CITY BREAKS

WITH GOVERNMENTS AROUND THE WORLD FACING DETERIORATING INFRASTRUCTURE, SYSTEMS NEED TO BE PUT IN PLACE TO MONITOR IT AND PRIORITIES MAINTENANCE. MARK CARMICHAEL LOOKS AT SOME POWERFUL SATELLITE RADAR TECHNIQUES THAT CAN BE USED TO ANALYSE SURFACE CHANGES AT LOW COST

City and municipal governments around the world face considerable challenges maintaining or expanding their critical infrastructure. Population growth in urban areas, constrained finances and reduced tax revenue conspire to hinder or stop maintenance on ageing systems and slow new development.

The first step in prioritising infrastructure maintenance is an effective, accurate and cost-efficient means of monitoring that can deliver the pertinent information required to make decisions and to budget accordingly. Multi-temporal interferometric synthetic aperture radar (InSAR) is a complementary technology that make traditional monitoring more efficient. There are several proven, reliable techniques for using InSAR to monitor very large areas and deliver the critical information urban planners and engineers need to understand the state of buildings, bridges, roads, airports and underground tunnels.

InSAR is a powerful radar technique that exploits the all-weather monitoring capabilities of SAR satellites such as RADARSAT-2. It uses multiple SAR images to generate maps of surface deformation based on minute differences in the phase of radar waves returning to the satellite. This enables the detection and measurement of millimetre-to-centimetre-scale changes in surface deformation. The routine nature of satellite monitoring is useful to detect, track and visualise growing surface movement hot spots. The oil and gas industry has used this technique for decades as a cost-effective means of detecting surface changes that can impact their operations and assets.

HDS-InSAR

One of the more powerful InSAR techniques is homogenous distributed scatterer (HDS)-InSAR, which uses adaptive filtering to preserve boundaries between different types of scatterers. Adaptive filtering reduces the noise of smooth, low-backscatter areas such as asphalt and bare ground, while optimally preserving the spatial resolution to increase both the accuracy and geographic precision of the deformation result. HDS-InSAR results enable more targeted monitoring, to identify the infrastructure in greatest need of repair.

Medium- to high-resolution SAR imagery for use in the HDS-InSAR technique is desirable for urban infrastructure monitoring, to better capture detailed infrastructure from point targets such as metal and building corners, and coherent distributed targets such as asphalt and

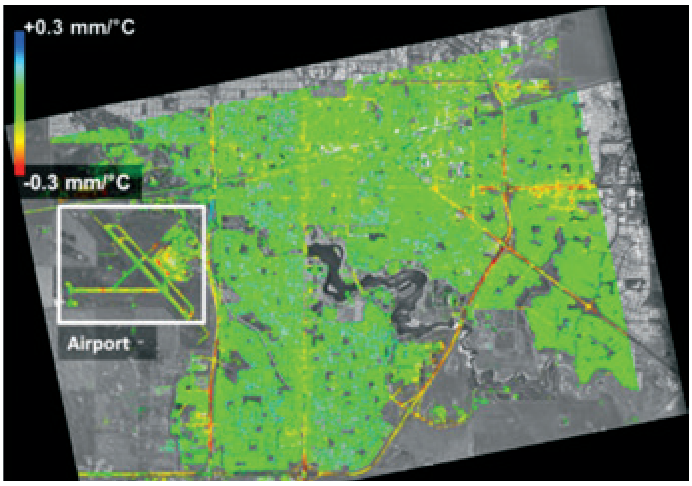


Figure 1. Temperature-correlated displacement in the radar LOS direction, RADARSAT-2. RADARSAT-2 data and product © MacDonald, Dettwiler and Associates (2011-13). All rights reserved.

concrete surfaces. It combines the advantages of differential InSAR (DInSAR) and persistent scatterer interferometry (PSI) by suppressing noise over distributed targets, while preserving point targets. The HDS method requires about 15 scenes or more for robust deformation results, while increasing point densities by an order of magnitude over PSI.

Of particular importance is the separation of temperature-correlated displacement anticipated in infrastructure design from the long-term displacement trends that can pose a hazard. Without temperature-correlated displacement taken into account, linear deformation rate estimates can show considerable bias for observation periods of less than a few years.

Examples of HDS-InSAR

MDA has successfully mapped surface deformation over several Canadian cities using RADARSAT-2 and TerraSAR-X data. HDS-InSAR identified areas where surface displacement affects the durability and stability of a variety of urban infrastructure, pointing to a cost-effective means of wide-area urban infrastructure monitoring, particularly using high-resolution RADARSAT-2 data to detect seasonal deformation and potentially hazardous long-term deformation trends at high accuracies and dense spatial coverage.

MDA's operational solutions have monitored urban infrastructure in a variety of geographic settings. The following examples illustrate its ability to capture detailed information over very large areas, and pinpoint threats to the operation and life of infrastructure.

Airport surface deformation caused by temperature

HDS-InSAR and the unwrapped phase model-detected surface deformations were inverted in the RADARSAT-2 Spotlight image stack over a Canadian airport. Figure 1 shows the seasonal displacement rate map measured in the radar line-of-sight (LOS) direction. Yellow and red indicate areas where the surface moves towards the radar during colder temperatures, while the green areas show negligible displacement. The average radar intensity image over the entire image stack is in the background.

Long-term linear and temperature-correlated displacements are benign across most of the adjacent city. Some areas, such as the airport tarmac and several major roads, experience strong seasonal displacement consistent with frost heave that, over time, can result in significant damage to asphalt that plays a key role in air safety.

Figure 2 shows the enlarged subset of the airport illustrating dense coverage of the airport tarmac and buildings, yielding information on both distributed and point targets with the HDS-InSAR method. The airport tarmac shows minimal linear deformation trends although seasonal motion amplitudes of up to 1cm/year, consistent with winter frost heave resulting when water in the underlying wet clay soils freezes, causing uplift.

The deformation time series for two points shown in Figure 3 include both 'raw' deformation (blue points) and temporally filtered deformation time series (blue solid lines). Point (A) shows a slight

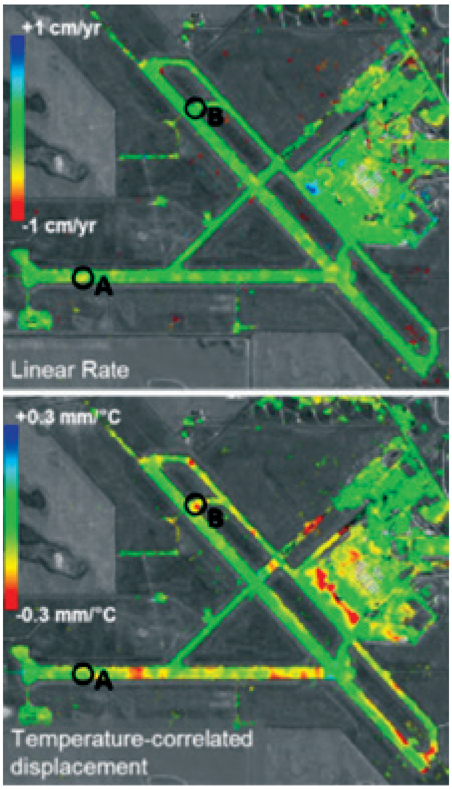


Figure 2. Linear displacement rate (top) and temperature-correlated displacement (bottom) in the radar LOS for airport subset derived from RADARSAT-2. Deformation time series for points (A) and (B) are displayed in Figure 3.

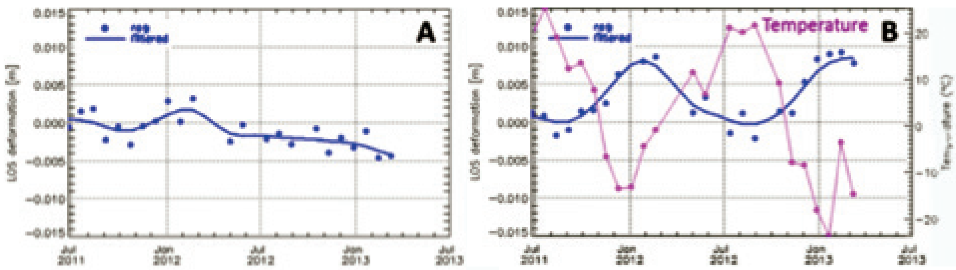


Figure 3. The deformation time series for points (A) and (B) from Figure 2 show both raw (blue points) and temporally filtered deformations (blue lines). The bottom image also plots mean daily air temperature (magenta) on image acquisition days referenced to the right-hand Y-axis.

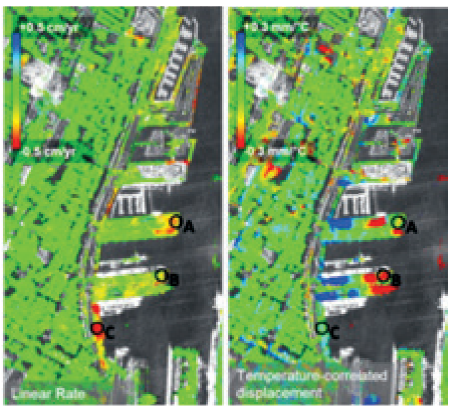


Figure 4. Linear displacement rate (left) and temperature-correlated displacement (right) in the radar LOS derived from RADARSAT-2. Deformation time series for points (A), (B) and (C) are displayed in Figure 6.

Figure 5. Linear displacement rate (left) and temperature-correlated displacement (right) in the radar LOS derived from TerraSAR-X. Deformation time series for points (A), (B) and (C) are displayed in Figure 6.

subsidence trend of approximately 0.25 cm/year, superimposed on a weak temperature-correlated displacement signal. Point (B) has a negligible linear rate but displays strong seasonal displacement. Mean daily temperatures overlaid on the point (B) time series show that the coldest periods in January coincide with the strongest movement, consistent with frost heave.

Separating mean daily air temperature from seasonal and long-term linear displacement measurements through correlation does not mean that temperature fluctuations are the sole cause of surface deformation. Seasonal displacement is likely due to a complex interplay of temperature, precipitation, snow distribution, and soil moisture.

Long-term and seasonal displacement of piers, Central Canada

RADARSAT-2 and TerraSAR-X satellite image stacks used for HDS-InSAR monitoring of a large city in Central Canada shows long-term linear displacement as benign over most of the area, however, several areas of the city experience temperature-correlated displacement including bridges, quays, and steel infrastructure.

Figures 4 and 5 show the radar line of sight (LOS) linear rate and temperature-correlated displacement for a RADARSAT-2 Spotlight stack in the port. Several of the piers and promenades are experiencing persistent deformation, identified by their strong linear displacement rates. The deterioration of the piers and ongoing repairs is documented in reports from the port corporation.

An incidence angle difference of 9° prevents a direct comparison of RADARSAT-2 and TerraSAR-X LOS displacements, but trends are consistent between the two ascending stacks. The RADARSAT-2 result shows slightly higher target densities than TerraSAR-X, particularly over roads, which may be partially due to the higher temporal coherence and higher phase quality of the C-band compared to the X-band data through winter acquisitions. A second contributing factor is that the RADARSAT-2 Spotlight data have a higher azimuth resolution.

Figure 6 shows point (A) is located on the deteriorating pier, and displays slow long-term displacement of ~0.5 centimetres/year superimposed on a stronger seasonal displacement signal. HDS-InSAR has separated long-term displacement trends from the seasonal effects, and while thermal dilation has likely been accounted for in the pier's design, the long-term displacement trend could eventually lead to hazardous conditions. Point (B) on an adjacent quay illustrates strong seasonal displacement, and Point (C) on the promenade has a high linear rate of ~1cm/year away from the radar, consistent with slumping towards the river.

Subway tunnelling, Western Canada

Increasing populations and economic development worldwide has led to increased construction of urban tunnels. Monitoring the stability and safety of ageing underground infrastructure and its interaction with geology and natural hazards, has developed into a formidable problem. More critical is a dependable and timely monitoring method for new tunnel construction, and its potential impact on surrounding geology and existing infrastructure.

MDA has shown improved monitoring performance by combining HDS-InSAR with temporal matched filtering to detect and monitor tunnelling, shown in a study of the Canada Line underground transit line in Vancouver, Canada. Table 1 shows the RADARSAT-1 and RADARSAT-2 data stacks used in the study.

Figure 7 shows annual subsidence rates averaged over temporal extents, based on the two data stacks processed in an earlier study using the older dual scale PSI. The previous results show a number of interesting ground instabilities (cyan marks stable ground; red marks ground displacement away from the sensor, usually due to subsidence).

The majority of subsidence in Vancouver corresponds to former peat bogs, which are drying out and compacting after urbanisation, and show a constant subsidence rate

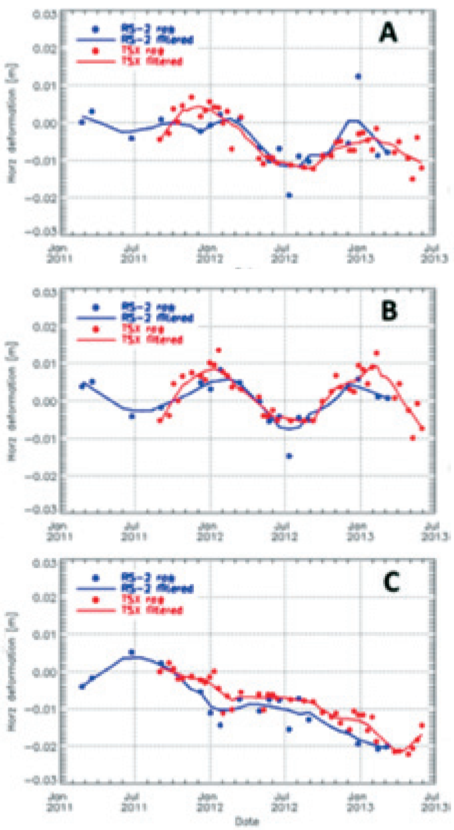


Figure 6. Deformation time series projected to the horizontal for points (A), (B) and (C) from the image products above. RADARSAT-2 displacements are shown in blue, and TerraSAR-X displacements are shown in red. RADARSAT-2 data and product © MacDonald, Dettwiler and Associates (2011-13).

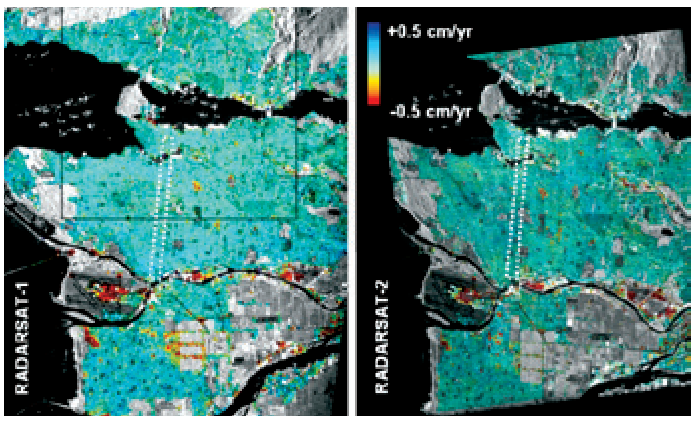
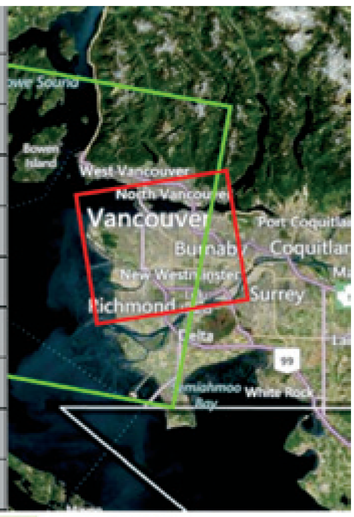


Figure 7. Results obtained with old method: linear subsidence trend maps obtained with dual scale-PSI for the RADARSAT-1 (2003-2009) and RADARSAT-2 (2009-2011) data stacks. Tunnelling sites shown as dashed rectangles. The black rectangle shows subset area of RADARSAT-1 data reprocessed with the new method.

	RS2-UF18	RS1-F2
Width [km]	24	50
Length [km]	21	50
Resolution [m]	3	9
Rg Posting [m]	1.9	7.1
Az Posting [m]	2.1	5.1
Pass Direction	A	D
Incidence Angle	45	41
Lambda [cm]	5.55	5.65
Polarization	HH	HH



2003	2004	2005	2006	2007	2008	2009	RADARSAT-1
RADARSAT-2	2009	2010	2011	2012			

Table 1. Specifications of the 28 scene RADARSAT-2 (Ultrafine) and 61 scene RADARSAT-1 (Fine) HDS test data sets. 'A' denotes an ascending satellite pass, 'D' denotes a descending pass.

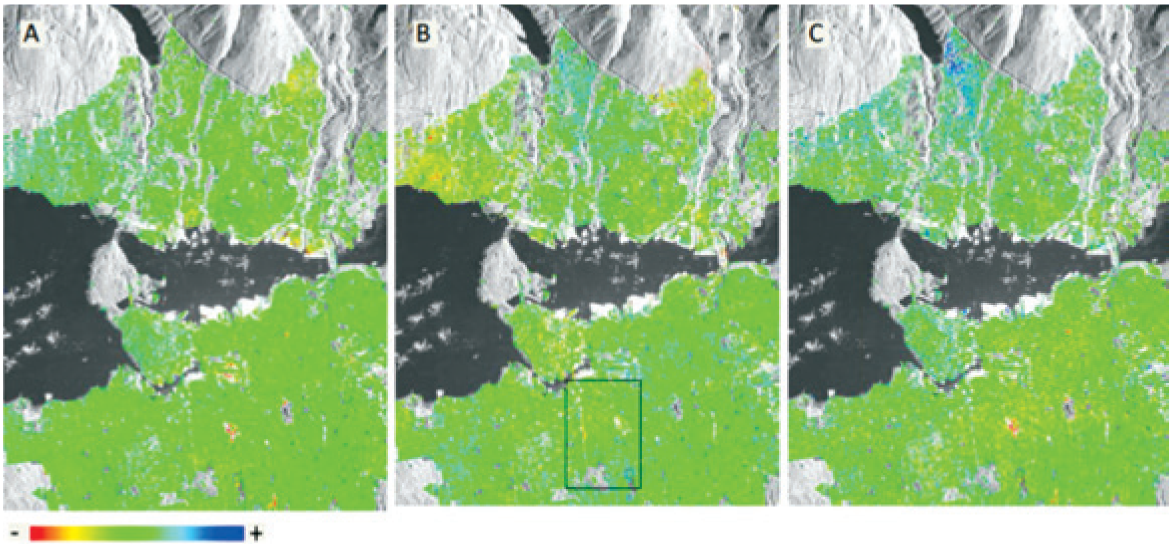


Figure 8. Ground displacement maps for the RADARSAT-1 data stack derived using HDS-InSAR (on the subset outlined in the previous figure) and subsequent decomposition via a-posteriori matched filtering. A: constant linear rate (+/- 5 mm/year); B: step change in linear rate (+/- 5 mm/year); C: normalised temperature correlated change.

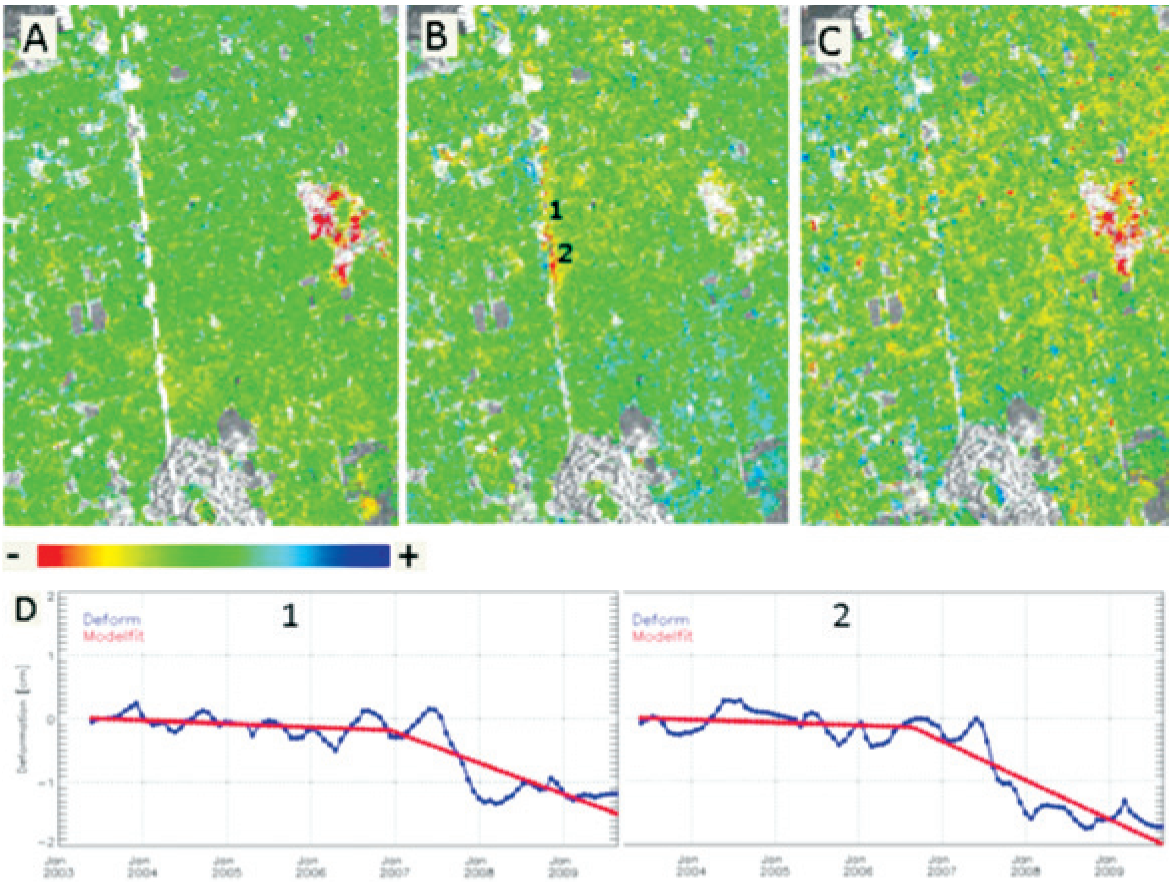


Figure 9. Ground displacement caused by Canada Line subway tunnel construction (shown by white dashed line). A: constant linear rate (+/- 5 mm/year); B: step change in linear rate (+/- 5 mm/year); C: seasonal change; D: two example time series.

superimposed by seasonal subsidence variations due to temperature and rainfall. Other detected ground displacement relates directly to the ground disturbance of above-ground and underground building activity that took place as the city prepared for the 2010 Olympic games. A step change in the subsidence rate is directly associated with building activity.

For the study, a spatial subset of the RADARSAT-1 data stack (black outline, left) was processed with the new method of HDS-InSAR and a-posteriori temporal filtering. The results of the final partitioning of the ground displacement are shown in Figure 8. In Figure 9, the first site A is the subway tunnel for the Canada Line. Construction of the tunnel commenced in October 2005 and was completed in August 2009. The tunnel is more than 9km long, and was constructed as a combination of cut-and-cover (6.5km) and bored tunnelling (2.5km). The tunnel has a diameter of 10m at a depth of between 10m and 30m (bored tunnel). Figure 9 shows the ground displacement components for a subset of the Canada Line tunnel.

A and C both show the location of a larger former peat bog in the eastern part of the subset. B clearly shows the ground displacement associated with subway tunnel construction. This method of combining (high spatial density) HDS-InSAR with a-posteriori matched temporal filters successfully isolates ground displacement caused by subsurface disturbance from ground displacement caused by other long-term and seasonal processes.

Summary

Traditional infrastructure monitoring methods are struggling to keep pace with the rate of change, and it is clear a new, cost-effective and responsive means of monitoring infrastructure and planning new construction is required. The basis of effective decisions starts with access to the accurate, timely information high spatial resolution HDS-InSAR wide-area monitoring delivers in a cost effective manner.

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