Technical Guidance on Satellite-Based Deformation Monitoring of Bridges

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ABSTRACT

Since 2014, the National Research Council Canada (NRC) has led partnerships in which the application of radar satellite imagery for bridge deformation monitoring has been validated in five major case studies (including the North Channel Bridge in Cornwall (ON), the Jacques-Cartier, Victoria and Samuel de Champlain bridges in Montreal (QC), and the Confederation Bridge leading to Prince Edward Island (PEI).

Based on the knowledge and experience developed in these bridge case studies, a set of technical guidelines is summarized and presented in this paper, which discusses the characteristics of bridges and the satellite parameters that can affect and improve the quality of satellite-based bridge deformation monitoring. The overarching goal of these guidelines is to enable more efficient and accurate monitoring of bridges using radar satellite imagery by recognizing the limitations of the technology and by better understanding which bridge and satellite parameters can optimize its application.

INTRODUCTION

Over the past decade, satellite monitoring has emerged as a viable option for the remote monitoring of infrastructure assets, particularly in the public transportation sector [1]. Remote sensing using Synthetic Aperture Radar (SAR) satellite sensors can detect deformations on the ground developing over time from an interferometric analysis [2]. When applied to bridge infrastructure assets and their surroundings, deformations that may be due to excessive loads, ground settlement, truck/ship impacts, and extreme weather events can be monitored. This is made possible by today's advanced computer algorithms and the more frequent availability of high-resolution satellite imagery.

Satellite technology is very promising and valuable for remote monitoring of highway and railway bridges and other transportation infrastructure assets to optimize preventive maintenance management, extend the life of structures, and minimize service interruptions due to overdue repairs in order to ensure structural integrity after extreme weather events and to increase user safety.

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This paper presents a set of guidelines to enable efficient and accurate monitoring of bridges using SAR satellite imagery by recognizing the limitations of the technology and by better understanding the bridge and satellite parameters that can optimize its use.

BRIDGE FEATURES AFFECTING INSAR SATELLITE MONITORING

The suitability of a particular bridge for radar satellite monitoring depends on the different features of the bridge and its surroundings. Suitability here refers to the quantity and quality of the persistent backscatters (PS) that are returning from the bridge to the satellite for imaging, processing, and determination of displacements measured in the satellite line-of-sight (LOS). This section discusses how certain bridge features may affect SAR monitoring suitability, and provides strategies for improving it.

Bridge Type and Geometry

Bridges with tall superstructures above deck level may have risks of layover and shadow effects that can complicate the analysis. Examples are cable-stayed, suspension, and steel truss bridges (Figure 1). A good practice is to conduct a backscatter analysis on complex bridges (explained in the next section) to find the most suitable SAR image stack or combination of stacks based on incidence angle and satellite pass direction in order to mitigate layover, shadow, and/or multi-bounce effects.

(a) Types with lower risk of layover/shadow effects (b) Types with higher risk of such effects

Figure 1. Different types of bridge superstructures.

Bridge Orientation

The compass heading orientation of the bridge is a key aspect affecting SAR backscatter response and the relationship between the SAR LOS measurements and the bridge's local axes (e.g., longitudinal, lateral, and vertical). These factors have a major impact on how well the monitoring goal can be met. SAR satellites are limited to looking primarily in the east-west direction. Bridges that are oriented north-south (e.g., North Channel Bridge in Cornwall, ON [3]) pose additional challenges because (i) SAR line-of-sight will not be much sensitive to the longitudinal movement; and (ii) bridge and water backscatter returns will overlap (i.e., layover), which will reduce the coherence of the returns. Bridges that are oriented east-west (e.g., Samuel de Champlain Bridge in Montreal, QC [4]) have fewer such layover problems. Their SAR line-of-sight, however, will not be sensitive to lateral movement.

Changing Water Levels and Deck Clearance Above Water

Most river or coastal bridges can be expected to experience changing water levels over time due to seasonal fluctuations, especially in the context of climate change [5]. In addition, bridges with low deck clearance from water may be subject to undesirable multi-bounce effects. Water level fluctuations impart a dynamic component to the backscatter analysis of multi-bounce effects (explained in the next section).

Bridge Span Length and Total Length

For a given resolution of available satellite imagery, measured bridge deflections, for example, will be relatively more accurate for bridges with longer spans. Current technology offers displacement measurement accuracies of 1-2 mm [6].

Long bridges may pose additional challenges for InSAR monitoring because they may traverse extensive water areas that have incoherent radar response. Dynamic atmospheric phase delays can result in significant phase residuals in SAR interferograms. These phase residuals can usually be estimated and removed because they occur at long spatial scales (several kilometers) and are uncorrelated in time. However, this estimation fails over water bodies with scales equal to or greater than the atmospheric scale length. A good example of this issue is the 13 km-long Confederation Bridge in Eastern Canada [7]. An alternate approach may be applied to estimate the atmospheric phase residuals over a 1D linear extent of the coherent bridge elements.

Traffic Pattern

Variable traffic may result in differential loading and a corresponding noise-like deformation component that may reduce the estimation accuracy of systematic deformation components such as thermal sensitivity or linear displacement rate. A mitigation strategy is to select the satellite pass direction corresponding to the local time with less traffic congestion. For example, at 45° N latitude, satellite pass directions occur at local times of 6 AM and 6 PM for descending and ascending passes, respectively.

Deck Slab Surface Roughness

Most bridge decks are built with relatively smooth surfaces (e.g., road and sidewalk surfaces), resulting typically in few backscatters from such surfaces. This could become an advantage if the deck is in layover with other elevated structural elements of interest, shifting the focus to elements with sharp edges (e.g., steel railing, steel truss, or dedicated corner reflectors). Bridges with limited scattering elements may therefore be difficult to monitor unless corner reflectors can be added at strategic locations on the structure since the PS-InSAR method is generally designed to track point-like coherent targets [2].

Bridge Location Latitude

Bridges located in southern Canada and in the USA will have fewer choices of stack incidence angles as they approach the equator compared to those located in northern Canada since satellite orbits converge as they approach the earth's poles.

Local Climate

Areas with lower variations of ambient temperature will provide less precise thermal movement sensitivity estimates. Ice and snow cover during winter time may cause temporal coherence loss in the measured data. These issues may be mitigated by acquiring images over a longer period of time to improve the estimate of thermal sensitivity or acquiring more images during summertime to reduce coherence loss due to snow and ice cover in wintertime. Trihedral corner reflectors may be installed at suitable locations on the bridge to provide additional coherent targets for deflection measurement [7].

OPTIMIZATION OF INSAR MONITORING APPROACH FOR BRIDGES

Building on the information presented in the previous section, additional guidance is given below with the aim of optimizing InSAR remote monitoring of bridges and its expected outcome.

Monitoring Goal

InSAR typically provides line-of-sight displacement estimates at regular time intervals. A key consideration is the question of which aspects of bridge displacements are of interest and whether these can be estimated with sufficient sensitivity and timeliness. Due to its regular but non-real-time acquisition, InSAR is well suited for characterizing displacement aspects that do not have a time-critical nature, such as subtle, gradual linear displacements and thermal response. InSAR may have a role in detecting displacements that are transient precursors to failure, but this should be carefully considered to ensure that monitoring intervals and reporting time lags fit well within the expected pre-failure time window. Also, such an application requires a good understanding of which structural elements are being coherently monitored by InSAR through a backscatter analysis.

Backscatter Analysis

Bridge construction drawings are a key input for comprehensive InSAR monitoring. They are necessary for performing a backscatter analysis since they provide details on the locations and dimensions of all structural elements and their connections. The drawings should also contain detailed geo-referencing information, which is important if ascending and descending image stacks are to be combined to derive 2D displacement decomposition. Such type of analysis relates features in the SAR imagery with bridge structural elements and shows which image features are expected to be temporally coherent (i.e., persistent radar response over time). A detailed backscatter analysis is important for optimizing and selecting the image stack viewing geometry and interpreting InSAR results indicating which specific structural elements are being monitored.

Some bridges may be adjacent to other structures that interfere with SAR imaging. This was observed at the North Channel Bridge in Cornwall (ON), where the piers from an old partially-deconstructed bridge overlaid onto parts of the new replacement bridge on the radar image [3]. A good understanding of the locations and dimensions of these structures is therefore required during the planning phase of the monitoring program.

External Digital Elevation Model

Correction for the topographic phase component of the signals is a key step in InSAR-based monitoring. This typically relies on a detailed digital elevation model (DEM) of the area of interest (AOI). However, most DEMs do not model the height of bridges, buildings, and other infrastructures. Bridges are complex 3D structures, and therefore the topographic phase might not be well represented by a simple DEM. For this reason, the height of point targets must generally be determined using the SAR data itself by modeling the residual height phase values for each target. This increases the minimum number of images required per stack to obtain robust solutions.

SAR Sensor Beam Mode – Resolution and Polarization

The selection of a particular beam mode involves a trade-off between spatial resolution, polarization, noise level, and spatial footprint of the images. Typically, beam modes with more polarization options and/or wider swath widths correspond to lower image resolutions. Bridges are relatively narrow structures, and therefore it is desirable to select a mode that provides as high spatial resolution as possible. This has several benefits: (i) smaller resolution cells decrease the chance that multiple scattering elements will occur in a single resolution cell, therefore, increasing the number of temporally coherent targets; (ii) this may also allow for spatially resolving displacement along vertical and lateral directions; and (iii) phase noise can be greatly suppressed by spatially averaging over a local window, which is only feasible for high-resolution modes. One possible exception is for long bridges that do not fit within a single spotlight mode image. In such cases, it may be more appropriate to select the highest resolution mode that contains the entire bridge length and some surrounding land areas, such as for the 13-km long Confederation Bridge in PEI [7].

SAR Image Stack Selection

Stack selection is a key element for optimizing an InSAR-based bridge displacement monitoring program to ensure that monitoring goals can be met. This should include consideration of beam mode, the most appropriate incidence angle(s), and whether more than one image stack geometry is appropriate, if available. The selection of which scenes to obtain from each stack should also be considered.

In some of the NRC-led bridge validation case studies [8,9], each bridge was monitored and analyzed using SAR data from two independent stacks of satellite imagery with opposite viewing geometries (ascending vs. descending). Typically, only one stack is required to conduct such analysis; however, having access to two stacks proved to be useful on several occasions. First, it helped clarify the understanding of specific observations by allowing the conduct of 2D decomposition in discretizing displacement measurements into the vertical and horizontal components. Second, it helped confirm or deny unusual trends observed from one stack. Two stacks of images with opposite viewing geometries, however, may provide more useful info but would be more expensive in terms of the number of images to acquire and analysis effort.

For the Confederation Bridge, 3-m resolution Ultrafine stacks with a 20-km swath were used for InSAR analysis since the bridge is 13-km long and thus could not fit entirely within the smaller 8-km footprint of the 1-m resolution Spotlight stacks. An open question is whether the InSAR analysis accuracy could be improved by using two adjacent spotlight stacks from the same viewing geometry to cover the entire bridge with the highest-resolution imagery available. However, it is not clear at the moment if this would improve the measurement accuracy over the use of a single stack of the coarser Ultrafine imagery.

Incidence Angle

In selecting the most appropriate incidence angle, one should consider both the backscatter response of the bridge structure and the sensitivity of the line of sight to the expected displacement direction. The spatial distribution of the radar backscatter of bridge elements will depend on the chosen incidence angle.

This behavior is potentially complex due to the fact that the bridge structure may cast a shadow, multiple bridge elements may have the same radar range and therefore overlap in the radar image (layover), and significant double-bounce scattering may overlap with single-bounce returns. Any double-bounce and layover effects involving water will vary along with changes in water level.

An incidence angle should be selected so that bridge elements of interest do not lie in the radar shadow of others and provide a backscatter response that does not overlap with the backscatter of other elements. A backscatter analysis should therefore be performed for the range of expected incidence angles and water heights in order to select the most appropriate incidence angle for the monitoring program.

LOS Sensitivity to Bridge Displacement

For the range of available incidence angles, one can compute the projection of the longitudinal, lateral, and vertical unit vectors into the LOS unit vector in order to assess the sensitivity to each of the bridge displacement components. For example, longitudinal sensitivity may be of primary interest for monitoring the thermal behavior of a bridge, whereas vertical sensitivity may be most appropriate for a bridge at risk for pier failure due to scouring.

Temporal aspects – Sample Rate and Seasonal Factors

The temporal sampling rate of a spaceborne SAR image stack is limited by the orbit repeat interval of the satellite or the constellation of satellites. Within this limit, it may be appropriate to include only a subset of these repeats in a bridge monitoring program to optimize monitoring within a given image budget. It is noteworthy that bridge structural elements do not strongly de-correlate with time, and therefore decorrelation does not constrain the temporal sampling frequency.

The optimal temporal sampling strategy depends on the monitoring goals. If the goal is to assess the thermal response of bridge elements, then scenes should be acquired to provide the greatest variation in thermal conditions (i.e., spanning warm and cold seasons). If the goal is to measure long-term displacements, then scenes should be acquired over a longer period if possible (minimum one year). If the goal is to detect the sudden onset of a failure precursor displacement, then scenes should be acquired as frequently as possible with minimal lag between acquisition time and reporting. In this case, it may be appropriate to use a multi-stack approach so that effective sample rates can be increased beyond the orbit repeat interval. If hazards only exist seasonally, then acquisitions can be limited to the hazard periods once a sufficient stack size has been accumulated. Also, to be considered is whether archive data already exist for the target structure, allowing for retrospective analysis. Multi-temporal PS-InSAR analysis of coherent persistent scatterers requires a minimum number of images in order to identify coherent targets. At least 15 images (preferably > 20) are required for robust PSI analysis.

For bridges in cold climates, the seasonal impact of snow and ice should be considered. If the bridge elements being monitored are known to accumulate snow and/or ice, and the goal is assessing long-term displacement or thermal response, then it may be good not to acquire winter scenes since they are most prone to decorrelation from snow and ice, or to install artificial corner reflectors at strategic locations on the bridge.

SUMMARY

Based on the knowledge and experience accumulated from previous research and field validation work conducted by the NRC on InSAR monitoring of bridges since 2014, a set of technical guidelines is summarized and presented in this paper. The guidelines discuss the bridge characteristics and the satellite parameters that can affect the monitoring results and provide strategies to improve the quality of satellite-based bridge deformation monitoring. The overarching goal of these guidelines is to enable more efficient and accurate monitoring of bridges using radar satellite imagery by recognizing the limitations of the technology and by better understanding the bridge and satellite parameters that can optimize its application.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of Transport Canada, as well as Infrastructure Canada through NRC's Initiative on Climate-Resilient Buildings and Core Public Infrastructure. Special thanks go to the Canadian Space Agency for the provision of the radar satellite imagery that was used for several bridge case studies.

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