Large-scale and long-term settlement monitoring: the benefits of using remote sensing for major infrastructure projects

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ABSTRACT
Through specialized interferometric processing of Synthetic Aperture Radar (SAR) remote sensing data, a technique referred to as InSAR, it is possible to obtain high accuracy infrastructure surface change maps over relatively large regions. Applying InSAR techniques to modern space-based SAR datasets can provide surface change maps every 4 to 23 days with a spatial resolution of 1 to 3 meters. This technique is currently being used to monitor key areas of the Ottawa Light Rail Train (OLRT) construction for surface movement over the duration of the construction. The steps to ensure a successful remote sensing monitoring program include a feasibility study, a proper baseline establishment, and an on-going monitoring period where the monitoring requirements are addressed through proper data planning and processing. The OLRT case is an example of using InSAR tools for large infrastructure projects.

RÉSUMÉ
Grâce à un traitement interférométrique spécialisé de données de télédétection à radar à synthèse d'ouverture (RSO), une technique appelée InRSO, il est possible d'obtenir des cartes de haute précision des changement de surface de l'infrastructure sur de relativement grandes régions. L'application de techniques RSO aux données spatiales RSO actuelles peut fournir des cartes de changement de surface tous les 4 à 23 jours avec une résolution spatiale de 1 à 3 mètres. Cette technique est actuellement utilisée le long des zones clés de la construction du train léger sur rail d'Ottawa (TLRO) pour surveiller des mouvements de surface pendant la durée de construction. Les étapes pour réussir un programme de surveillance de télédétection comprennent une étude de faisabilité, un établissement d'une base de référence, et une période de surveillance continuelle où les exigences de surveillance sont traitées grâce à une planification et à un traitement adéquats des données. Le cas du TLRO est un exemple de l'utilisation d'outils InSAR pour les grands projets d'infrastructure.

1   INTRODUCTION

Remote sensing is defined as any technique for measuring, observing or monitoring a process or object without physically touching the object under observation (non-intrusive). Compared to the sparse point measurement available through standard geodesy techniques (e.g., GPS, levelling points), remote sensing techniques can provide a wider and more uniform spatial coverage. One such technique is Interferometric Synthetic Aperture Radar (InSAR), which is capable of measuring surficial changes in the order of millimetres for every single pixel in an image. Recent satellite constellations also enhance the frequency of monitoring (every 4 to 12 days) and a higher density of measurement (1m to 3m spatial resolution).

Started in 2013, the 12.5km Ottawa Light Rail Train (OLRT) project is an ongoing project of a 2.5km tunnel through the downtown of Ottawa, Ontario. For this mega project, early warning is crucial to identify issues and to mitigate potential long-term impacts of project construction. To provide increased information on possible impacts, levelling surveys are used. However, because of its size, one key area to the south of the tunnel would be too costly to monitor with a suitable density of discrete leveling tools. An InSAR monitoring program was initiated as a cost effective alternative in the spring of 2014, shortly after the start of tunnel excavation.

The spaceborne dataset collected for the project contains a wealth of information about the city's critical infrastructure: bridges, railroads, train stations, airport runways, etc. InSAR derived results, with a standard deviation of +/- 4mm, present a robust large scale monitoring method complementary to traditional techniques. To extend life of aging critical infrastructure and assessment of climate change impacts, the monitoring program should include a long-term remote sensing component.

2   OLRT PROJECT OVERVIEW AND GEOTECHINCAL ISSUES

On December 2012, the Rideau Transit Group (RTG) led by ACS Infrastructure Canada Inc., with EllisDon Corporation, EllisDon Inc., Dragados Canada Inc., SNC-Lavalin Capital, SNC-Lavalin Constructors (Pacific) Inc., and Veolia Transportation Services Inc. as prime team members, successfully won the OLRT Bid. The project will provide rapid and high quality transit service from the Tunney's Pasture employment node in the west to the Blair Station in the east. This 12.5km, 13 station LRT system includes a 2.5km tunnel to address increasing traffic through the downtown core. The three central underground stations will be constructed within the tunnel section. It is the largest infrastructure project in the City's history and the light rail elements consist of the first phase

of the City's 2008 Transportation Master Plan (Schepers, 2012).

Figure 1. Downtown Ottawa core with OLRT line in red and LEDA clay zone defined in orange

The project's construction schedule started in 2013 and the O-Train Confederation line is expected to begin Revenue Service in 2018. The tunnel will be constructed through three entry points: the east portal, the west portal and a central shaft site at the intersection of Queen and Kent Streets (see Figure 1 for tunnel reference). Based on the downtown Ottawa transit tunnel planning and environmental assessment study (City of Ottawa, 2009), most of the route downtown is underlain by shallow bedrock, likely at depths ranging from about two metres to five metres below existing ground surface between the west portal and Rideau Centre area. In the vicinity of the Rideau Centre, a known valley in the rock exists where the surface of the bedrock is much deeper. South of Laurier Avenue, the bedrock becomes progressively deeper, extending to depths ranging from about five metres to possibly 25 metres below existing ground surface. The subsurface conditions from about Waller Street to Mann Avenue likely consist of sensitive silty clay (referred to as LEDA clay in Figure 1) overlying deposits of glacial till and sand. South of Mann Avenue the subsurface conditions likely consist of significant deposits of sands underlain by glacial till. Both of these areas will have substantial groundwater issues. In addition, the published information indicates that at least three faults cross the tunnel alignment in the downtown core. Additional faults and associated tributary faults likely also lie within the study area. These faults are now considered inactive but create important features likely to impact the overall bedrock quality and hydro-geological regime. These groundwater issues coupled with different type of soils along the corridor could potentially lead to a different pattern of deformation along the OLRT corridor.

3   INSAR TECHNIQUES

A SAR-based satellite carries a radar antenna pointed to the Earth's surface in a plane perpendicular to the orbit. The radiation transmitted from the antenna has to reach the scatterers on the ground and then reflect back to the antenna in order to form the SAR image. The microwave field backscattered by the scatterers distributed in a ground cell carries amplitude and phase information and is represented as a complex number by a pixel in the SAR image; the intensity of the complex number is a function of the electrical and geometrical properties of the scatters and the phase is related to the slant range distance between the antenna and the scatterers.

The InSAR technique has received much attention since the early 1990s with the launches of satellites ERS-1, JERS-1, and RADARSAT-1. These satellites were used to demonstrate that it was possible to measure surface change with millimeter accuracy by processing the images with techniques aimed to provide topography (Massonnet et al. 1998). To use these InSAR techniques to derive deformation, two or more SAR images need to be acquired at different times to allow proper sampling of the deformation event. The dataset is then co-registered by re-sampling all images to the same geometry. The phase difference between the pixels representing the same location on the ground can then be usefully exploited to generate ground deformation maps once topographic corrections are applied.

Two different InSAR techniques have been used for monitoring the OLRT area of interest: a short-term differential InSAR method (D-InSAR) based on the difference of two radar scenes; and a long term stacking technique known as Persistent Scatterer Interferometry (PSI) that sums 20 or more images to provide an enhanced deformation estimate with less residual noise and higher accuracy.

3.1   D-InSAR

The multiple images used in D-InSAR processing can be thought of as "time-lapse" imagery. If the orbit path and imaging geometries of all the SAR images are identical, the measured interferometric phase of each pixel in each image is due to topography with a portion attributed to noise from orbit uncertainties and atmosphere propagation delays (Rosen et al., 2000). Movement between the acquisition periods will be detected by calculating the phase differences of the corresponding pixel in two images acquired at the beginning and end of the period (InSAR image pair). In particular, Figure 2 is a simplified illustration of the variation in phase due to ground movement between two images. The change in the distance d between the satellite and any point on the ground (change along the line-of-sight of the SAR) is simply the fraction, as determined from the interferogram phase $(\phi 2 - \phi 1)$ for the two images, of half the radar wavelength (λ).

To obtain the D-InSAR interferogram, one radar image is considered to be the master image and the second radar image (slave) is re-sampled into the master's geometry. An interferogram, which contains the phase difference information between image pair, is derived after precise co-registration of the images (example in Figure 3 of arctic monitoring). The unwrapped phase difference can be obtained after topography removal from the interferogram and then converted to line-of-sight displacements in the slant range direction.

Finally, once the processing is completed, all the radar deformation maps can be projected into a vertical plane and can be compared to derive the deformation due to change between acquisition times. The accuracy of this technique is sub centimetre and is generally limited by residual atmospheric noise that cannot be filtered out.
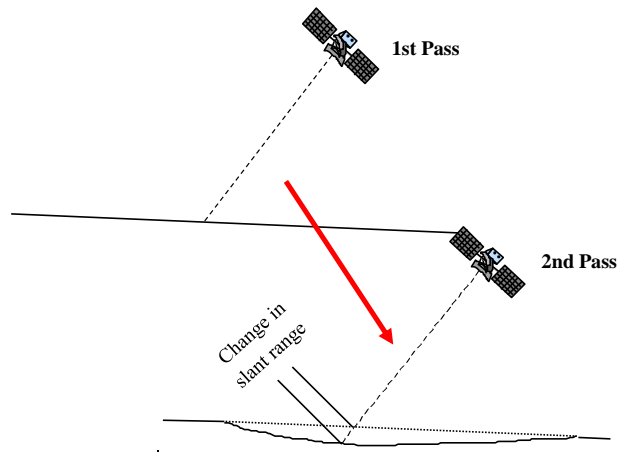

Figure 2. InSAR Measurement of Ground Movement

Finally, radar images acquired at different dates can be useful for interferometry only if the coherence is relatively high among the images. Coherence is the degree of similarity between two radar images and can be negatively affected by vegetation change, snowfall or melt, or ground freeze or thaw. In an urbanized area, like the downtown core of Ottawa, coherence is typically high, as infrastructure provides a consistent return that is easily compared between different images.
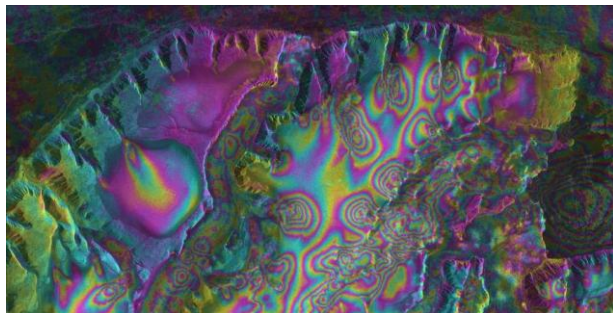

Figure 3. Interferogram example of Devon Island, Nunavut. Each color cycle represents 2π in phase change

3.2   PSI

The PSI technique is based on identifying point targets that are coherent over an extended timeframe. Unlike the D-InSAR technique, the PSI technique requires a higher number of images (15 - 20 recommended) to initiate the deformation mapping (Ferretti et al., 2000, 2001 and Werner et al., 2003). The long time series allows mapping of deformation histories, heights, and to correct for relative atmospheric path delays. Typical persistent scatterers (PS) are sub pixel scale objects, mostly part of man-made

metal or masonry structures (building, bridge, dam, railway tracks) and to a lesser degree natural rocks or retaining wall (Ferretti et al., 2005). The flowchart displayed in Figure 4 presents the theoretical optimized steps for persistent scatterer analysis (adapted from Gamma RS Tutorial, 2010). All Single Look Complex (SLC) data need to be processed to a common Doppler centroid.

Local weather conditions will be checked first. This data are used to help select images which are not affected by atmospheric events or severe weather. Using the screened images, a set of baselines are calculated in order to reduce the average baseline magnitude. Thus, the selected reference scenes will have low baseline decorrelation as well. Given the reference scene, the image set will be processed following the steps shown in Figure 4.
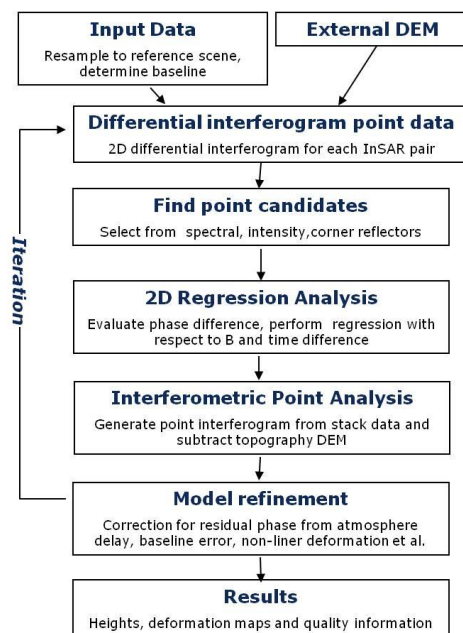

Figure 4. Theoretical optimized PSI flowchart (modified from Gamma Tutorial Software, 2010)

Point-like targets, i.e. PSs, are selected from either their phase coherence information, from their intensity characteristics or using pixel coordinates of actual installed corner reflectors. Interferometric analysis will then be performed on each individual point, and initial unwrapping of the point target phase is performed. A common phase reference point should be selected for the entire SLC stack. Once the phase of all the interferograms is unwrapped, the deformation results are generated. If a large coherent area is present throughout the dataset, it can be used for error estimation and a refinement model can be defined to apply to the data and partition the unwrapped phase into linear deformation, non-linear deformation, atmosphere effects, height correction, and noise using spatial and temporal filtering.

4   OLRT INSAR MONITORING

InSAR techniques have been used to monitor the OLRT construction since early 2014. The following steps were conducted to confirm the coverage and information content, and to establish baseline and on-going information potential:
1. Feasibility Phase;
2. Baseline Monitoring Phase; and
3. On-going Monitoring Phase.

Each of these stages are key components correctly establish long term monitoring using InSAR. The following sections will describe what was done during each phase.

4.1   Feasibility Phase

A feasibility study determines which satellite look direction is suitable for monitoring a particular area. There are geometric and coverage considerations to ensure that the long term data acquisition is suitable to derive the required information. This can be done with a minimal amount of data and in a very short time span.

For the OLRT, two COSMO-SkyMed interferometric pairs (4-day orbit, Stripmap Mode), one ascending and one descending, were acquired for evaluation. To decide the best data acquisition geometry for OLRT project, three image parameters were calculated: (1) The intensity and location of strong returns, typically indicative of stable targets; (2) Simulated radar image using the Digital Terrain Model (DTM) from the City of Ottawa, indicating zones of coverage and non-coverage (referred to as "shadow zones); and (3) Interferogram and coherence images to indicate the image quality and identify potential errors in the DTM provided by the city. These parameters were derived from the image pairs using the D-InSAR technique.

Figure 5 displays these parameters over the clay area in downtown Ottawa. The orbit and look directions of the satellite are indicated. In the averaged intensity image, bright pixels indicate a strong signal return to the radar satellite. Due to the look angle in the ascending image, tall buildings in the downtown core have a much higher intensity than expected. Although this will not affect any deformation results, it may be more difficult to properly identify and reference the exact location of some of the building returns.

Shadow zones were simulated using the orbit geometry and the DTM, and these were confirmed with the actual imagery. Some buildings behind taller buildings in the downtown core are in these zones, thus no information will be available on these. However, due to the selection of a steep incidence angle, these zones are minimal. The Parliament Hill area is an example of an area where shadow plays a role based on acquisition geometry. The white polygon in the simulated images (2nd set of images in Figure 5) show that the cliff behind the parliament building is well imaged in the Ascending geometry but poorly in the Descending geometry.

The phase and amplitude (intensity) signals were further evaluated using the interferogram and coherence images. The relative phase difference between the two acquisitions was extracted to generate an interferogram.

The relative phase is a sum of different components: surface movement, residual topographic errors, processing error and noise. In a perfect noise/error/ movement free environment, the interferogram will present a unique phase color throughout the scene. Comparing this interferogram to the DTM gives an indication of data quality as well.

The coherence product was then derived to measure the suitability of the image pair for InSAR processing and noise level between the two images. The coherence level ranges from 0 (no correlation) to 1 (full correlation). This parameter is typically affected by the time lapse between two acquisitions, properties of the imaged surface and potential change (vegetation and infrastructure growth). The coherence image is used as a threshold parameter to derive a final movement map. A low coherence area will not provide reliable movement and therefore no movement will be extracted for these pixels. Any dark pink and yellow pixels in the coherence image would indicate reliable movement information. In the downtown clay area (south of Laurier Street to Hwy 417 and Sandy Hill area), there are more than 100,000 pixels with a coherence level higher than 0.6. This is a good indicator of the extent and coverage that the final deformation products will achieve.

The results obtained from both radar look geometries show similar characteristics, and both were suitable for long term monitoring. The descending acquisition was selected for the following stages.

4.2   Baseline Monitoring Phase

The Baseline Monitoring Phase was conducted between July 18, 2014 and October 22, 2014, using the selected descending geometry. The goal of this phase was to obtain sufficient acquisitions over the area to generate a reliable deformation product. This initial product contains the baseline deformation during this period. If the acquisitions had been conducted prior to construction, the deformation could be used as a reference against which future deformation would be evaluated for anomalous measurements, thus establishing the "baseline". The acquisition dates are listed in Table 1.

The acquired images were processed using the PSI technique. All images were co-registered to a master image within 0.05 pixel accuracy. Once persistent scatterers were identified, intensive processing was done to identify stable areas, and to estimate and correct noise from the atmosphere using an iterations model. The radar phase was then unwrapped to derive displacement in the line-of-sight direction and then converted into vertical movement.

An innovative technique, called multi baseline InSAR, can be used to increase the number of data comparison possibilities. This method generates interferograms between all possible data combinations. This method enables us to expand an *n* number of interferograms dataset using traditional stacking technique to an *n*(n+1)/2* series of interferograms. From this much larger number, the most reliable interferograms are selected using a number of criteria, including correlation between images, baseline sizes, and atmospheric noise during the acquisitions.

Average Intensity

Simulated Image from DEM

Interferogram

Coherence

Figure 5. D-InSAR analysis over the clay area in downtown Ottawa using COSMO-SkyMed stripmap interferometric image pairs. Ascending pair (left column). Descending Pair (right column)

The selection is made to minimize residual error and to ensure high accuracy when deriving the final subsidence measurements. For the baseline phase dataset, 72 out of the 231 possible interferograms were used. The three scenes aquired in July 27, August 31 and September 04 (marked as grey in Table 1) were completely ignored (mostly due to severe storms during acquisition leading to high atmospheric noise).

The average intensity and coherence images were generated using the 72 interferometric pairs. Low coherence points indicated that valid movement information cannot be derived from these points and therefore they will be masked out in future processing. These low coherent points correspond generally to areas with geometric distortion, e.g., shadows, vegetated areas and/or change in surface of infrastructure such as roof changed, deck of bridge replaced. Figure 6 displays the averaged coherence image with a mask applied to the areas with coherence value less than 0.3. The higher coherence level areas remained in this figure are the points at which deformation is within an acceptable accuracy metric.

Table 1. COSMO-SkyMed data set for baseline study.

Image #	Date	Image #	Date
1	2014-05-07	12	2014-08-31
2	2014-05-11	13	2014-09-04
3	2014-07-18	14	2014-09-12
4	2014-07-26	15	2014-09-13
5	2014-07-27	16	2014-09-16
6	2014-07-30	17	2014-09-20
7	2014-08-03	18	2014-09-28
8	2014-08-11	19	2014-09-29
9	2014-08-15	20	2014-10-14
10	2014-08-19	21	2014-10-18
11	2014-08-27	22	2014-10-22

Figure 7 presents the total vertical displacement derived using the dataset from May 7, 2014 to October 22, 2014 in the downtown Ottawa area. Cyan indicates no movement. Positive movement (red) indicates an upward displacement whereas a negative (blue) represents a downward movement. The light yellow color is associated with thermal expansion of high rise buildings (positive movement). This movement can sometimes manifest itself with lateral and vertical movement. All the buildings with sufficient spaceborne SAR coverage present no apparent deformation. Along the OLRT corridor, no deformation was observed.
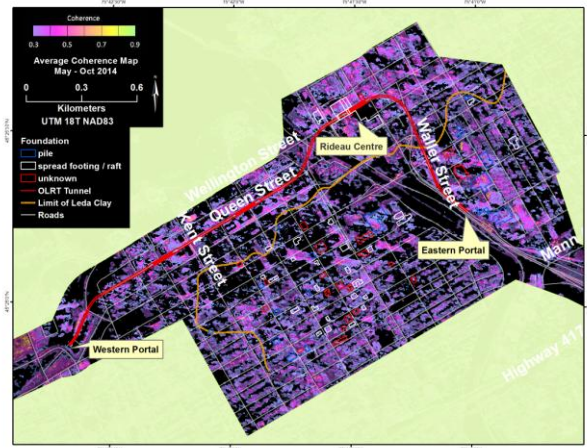

Figure 6. Average coherence image with coherence level larger than 0.3 over the OLRT tunnel construction area

For each identified PS target, time series analysis can be performed. An example is presented in Figure 8 where raw measurements (in blue) show a linear trend between -0.003m and +0.003m. This point is located near LeBreton station and the West entrance portal of the OLRT Tunnel. As observed, the vast majority of valid points located along the tunnel and corridor have a standard deviation of 0.003m or less. With 19 data captures this accuracy meets the displacement measurement accuracy required which was stated as between 3-5mm.

Figure 7. Vertical displacement map from May 7, 2014 to Oct 22, 2014 over tunnel area
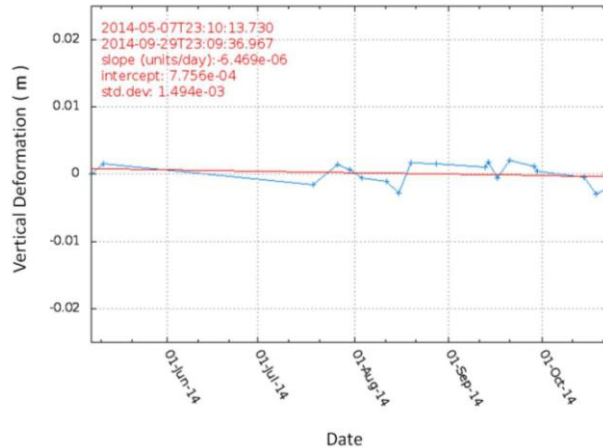
Figure 8. Vertical movement of a PS from May 7 to Oct 22, 2014

4.3 On-Going Monitoring Phase

Based on project monitoring requirements and the results of the baseline study, the InSAR study was adopted for the duration of the construction. The monitoring requirements are to provide a monthly deformation map until January 2017, with bi-annual reports required until mid-2018. The monthly deformation maps are checked for anomalous areas. If and when any of these are noticed, an in-depth analysis is done on a pixel by pixel basis to fully quantify the movement.

Data is acquired three times a month to produce the monthly deformation maps, while for the bi-annual monitoring, 10 acquisitions per reporting period are planned to ensure that the infrastructure is sampled at a high enough frequency.

5 CONCLUSION

InSAR monitoring is a powerful tool for meeting monitoring requirements for large scale infrastructure projects and for long term project. The example in this paper covers the entire Ottawa downtown core with a single image footprint and deformation points are derived over more than 60% of the downtown region with an accuracy of 5mm or better. In most cases, the accuracy is closer to 3mm. The information can be used to evaluate trends over large areas, but it can be also derive deformation on infrastructure with resolutions down to 3m, thus allowing for modelling long term behaviour and even identifying anomalous behaviour.

The set-up times and costs associated with using InSAR are relatively small, especially when used to confirm the feasibility of the monitoring and to establish a pre-construction baseline. An on-going monitoring program can be developed for many different applications by applying different data acquisition intervals, coverage areas, and level of detail or resolution of the features being monitored, to produce the desired results.

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