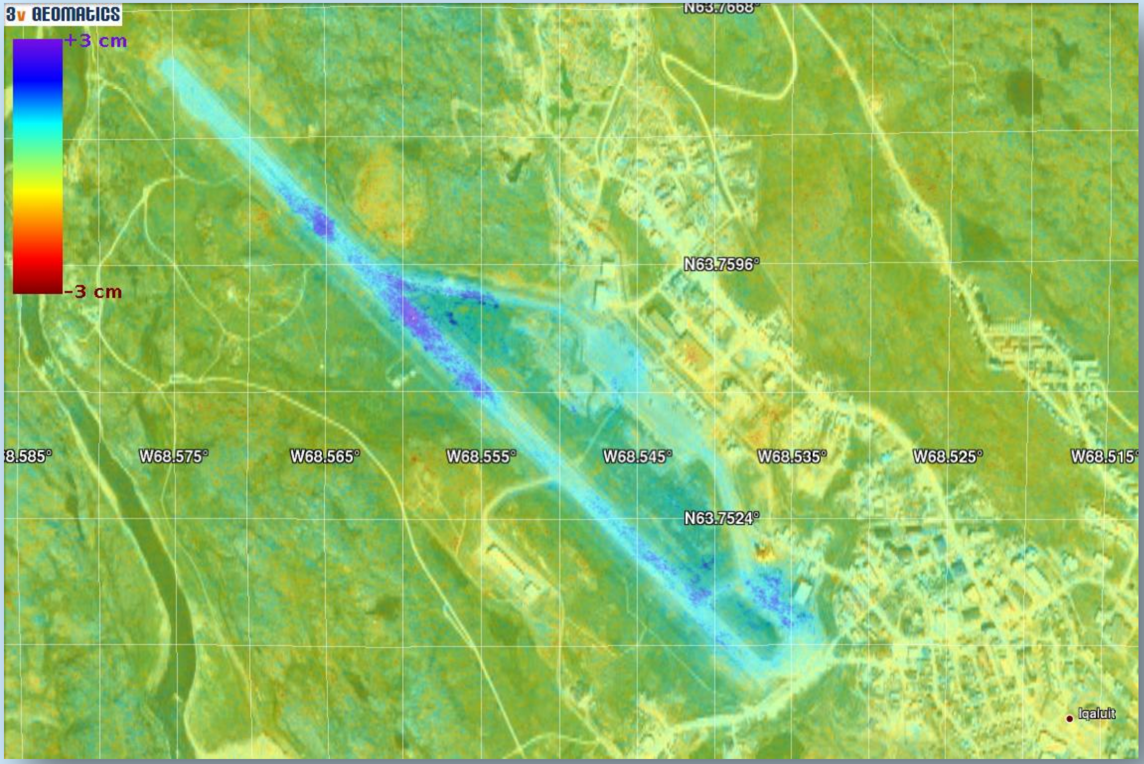


Andes, Chile (4500 m elevation)

Previous applications

→ Infrastructure monitoring, Iqaluit Airport

- Iqaluit is the largest community in the Nunavut territory in Canada (64th parallel).
- Ice-rich permafrost identified within the municipality, which may affect structural integrity of its infrastructure, as the ground thaws and re-freezes.
- Project goal to identify localized displacement basins causing cracking and tilting of infrastructure.
- Analysis of archived radar images confirmed seasonal uplift at Iqaluit airport.
- Technology may assist in future expansion planning of northern communities.



Experimental program
→ Project overview and objectives

- **R2SHM project launched in January 2011 for 2 years:**
  - Funding organization: Canadian Space Agency
  - Developers (satellite technology): 3v Geomatics
  - Advisors (bridge monitoring): National Research Council Canada

- **Main project objectives:**
  - To optimize advanced processing methods in order to further exploit RADARSAT-2's sophisticated imaging capabilities;
  - To apply remote sensing technology to bridges and other infrastructure assets;
  - To develop a cost effective and practical bridge monitoring strategy combining both remote and in-situ monitoring.

Canada's RadarSat-2

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Experimental program
→ Bridges monitored by RadarSat-2

Twelve bridges in Canada were selected for the R2SHM project

- Some are busy urban bridges; some others are under in-situ monitoring;
- 12 radar images are required for initial identification of stable point targets;
- 15 radar images are required for reliable displacement measurements.

Vancouver

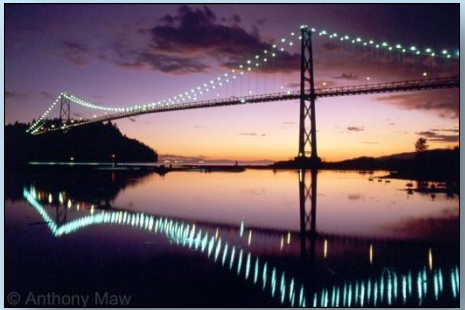
- Lions Gate Br.
- Burrard St. Br.
- Cambie Br.
- Granville Br.

Montréal

- Champlain Br.
- Champlain Ice Br.
- Jacques-Cartier Br.
- Honoré-Mercier Br.

Ottawa

- Macdonald-Cartier Br.
- Alexandra Br.
- Chaudière Br.
- NRC Campus Br.



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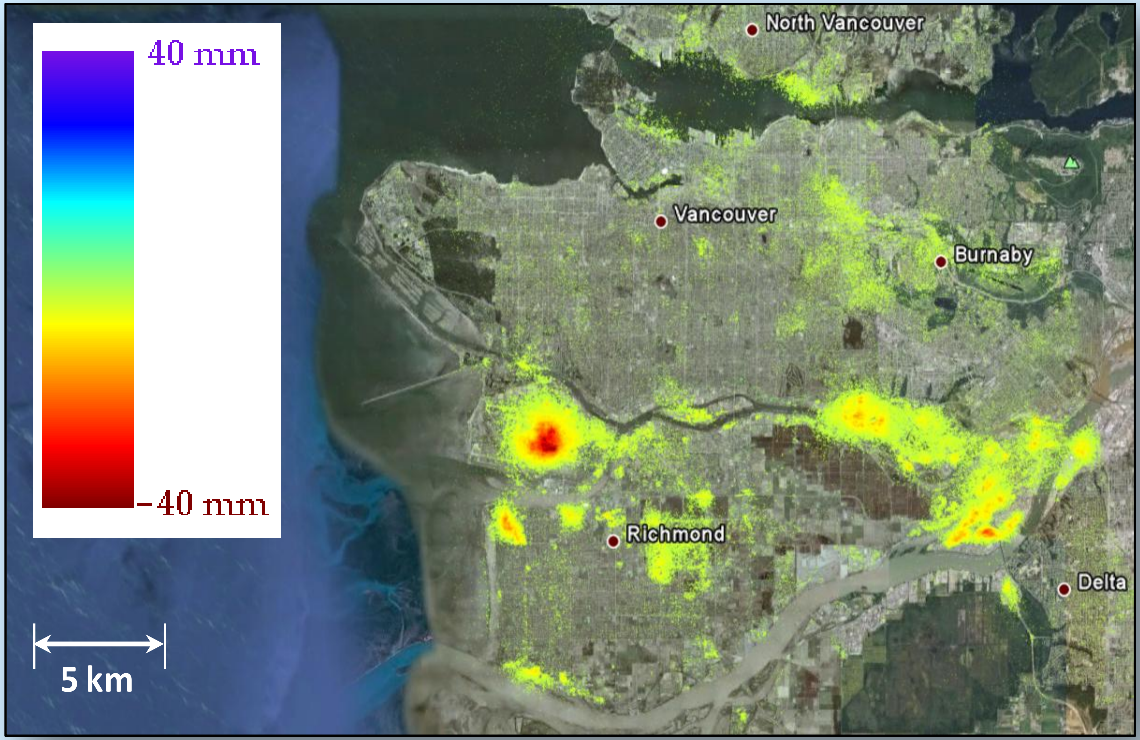
Early results

→ Ground movement in Vancouver

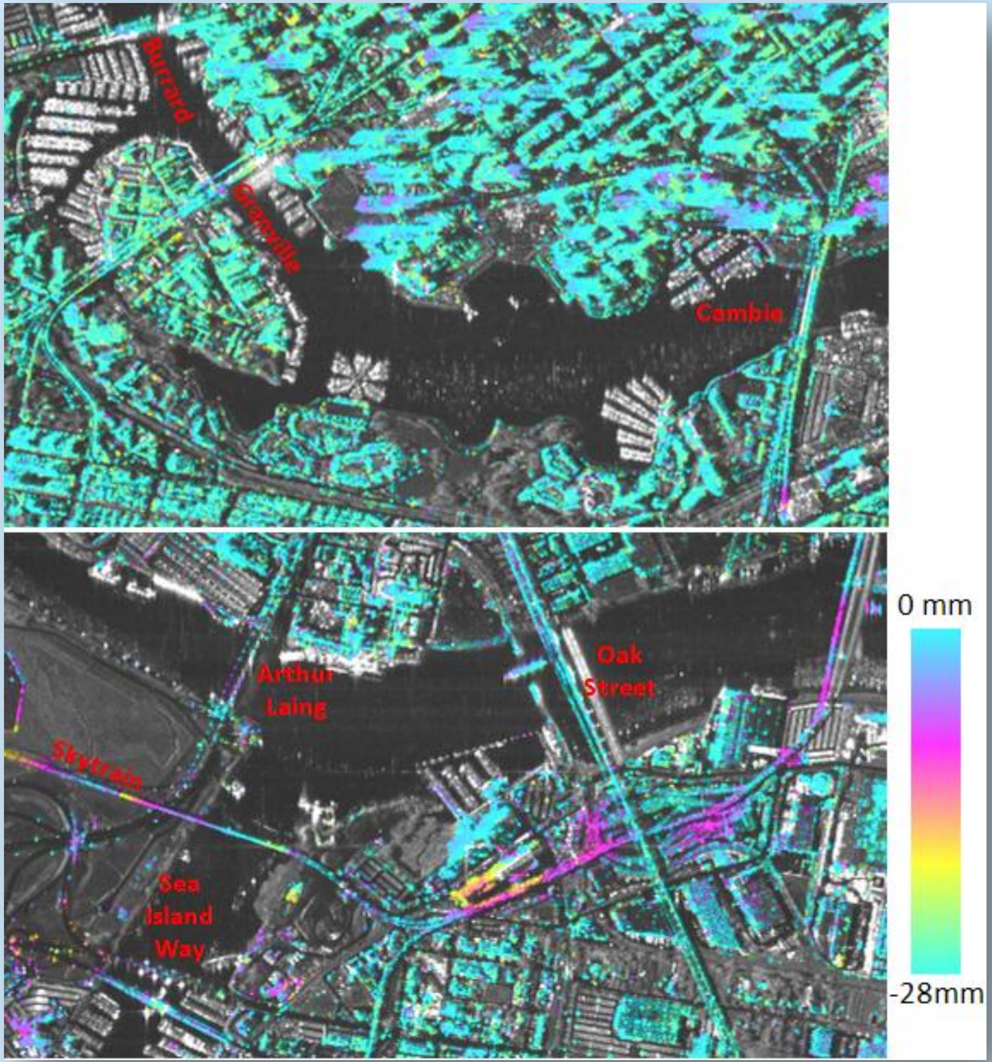
- **Stacks of radar images were obtained for the Greater Vancouver Area, and analysed to identify point targets (PT) on urban infrastructure assets:**
  - 450 points/km^2 (Fine-quad beam mode, 8-m horizontal resolution)
  - 3100 points/km^2 (Ultrafine beam mode, 3-m horizontal resolution)
- **Analysis shows downward displacements (in red) of up to 40 mm over 3 years at Vancouver Intl Airport.**
- **Many bridge structures can be covered in a single image up to 100x100 km^2.**
- **Several hundreds of PT can be obtained on a single bridge for analysis.**



Early results

→ Cumulative displacement mapping of bridges

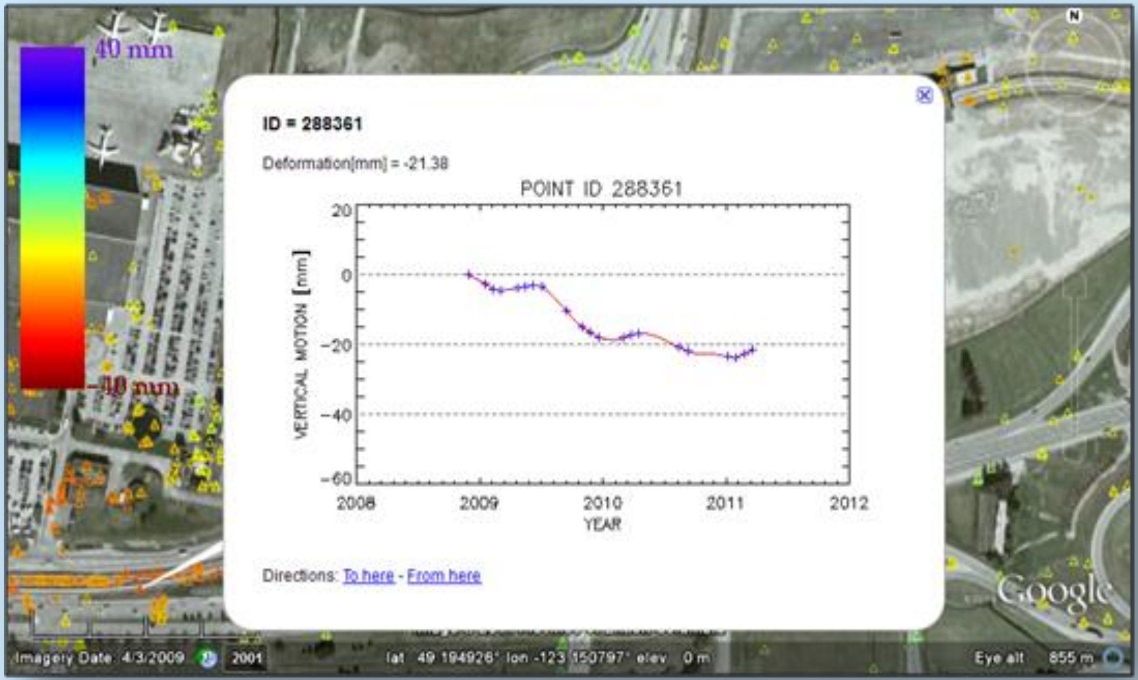
- Figure shows cumulative displacement measurements on selected bridges in Vancouver, BC (over a 2-year period).
- The Lions Gate Bridge and the Skytrain (Canada Line) exhibit thermal displacement manifesting as cyclic displacement fringes along the length of bridge.
- Effect more apparent on long span bridges.



Early results

→ Displacement profile (transit line)

- In addition to spatial displacement mapping, displacement histories can be extracted at discrete targets on infrastructure installations.

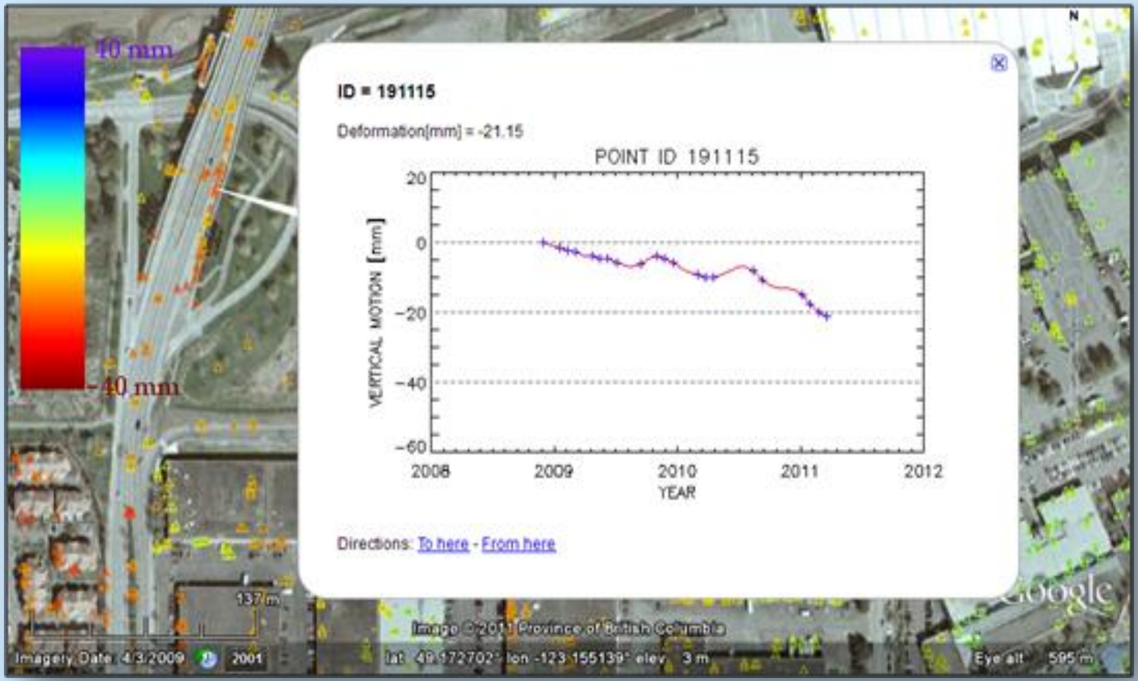


Rapid transit line (monitoring period of 2 years)

Early results

→ Displacement profile (bridge deck)

- **Example of a urban bridge monitored over a period of 2 years:**



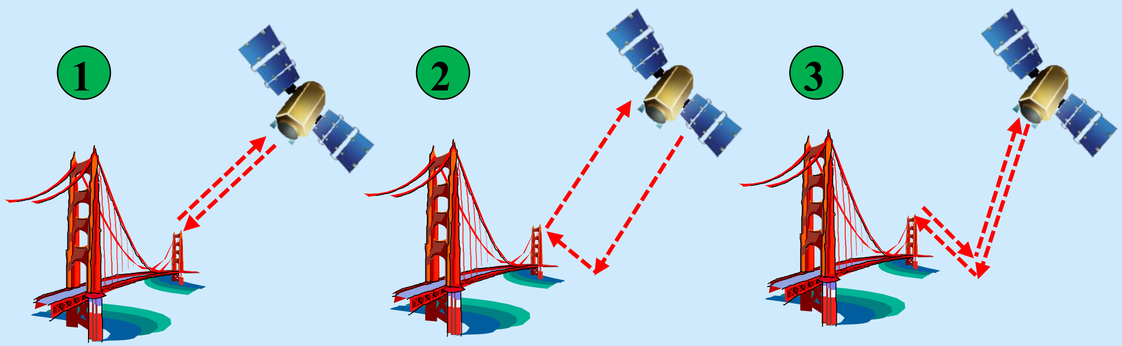
- **Trend shows steady sinking at that point target (20 mm over 2 yrs).**
- **Analysis of surrounding PTs can be conducted to find whether the bridge is sinking uniformly, or faster at some supports which could be worrisome.**

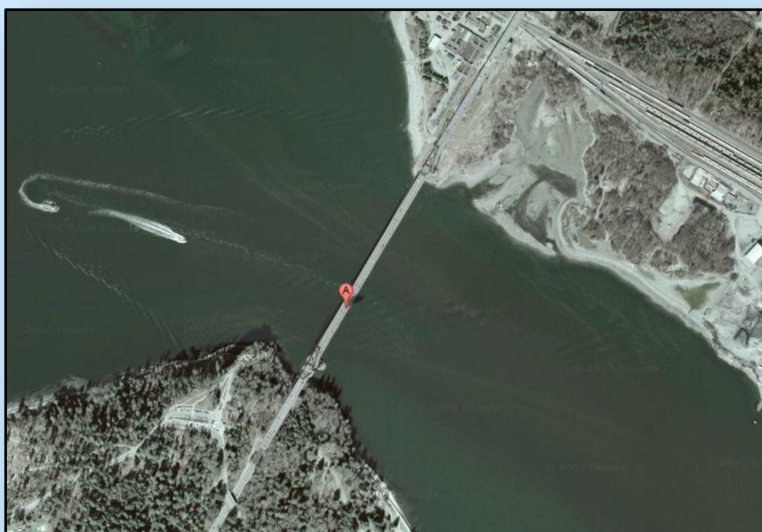
Early results

→ Required improvements for R2SHM

Ghost images of bridges over water

- Radar images are formed based on the time it takes for the signal to be returned.
- Solved by filtering signals with comparison to digital elevation bridge model.





Google image of Lions Gate Bridge

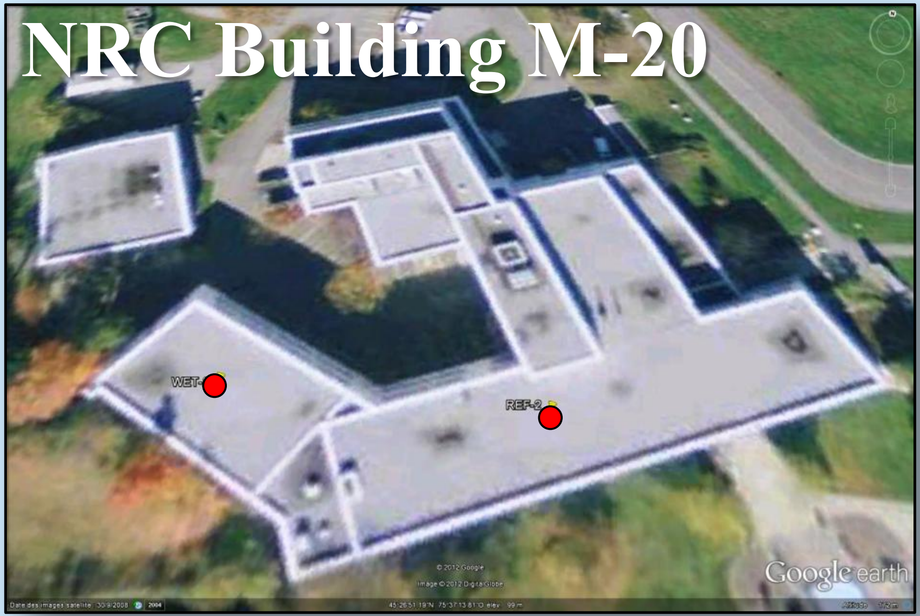
Radar image of Lions Gate Bridge

Early results

→ Required improvements for R2SHM

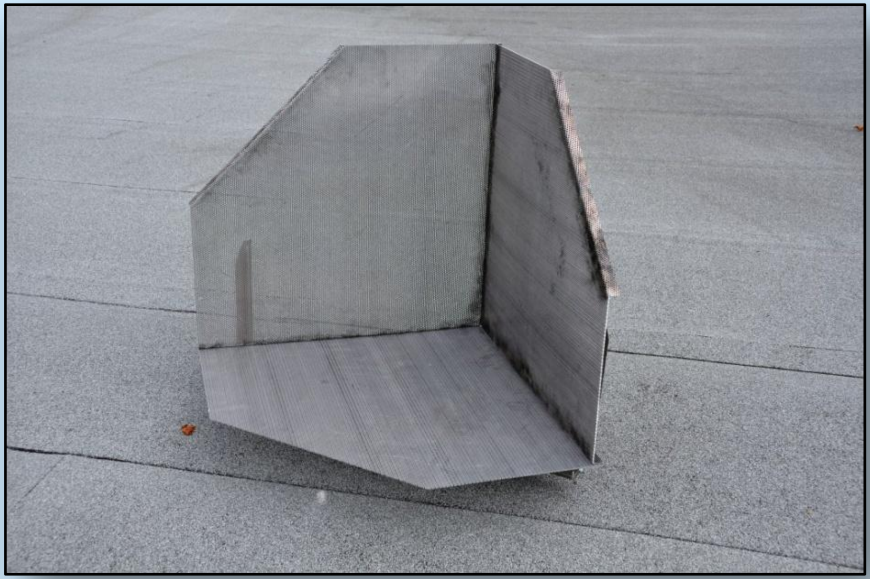
Effect of debris or snow on measurement accuracy

- Debris like durt and tree leaves, or snow, may accumulate on bridges.
- Experiment below aims at finding how much these can affect the signals.
  - One reflector is left untouched (accumulation of tree leaves and snow).
  - Other reflector is the control (kept free of debris).
  - Measured vertical elevations (initially identical) are compared over time.

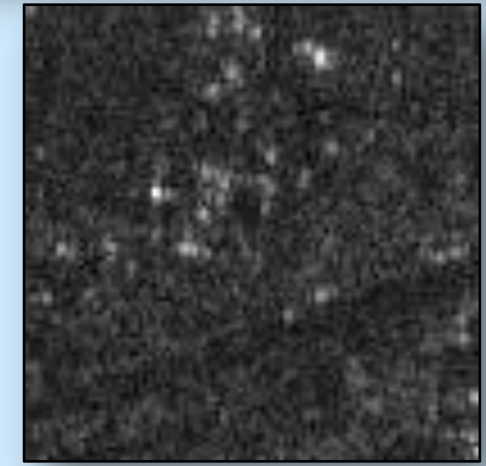


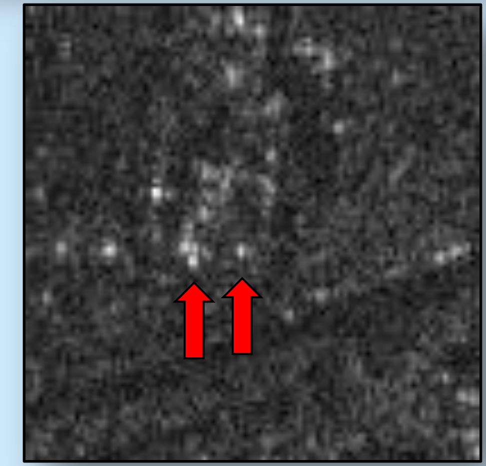
Early results

→ Required improvements for R2SHM



Radar image before CR installation





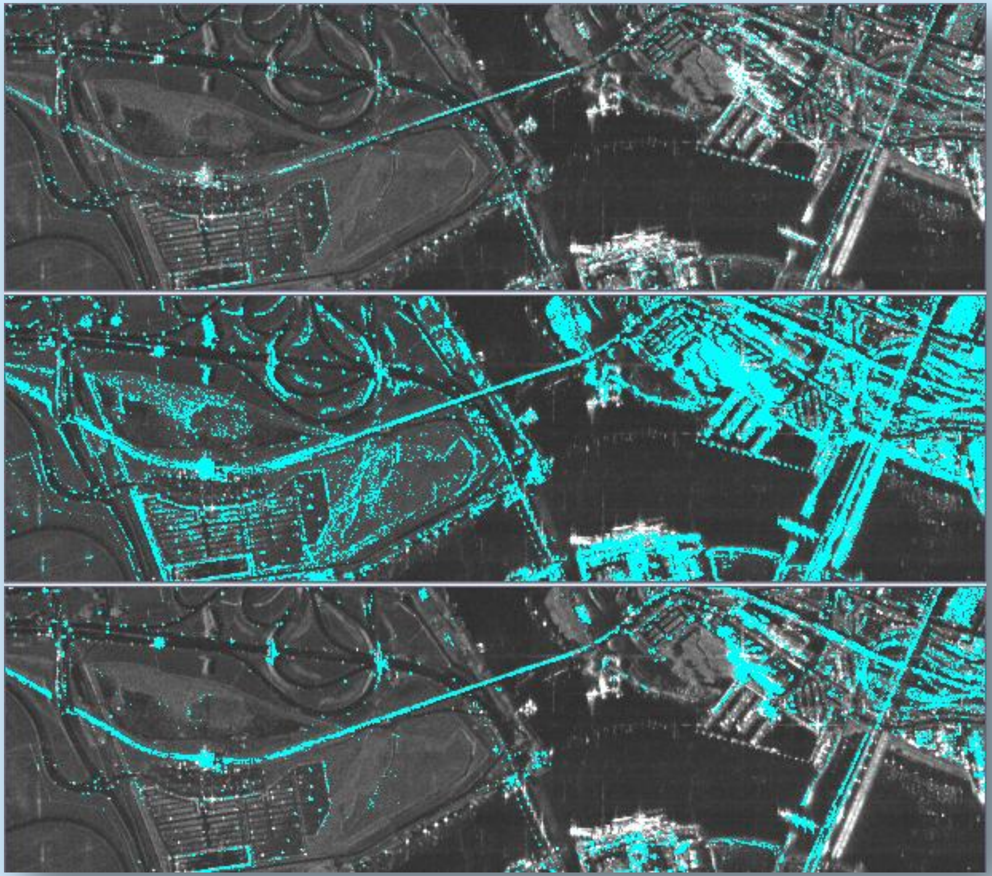
Radar image after CR installation

Early results

→ Required improvements for R2SHM

Point target identification techniques (example of acquisition over Richmond, BC)

- PT ID techniques use pixel properties like stability of spectrum, amplitude, or phase as a scoring function.
- Spectral stability (top picture) identified the least targets with many stable targets missed.
- Ampliture stability (middle pict) identified the most targets with many false PT over vegetation.
- Phase stability (bottom picture) identified the right balance of point targets. However, it is the most computationnaly intensive.

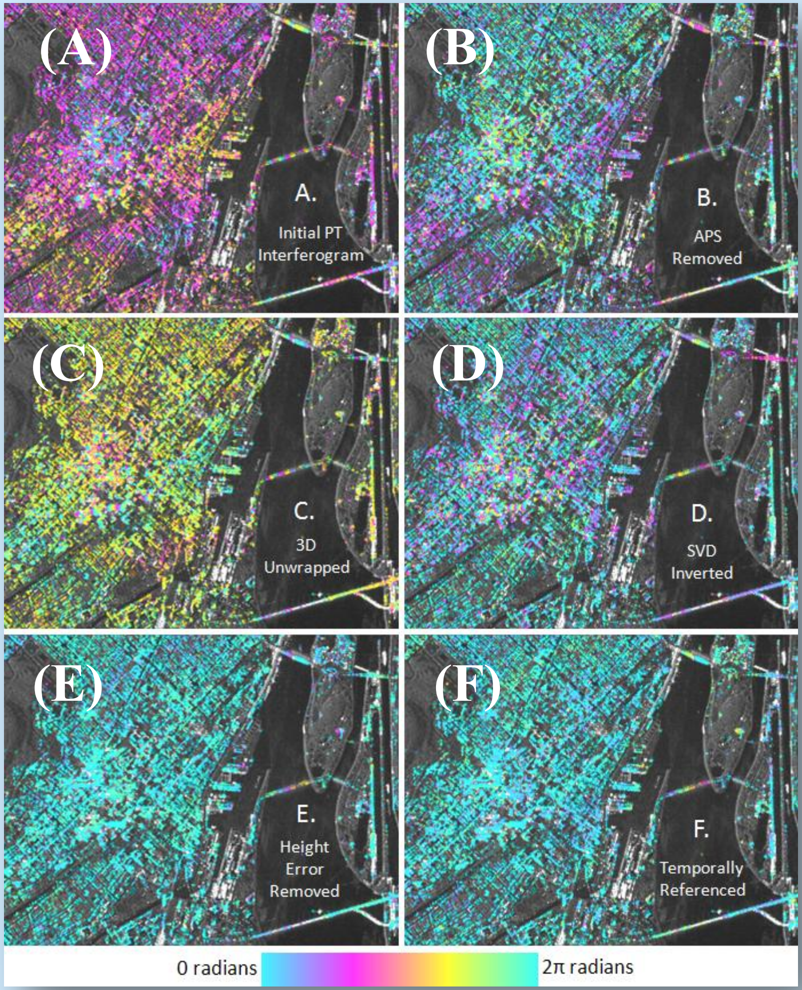


Early results

→ Required improvements for R2SHM

Noise suppression and filtering (example of acquisition over Montreal, QC)

- Phase decomtamination is the process of segregating the target signal by modeling and removing all other phase contributions.
- For bridge monitoring, displacement of a point target is of prime interest, and other signal components must be removed.
- Different noise suppression steps include:
  - (a) initial point target interferogram
  - (b) removal of atmospheric contaminants
  - (c) 3D unwrapping
  - (d) invertion by singular value decomposition
  - (e) removal of height error
  - (f) temporal referencing



Case Study

→ Thermal displacement analysis of bridge

- Lions Gate suspension bridge connects City of Vancouver to the north shore.
- Built in 1938 with a main span of 473 m and two approach spans of 187 m each.
- Vertical displacements of Lions Gate Bridge are the most challenging to analyse, comprising two uncorrelated signals: (i) elevation error, and (ii) thermal deform.

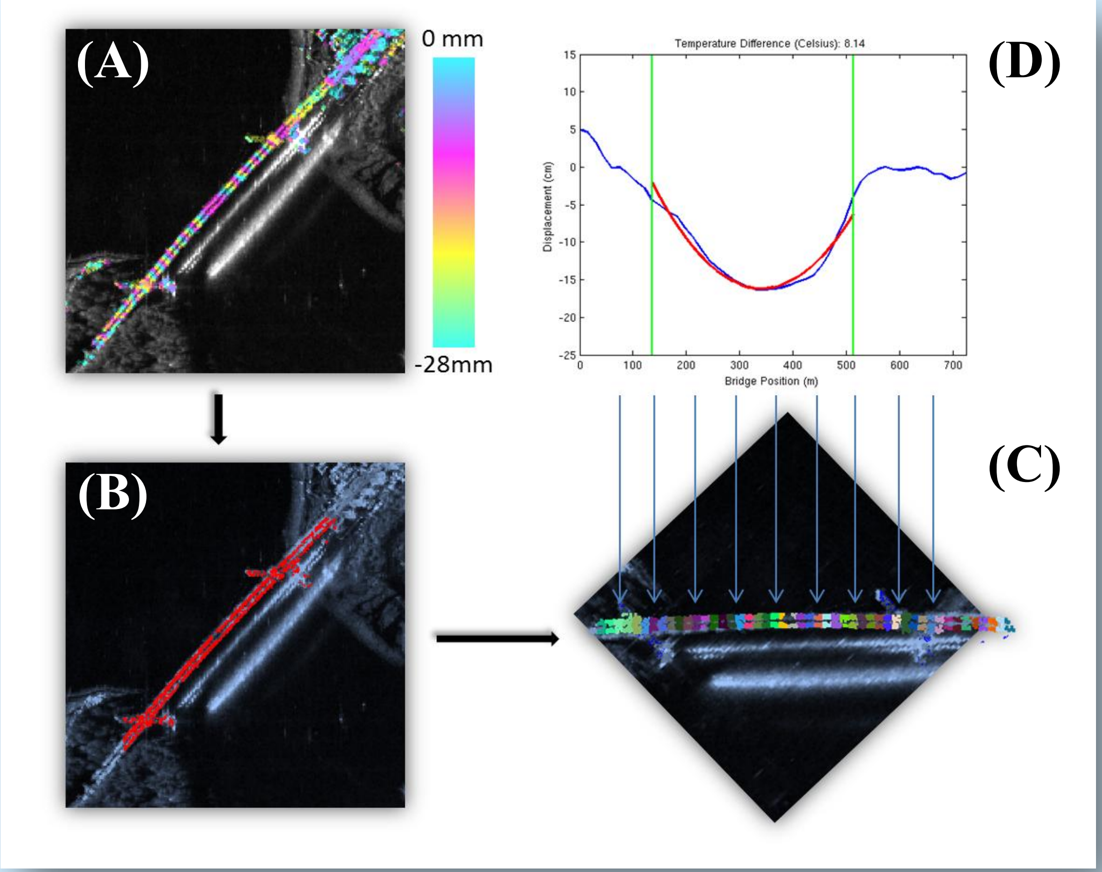
➢ These must be removed in order to identify abnormal, critical displacements.

➢ Thermal data can advantageously used to validate measurements from space.

Case Study

→ Thermal displacement analysis of bridge

- Procedure was developed to isolate thermal effects.
- Fig. (a) illustrates an interferogram in which coloured fridges are indicative of large thermal displacements.
- In Fig. (b), pixels were selected for analysis, eliminating ghost effect.
- In Fig. (c), neibour pixels are averaged and grouped into 50 bins to reduce noise.



- Fig. (d), shows the best-fit relation of the filtered vertical thermal displacements of Lions Gate Bridge measured by RadarSat-II satellite at a give time.

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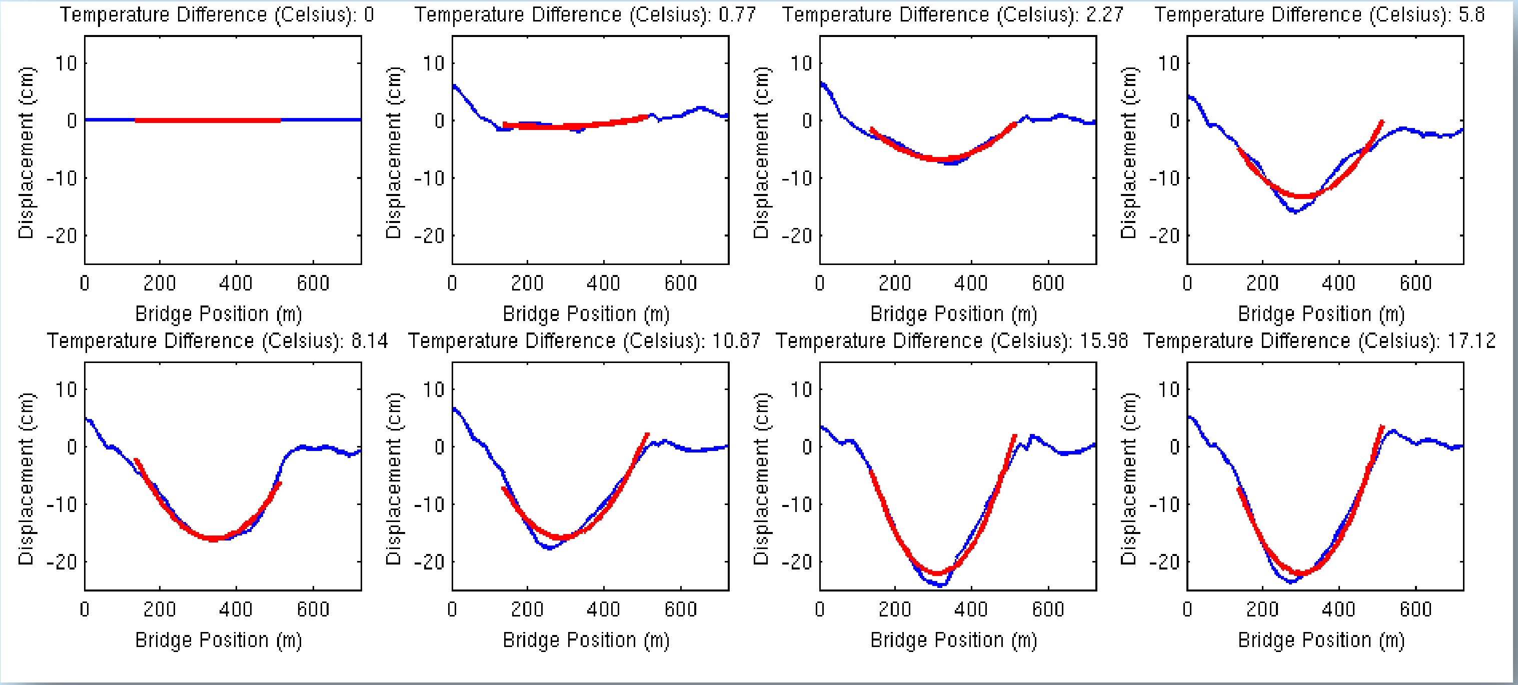
Case Study

→ Thermal displacement analysis of bridge

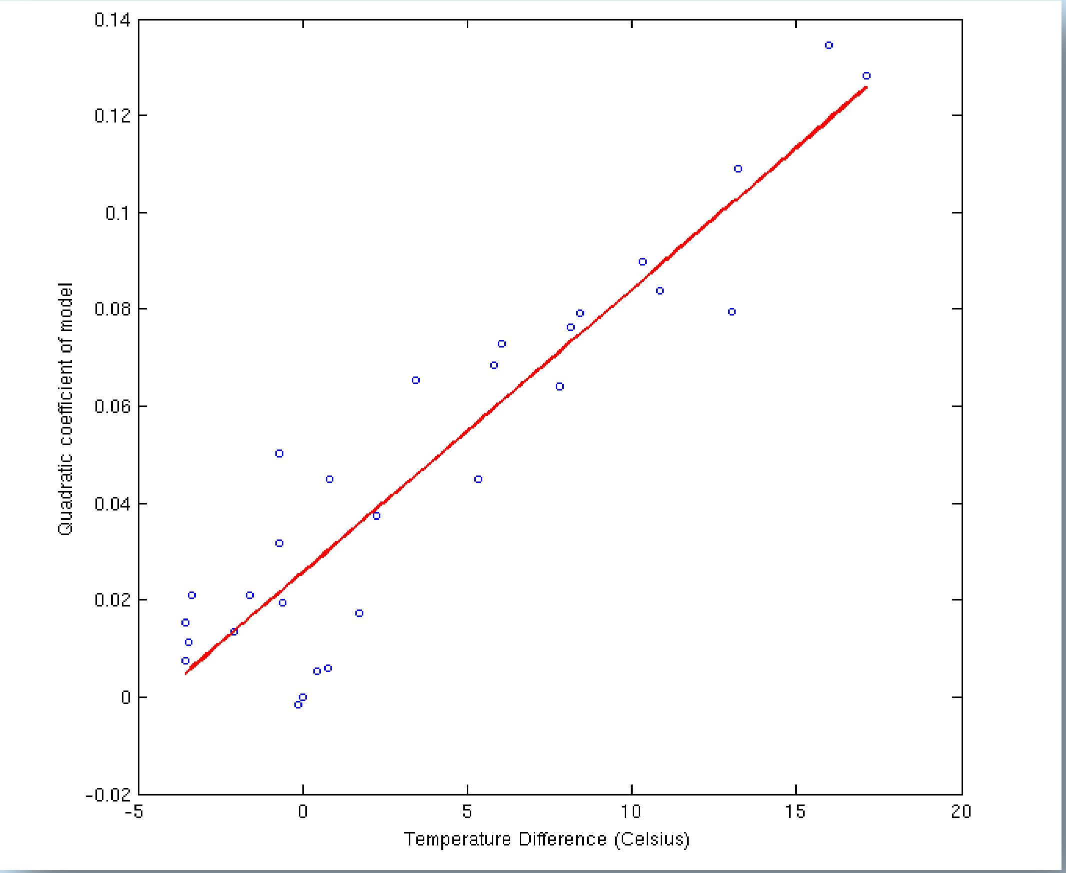
- Fifty vertical displacement measurements were generated along the main span of the bridge between pairs of InSAR images acquired over two a period of 2 years.
- These profiles were fitted using quadratic polynomials.
- Selected bridge vertical relative displacement profiles are shown in the figure (ordered in increasing temperature difference from baseline interferogram).



Case Study

→ Thermal displacement analysis of bridge

- Figure illustrates the linear correlation between the quadratic coefficients of the obtained best-fit polynomials and the temperarure changes between the compared pairs of interferograms.
- A strong correlation of 0.93 was obtained, providing some additional confidence in the InSAR displacement results of the Lions Gate Bridge.
- This approach could also be conducted using FE simulations of bridge thermal behaviour.



Applicability of InSAR

→ to bridge monitoring (1/2)

Criteria	Applicability
Primary bridge component	Bridge deck, visible superstructure, approach slab – Not suitable for substructure monitoring
Type of measurable quantity	Vertical displacement (mainly) with mm accuracy – Not suitable for strain and other variables
Frequency of measurement	Period of 24 days, ideal for long-term displacement monitoring – Not suitable for vibration or dynamic monitoring

Applicability of InSAR

→ to bridge monitoring (2/2)

Criteria	Applicability
Type of bridge defects	Global metrics limited to bridge settlement, thermal deformation, and deformed shape of long-span bridges. – Suitable for changes in bridge length (long bridges) – Not suitable for deck cracking, delamination, spalling
Land area coverage and horizontal resolution	-Ultra-fine beam mode: 10-30 km at 3-m horiz. resolution (ideal) -Fine beam mode: 50 km at 10-m horiz. resolution (long bridges) -ScanSAR wide mode: 500 km at 100-m horizontal resolution
Cost of technology	Image acquisition may be costly; but not in terms of cost per bridge.

Foreseen benefits and conclusions

Remote monitoring of bridges with RadarSat-2 could:

- Provide displacement mapping of bridge foundations;
- Provide elevation data of non-instrumented bridges between inspections;
- Complement and validate limited onsite inspection data;
- Identify suspicious or abnormal vertical displacements (and send alerts);
- Help prioritize and optimize bridge inspection and maintenance.

Conclusions

→ Preliminary findings

Based on the early results of this on-going R2SHM project, these preliminary conclusions are drawn:

• InSAR can be used to identify and monitor elevation changes of hundreds of targets over a single bridge structure, with sub-centimeter accuracy.

• Satellite-based radar images can be taken over an entire urban area to periodically monitor hundreds of bridges simultaneously, though clouds and at night.

• Remote monitoring can identify problems early (e.g. deck deflection, foundation settlement, river level) and help prioritize in-situ bridge monitoring and inspection.

• Remote monitoring (high spatial density) & in-situ monitoring (high temporal density) can be combined avantageously to obtain more accurate information.

• Foreseen benefits of remote monitoring include: monthly bridge displacement monitoring, improved bridge serviceability, and fewer bridge accessibility issues in remote locations in harsh environments.

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Acknowledgments

PROJECT PARTNERS

- **Funding organization:** Canadian Space Agency (www.asc-csa.gc.ca)
- **Developers (satellite technology):** 3v Geomatics (www.3vgeomatics.com)
- **Advisors (bridge engineering):** National Research Council Canada (www.nrc.gc.ca)

CONTACT: **Daniel.Cusson @ nrc.gc.ca**