Satellite Monitoring of Transportation Infrastructure

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ABSTRACT

Harsh weather conditions caused by climate change and increased traffic loads can accelerate the aging process of core public infrastructure. Conventional condition assessment methods primarily rely on visual inspections conducted years apart, making it difficult to detect subtle, ongoing changes in performance resulting from structural deterioration. Consequently, engineers may be unable to initiate early countermeasures to prevent service disruption or structural failure. In response, public infrastructure owners are actively seeking innovative solutions that can help maintain high levels of user safety, reduce service disruption, extend the service life of infrastructure, and lower overall life-cycle costs. To this end, the National Research Council Canada, Transport Canada, and Infrastructure Canada have collaborated for several years to adapt, further develop and validate space-based earth observation technology for monitoring key public infrastructure, including bridges and, more recently, marine ports and airports. Case studies on runways of the Vancouver International Airport and wharves of the Vancouver Fraser Port have been conducted to validate remote satellite observations with in-situ surveying subsidence measurements.

Satellite image interferometry allows the mapping of displacement by determining the signal phase change within pairs of co-registered pixels from two radar images of the same target taken at different times. The result is a line-of-sight (LOS) displacement measurement that can be used to remotely assess uplift, subsidence, and horizontal motion taking place over time. Since it is a 1D measurement taken at an angle from the zenith, the vertical and horizontal components are unknown a priory. Thus, attempting to validate satellite LOS measurements with in-situ surveying vertical measurements can be challenging since one has to make valid assumptions about the horizontal movements of the ground targets being measured – in our case, the riding surface of the airport runways or the port wharves. This paper compares satellite-measured displacements and field survey measurements at selected locations and discusses challenges associated with the interpretation of satellite measurements.

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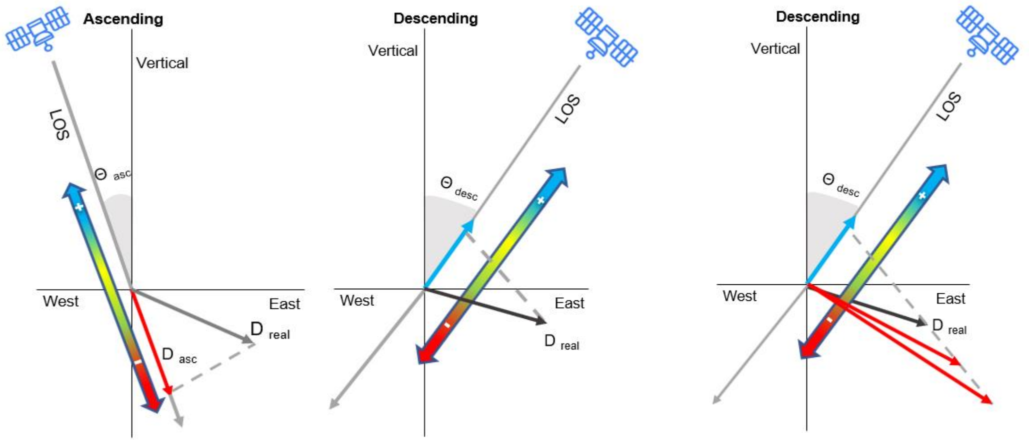
BACKGROUND

As studies show [1], [2], linear transportation infrastructure ages faster under harsher weather conditions due to climate change and increased usage (e.g., traffic loads). Traditional condition assessment methods are typically based primarily on visual inspection, with years between main inspections. They carry the risk of failing to detect ongoing subtle changes in performance due to structural degradation that might otherwise prompt engineers to take early countermeasures to prevent potential service interruptions and structural failures [3]. Public infrastructure owners may benefit from innovative solutions that can help them maintain a high level of safety for users, avoid prolonged service interruptions, and extend lifespans, which can reduce the life-cycle cost of their infrastructure. In this regard, Transport Canada, Infrastructure Canada, and the National Research Council of Canada (NRC) have worked together for several years to adapt, further develop and validate space-based earth observation technology to monitor bridge displacements. The partners recently went one step further to extend the scope to new types of transportation infrastructure such as marine ports, airports, and railways of national importance. This document describes two case studies comparing settlement records for the north runway of the Vancouver International Airport and a segment of one of the wharves of the Port of Vancouver derived from satellite-based measurements and conventional surveying methods implemented by the respective authorities.

SATELLITE VIEWING GEOMETRY

Most radar satellites follow near-polar orbits and therefore travel in a North-South orbit (and vice versa) with their radar line of sight (LOS) looking East-West at a given angle of incidence from the vertical. Radar images can be acquired when the satellite travels from South to North (ascending orbit) with the LOS looking to the East or when the satellite travels from North to South (descending orbit) with the LOS looking to the West (Figure 1.a). By convention, negative values (red) indicate movement away from the satellite, while positive values (blue) indicate movement towards it. As a result, the same movement vector can produce different satellite readings when viewed from different path directions and angles of incidence, as shown in Figure 1.a. For example, an Eastward-downward movement (D_{real}, represented by the gray arrow) can be measured as a negative movement (away from the satellite) in ascending mode (D_{asc}) or as a positive movement (towards the satellite) in descending mode (D_{desc}).

Furthermore, finding the real underlying movement that resulted in a given LOS measurement from the satellite can lead to several ambiguous solutions, as illustrated in Figure 1.b. It is, therefore, preferable when assessing satellite measurements to know a priori what to expect as a movement either from validated assumptions, predictive models, or existing in situ measurements.



(a) Projection of real movement onto the line of sight for ascending and descending satellite passes [4]

(b) Projection of different hypothetical values of real movement onto the line of sight for a descending pass (modified from [4])

Figure 1: Projection of movements on the Line of Sight (LOS)

INTERPRETATION OF DISPLACEMENT MEASUREMENTS

When motion can be predicted using numerical methods or trends based on in situ sensor measurements, comparing these predictions to satellite measurements for verification is straightforward as it is easy to convert vertical and horizontal component model predictions to LOS measurements, given the satellite viewing geometry.

For example, Figure 2 illustrates four simple cases that depend on the satellite's orbit direction (descending or ascending) and the considered motion component (upward or Eastward). Based on the above sign convention, the upward motion will be measured as a positive LOS regardless of the flight direction (Figure 2.a and Figure 2.c), while the Eastward (horizontal) motion will be measured as a positive LOS for a descending orbit (Figure 2.b) or as a negative LOS for an ascending orbit (Figure 2.d). Considering the above observations, the movement of the LOS in the V-E plane can be calculated as follows:

$$D_{LOS} = D_V \cos\alpha + D_L \sin\alpha \ \text{(for descending orbit)} \tag{1}$$

$$D_{LOS} = D_V \cos\alpha - D_L \sin\alpha \ \text{(for ascending orbit)} \tag{2}$$

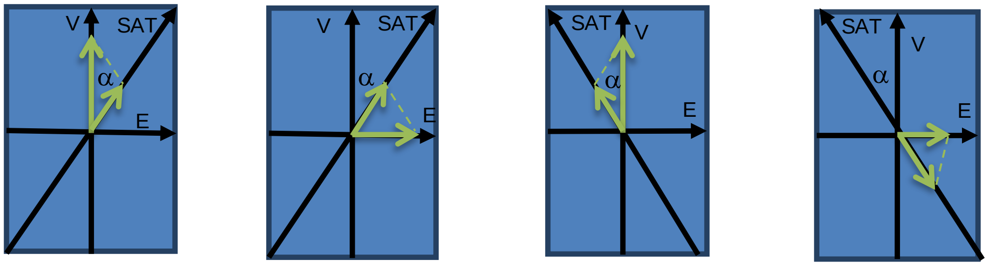
where D_{LOS} is the calculated line-of-sight displacement; D_V is the vertical displacement component; D_L is the longitudinal displacement component; and α is the angle of incidence of the satellite's line of sight.

Equations (1) and (2) apply to linear structures that lie perpendicular to the trajectory of the satellite projected on the ground. The next step is to consider the angular difference between the direction of the satellite's trajectory and the orientation of the structure. Consequently, the LOS displacement can be calculated as follows [5], [6]:

$$D_{LOS} = D_V \cos\alpha - D_L \sin\alpha \sin\beta \ \text{(for either orbit)} \tag{3}$$

where β *is* the angle, measured clockwise, between the orbit of the satellite and the longitudinal axis of the facility. Assuming negligible horizontal movement, D_L, the vertical movement, D_V, can be calculated as follows:

$$D_V = D_{LOS} / \cos \alpha \ (if\ D_L \sim 0) \tag{4}$$



(a) Descending pass: Upward movement = positive LOS

(b) Descending pass: Eastward movement = positive LOS

(c) Ascending pass: Upward movement = positive LOS

(d) Ascending pass: Eastward movement = negative LOS

Figure 2: Viewing geometry for either descending pass or ascending pass of the satellite, where upward or Eastward movement is projected onto the satellite LOS

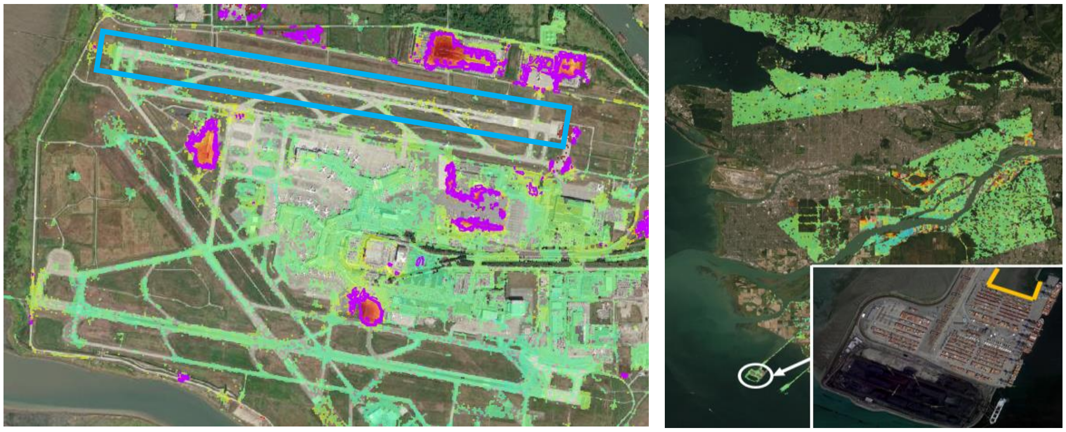
CASE STUDIES AT VANCOUVER AIRPORT AND PORT OF VANCOUVER

Description of the Sites and Measurement Methods

Figures 3.a and 3.b show satellite views of the monitored Vancouver International Airport and Port of Vancouver, respectively, along with satellite-measured displacement point clouds obtained from an interferometric synthetic aperture radar (InSAR) analysis conducted by 3v Geomatics. Details on the InSAR method can be found in [6] and [7]. The SAR datasets used to monitor the sites were obtained from the German TerraSAR-X satellite in ascending orbit. A total of 66 images to cover both the airport and the port were acquired in Stripmap mode using an incidence angle of 30.5°, with a pixel resolution of 3 m, a footprint of 60 km x 33 km, and a minimum revisit time of 11 days over a period of approximately 2 years.

For the Vancouver Airport, the investigation focused on the North Runway (Fig. 4.a, marked with a blue rectangle); thanks to the availability of the field survey datasets obtained from the Vancouver Airport Authority. Figure 4.a also shows the surveying stations spaced at approximately 100 m along the 3 km runway.

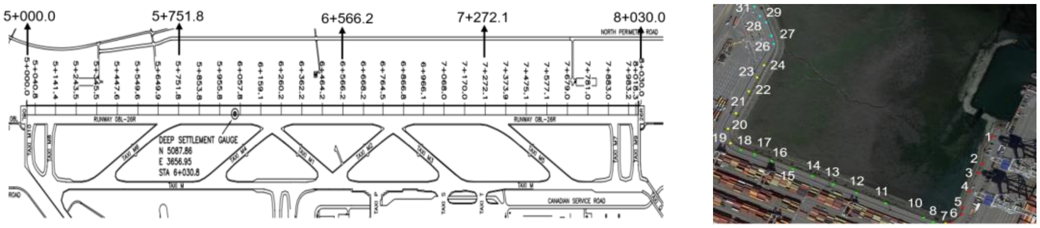
For the Port of Vancouver, the investigation focused on the Dyke Road portion of one of the wharves (Fig. 4.b, marked with a yellow line), thanks to the availability of the field datasets obtained from the Port of Vancouver Authority. Figure 4.b also shows the locations of the surveying stations along the seaside edge of the road.



(a) Satellite measurements of InSAR-derived displacement over the Vancouver International Airport
(surveyed area enclosed in blue rectangle)

(b) InSAR satellite measurements of Port of Vancouver and view of Dyke Road
(surveyed area identified in yellow)

Figure 3: Satellite views of Vancouver International Airport and Port of Vancouver



(a) Surveying stations along the Vancouver Airport North Runway

(b) Layout of surveying stations for the Port of Vancouver along Dyke Road

Figure 4: Surveying stations along: (a) Vancouver Intl. Airport's North Runway, and
(b) Port of Vancouver's Dyke Road (at Delta Port)

Figure 5 illustrates the dates for the obtained field survey datasets compared to the satellite image acquisition dates. For the airport's North runway, the surveying data was available for all stations along the runway as of August 14, 1996, and was executed intermittently over the years. The last survey dataset used in this study was measured on December 7, 2021. For Dyke Road at the Port of Vancouver, the surveying began on July 6, 2009, and the last survey dataset used in this study was measured on May 1, 2021. The radar satellite images for the investigated locations were obtained between June 21, 2019, and July 8, 2021. As shown in Figure 5, the 2-year period of satellite image acquisitions is bounded by the last two surveys taken at the airport and cover the last 3 surveys taken at the port.

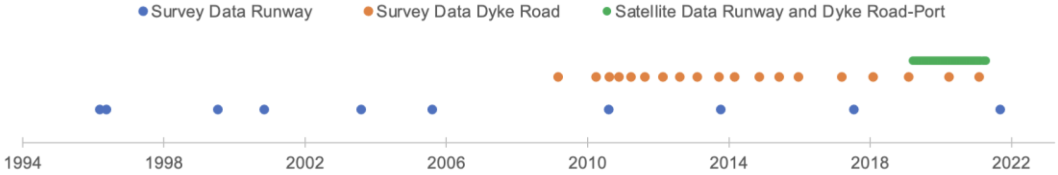
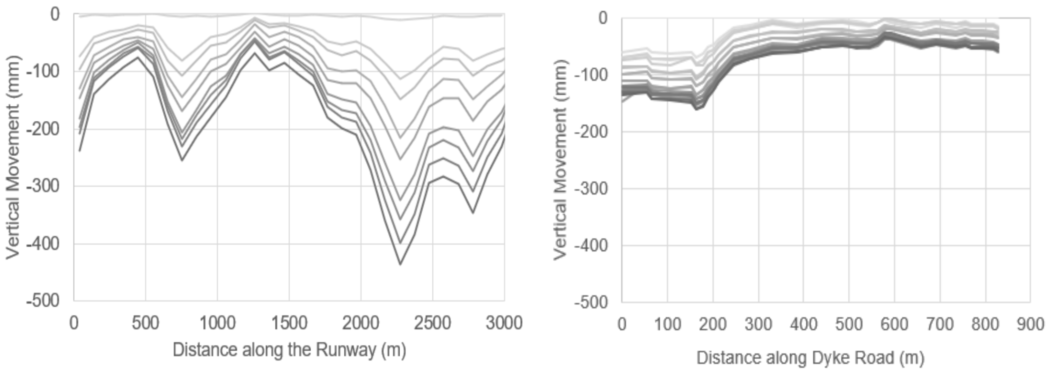


Figure 5: Dates of surveying campaigns at both sites vs. dates of satellite image acquisition

Changes in Elevation Profiles

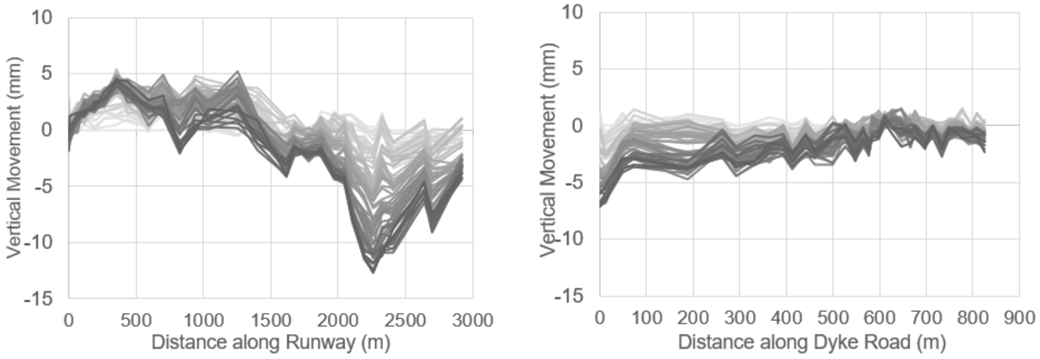
Figure 6 shows the measured changes in the elevation profiles over time (going chronologically from lighter to darker curves) for the airport runway (Figure 6a) and the port's Dyke Road (Figure 6.b). Actually, at 2.2 km from the West end of the airport runway, Figure 6a shows a significant settlement of 435 mm that occurred over a period of over 25 years. The largest settlement for the port's Dyke Road was measured to be 160 mm at the 5th measurement station (at 162 m), as shown in Figure 6.b.



(a) Vancouver Airport North Runway (b) Port of Vancouver – Dyke Road

Figure 6: Changes in elevation profile (from surveying data)

Figure 7 demonstrates the satellite-based vertical movement, D_V, calculated along the centreline of the airport runway (Fig. 7.a) and the port's Dyke Road (Fig. 7.b) for all the satellite images. The vertical movement datasets were obtained from the LOS satellite datasets (D_{LOS}), utilizing Equation 4, with the assumption of negligible horizontal movement ($D_L \sim 0$).



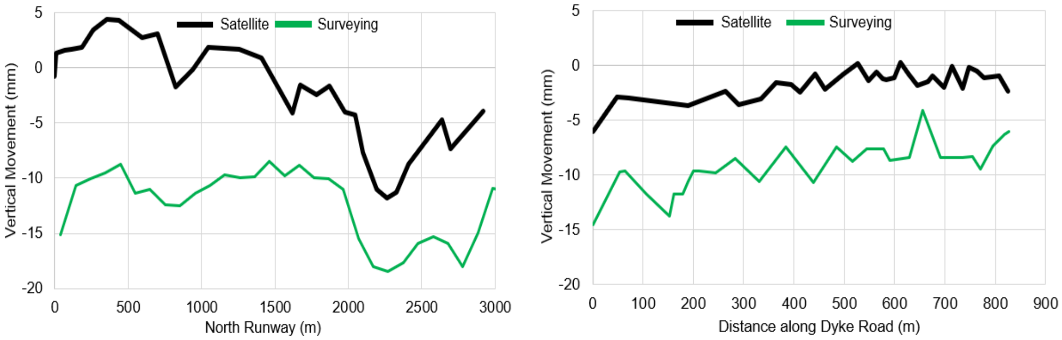
(a) Satellite-based North runway vertical movement (b) Satellite-based Dyke Road vertical movement

Figure 7: Changes in elevation profile (from satellite data)

Satellite vs. Surveying Measurement Comparisons

Figure 8 demonstrates the remote satellite vs. field survey data comparisons for both locations. In order to make a fair comparison between the field surveys and the satellite measurements, data processing with linear interpolation was conducted. For the airport runway, the last two elevation profiles from the surveying method in Figure 6.a were used to calculate new elevation profiles that would correspond to the first and last acquisition dates of the satellite imagery, being June 21, 2019, and July 8, 2021. The change in the elevation profile between these two dates was thus calculated along the runway, resulting in the green curve in Figure 8.a, which is deemed to be comparable with the total movement measured by the satellite (black curve). A similar process was applied for Dyke Road at the Port of Vancouver (Figure 8b). Details of this interpolation process are further discussed in [8].

In Figure 8, although the overall trend and peaks/valleys of the plots from the two compared measurement methods seem to agree well, for the Airport Runway, a discrepancy of approximately 15 mm at the West end of the runway, and around 7 mm near the East end of the runway, is apparent. For the port's Dyke Road, the discrepancy between the datasets is approximately 6 to 8 mm along the road. The assumption of negligible horizontal movement in the calculation of the vertical component of movement with Equation 4 from the satellite-measured LOS displacements may be a contributing factor, as observed by others [9].



a) North runway profile change between June 21,2019 and July 8, 2021: Satellite-based vs. Surveying-based

(b) Dyke Road profile change: Satellite-based vs. Surveying-based

Figure 8: Change in elevation profile of (a) airport runway and (b) port's Dyke Road over a two-year period (June 21, 2019 – July 8, 2021)

DISCUSSION AND CONCLUSION

This paper compares settlement measurements taken over the North Runway of the Vancouver International Airport and Dyke Road of the Port of Vancouver obtained from novel satellite monitoring techniques and conventional surveying methods conducted by the respective authorities. Comparisons demonstrated similar trends overall; however, discrepancies are observed. It is believed that the unknown horizontal component of movement may be the reason for this discrepancy; thus, the assumption of pure vertical movement may not be fully satisfied.

Equation 3 was used to verify if a missing horizontal component could explain the discrepancy between the field surveying measurements and the satellite-based PSI measurements. Assuming that a uniform Westward horizontal movement of the ground supporting the airport runway had occurred during the satellite acquisition period, it is found that a value of 17 mm over 2 years (or a uniform displacement rate of 8.5 mm/year) could explain the gap between the two sets of measurements. Similarly, assuming that a uniform Westward horizontal movement of the ground supporting Dyke Road at the Port of Vancouver had occurred during the satellite acquisition period, it is found that a value of 6 to 8 mm over 2 years (or a uniform displacement rate of 3 to 4 mm/year) could explain the gap between the two sets of measurements. In both cases, further investigation at the Vancouver International Airport site and the Port of Vancouver site is needed to independently determine the true horizontal movement.

In most satellite monitoring projects, one ascending or one descending stack of SAR imagery is used due to limiting factors such as costs of acquisition and analysis; however, assumptions are required on the expected sizes of movement in the different directions (i.e., East-West, North-South, and vertical). In order to eliminate some of the required assumptions, a second approach is sometimes considered, which is to acquire both ascending and descending image stacks, if available. Therefore, a 2D decomposition analysis to determine the East-West and the vertical components of movement can be conducted with the remaining assumption of negligible movement in the North-South direction since the satellite either looks to the West or the East. This approach would be adequate in the cases of Vancouver Intl. Airport or the Port of Vancouver, since it is believed that the horizontal ground movement has a strong Westward component. Further investigation is currently ongoing to confirm this assumption.

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