# Satellite Radar Data Analysis For Change Detection Of Rural And Urban Railways

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16. Abstract

Changes in vertical and horizontal alignment of railways impact service continuity, efficacy and safety of operations and may lead to cascading failures if go undetected. Conventional methods (e.g. GPS, surveying, dedicated inspection and measurement vehicles) are expensive, disrupt operations, do not provide network-wide monitoring and, typically do not monitor the rate of change over time and, thus, are not predictive by themselves. This work implements satellite radar image processing techniques for the intelligent monitoring of railway right of way and enable the change detection at critical areas, such as bridge approaches, grade crossings, or other areas with a history of geotechnical failures along the track. The proposed approach employs Differential Interferometric Synthetic Aperture Radar (DInSAR), Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR), and Coherence Change Detection (CCD) methodologies in radar signal processing. The proposed technology applies to (1) network-wide real-time monitoring and detection, (2) on-demand real-time monitoring of high-risk areas, and (3) accident investigation.

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## List of Abbreviations

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| CDC | Coherence Change Detection |
| HSR | High Speed Rail |
| InSAR | Interferometric Synthetic Aperture Radar |
| PS | Persistent Scatterer |
| PSInSAR | Persistent Scatterer Interferometric Synthetic Aperture Radar |
| ROW | Right of Way |

## Disclaimer



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## 1 SUMMARY

Changes in vertical and horizontal alignment of railways impact service continuity, efficacy and safety of operations and may lead to cascading failures if go undetected. Conventional methods (e.g. GPS, surveying, dedicated inspection and measurement vehicles) are expensive, disrupt operations, do not provide network-wide monitoring and, typically do not monitor the rate of change over time and, thus, are not predictive by themselves.

It is proposed to implement satellite radar image processing techniques for the intelligent monitoring of railway right of way and enable the change detection at critical areas, such as bridge approaches, grade crossings, or other areas with a history of geotechnical failures along the track. The proposed approach employs Differential Interferometric Synthetic Aperture Radar (DInSAR), Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR), and Coherence Change Detection (CCD) methodologies in radar signal processing. The proposed technology applies to (1) network-wide real-time monitoring and detection, (2) on-demand real-time monitoring of high-risk areas, and (3) accident investigation.

The proposed work leverages on the findings and experience gained in current studies at USC that developed and demonstrated the process in detecting moisture changes in the railway track and slopes and measuring small- and large-scale deformations in millimeter resolution [1].

## 2 BACKGROUND

Inspection, monitoring, assessment, and maintenance are integral parts of the freight and passenger railway industry for securing service continuity and efficacy and maintaining safety of operations. Proper drainage of the track and preserving the stability of slopes in cuts and embankments along the track are critical factors in preventing track settlement and track blockage from landslides and mud and rockslides that lead to derailments [2]. Detection relies on identifying and monitoring their underlying causes [3] [4] [5] [6] [7] [8]. Conventional methods for monitoring and inspection of the railway infrastructure use in-situ measurement practices (e.g. GPS, surveying and visual inspections) or video and measurement systems mounted on dedicated track inspection vehicles and can potentially disrupt operations. The frequency of deployment of conventional inspection and monitoring methods is relatively low due to the high cost associated with such operations and do not provide network wide monitoring. They typically do not monitor the rate of change of monitored parameters over time and, therefore, are not predictive in nature by themselves.

Early detection and improved prediction of the true risk potential for geotechnical failure is now feasible due to the advent of affordable satellite imagery coupled with recent advances in remote sensing, data collection and image analysis algorithms. InSAR techniques have been used in the past for monitoring areas for subsidence, landslides, earthquakes and volcanoes [9]. In recent times these techniques have started being used in other applications both geological and structural. InSAR techniques have been applied in railways in Asian countries like China and Taiwan. The techniques have been used to detect instability due to permafrost and ground water abstraction effecting the High-Speed Railway (HSR) [10]. In Britain, RailSAT is a research program that focuses on monitoring the deformations of railways in urban settings. RailSAT uses PSInSAR techniques in London where, due to urban settings, high number of PS can be detected from which subsidence can be accurately detected. Similar techniques have been used to detect sinkholes and ground subsidence around the world [11]. These techniques, along with in-situ measurements, show that InSAR technologies are accurate for Railway applications.

## 3 OBJECTIVES

The authors have developed the framework of a remote monitoring system that utilizes satellite data and other data sources for the identification and localization of critical areas along the railway Right of Way (ROW) that exhibit higher risk for geohazard failure initiation [12] [13]. In this work we implemented these procedures to:

1) Actively monitor a stretch of rail corridors for 12 months using satellite images. During the monitoring period we will focus on detecting track movement and possibly the presence of failure triggering mechanisms.

2) Conduct a historic satellite data analysis of rail corridors where known track movement has occurred in order to correlate the event to any triggering effects taking place prior to failures, as detected by the satellite data processing.

## 4 METHODS

Current studies at USC [1] [14] [15] established the potential to use commercially available satellite radar and optical imagery to monitor the ground surface for effects and conditions that could potentially trigger landslides and other ground hazards. Radar signal parameters are influenced by changes of site characteristics that form the triggering effects for a class of geohazards, as depicted in Figure 1.

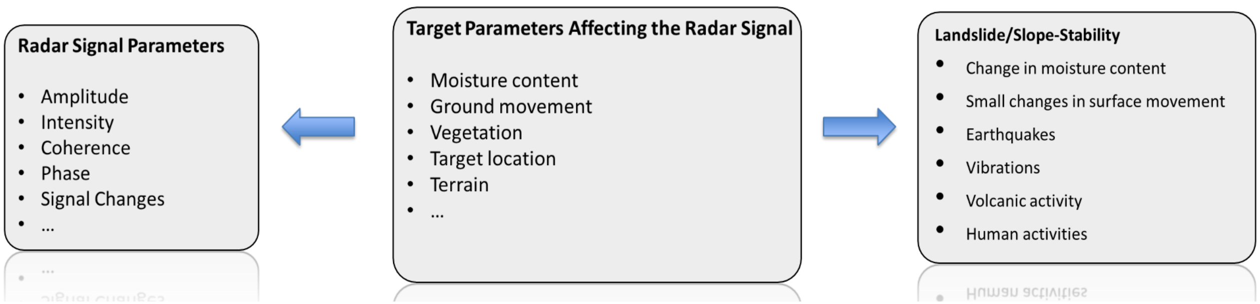


**Figure 1: Dependency between radar image parameters, ground characteristics and geohazards triggering effects**

The satellite data is available in the public domain and typical acquisition frequency is every twelve days. The USC studies concluded that it is possible to use current satellite technology to monitor the ground surface for large- and small-scale deformations and changes in the ground moisture content in adequate resolution. However, the current study focuses on the development of prediction models of landslides and other shallow geohazards.

*SAR Imaging*: InSAR techniques use Synthetic Aperture Radar (SAR) images for monitoring the earth's surface. Radar satellite images differ from the common visual satellite images in two fundamental aspects. Visual images depend on a light source, such as the sun, to illuminate the target and the camera sensors capture the reflected waves in the optical range of the electromagnetic spectrum. Radar images, on the other hand, rely on onboard radiating sources emanating radio waves that "illuminate" the target and the camera sensors capture the reflected waves in the radio frequency range of the electromagnetic spectrum. SAR equipped satellites orbiting the earth, capture high resolution images of wide areas of 250km$^2$ in a single image, and are not affected by cloud cover, or lighting conditions [16], [17]. SAR data covers most of the Earth's surface with a revisit period of twelve days. Furthermore, depending on the satellite in use, multiple orbit paths of the same satellite provide a more comprehensive understanding of the target surface. SAR technology detects two critical factors affecting shallow geohazards [18] surface displacement, and changes in soil characteristics, such as soil moisture in the top layer [16]. Displacement measurements are obtained using Persistent Scatter Interferometric Synthetic Aperture Radar (PSInSAR) techniques [19] while the Coherence Change Detection (CCD) technique is used to identify changes in soil characteristics. Key features of the SAR image formation and processing are introduced next before the PSInSAR and CCD techniques employed in this work are outlined.

*PSInSAR*: The PSInSAR technique is a subset of the InSAR methodology known as multi-temporal differential interferometric synthetic aperture radar. This type of analysis leverages basic InSAR techniques over an extensive sequence of images to obtain precise displacement measurements. The process involves identifying coherent targets, such as pixels or groups that exhibit high coherence throughout the analysis period and computing the displacement of each persistent scatterer (PS) using fundamental DInSAR analysis. The PS targets may include urban infrastructure like buildings, windows, roofs, railway lines, and natural objects like rocks and roads. Typically, a stack of SAR images with similar polarity and geometry, usually exceeding 20 images, is required for a PSInSAR analysis. While increasing the number of images in the stack enhances the accuracy of displacement measurements, it reduces the PS point density due to some PS points losing coherence in one image and ceasing to be a PS for the entire stack. The PSInSAR process adheres to the method outlined in [20]. Figure 2 shows an example of detecting displacement of the ground surface at PS targets, shown as green dots, in the vicinity of the railroad track as reported in the current study.

*CCD Timeline method*: The CCD technique utilizes two SAR images with consistent properties, such as polarization and geometry, to detect changes in SAR properties between the aligned pixels. The sensitivity of SAR image properties to changes allows the technique to detect even subtle changes not visible in other methods. The images must have similar geometry to reduce errors due to atmosphere and topography. VV polarization or VV-HH co-polarization is preferred due to its higher penetration ability and sensitivity to soil moisture. The coherence between the two co-registered images is evaluated by the sum of the spatial and temporal decorrelation of the signals, ranging from 0 to 1. An area with 0 coherence has changed between the image acquisitions, attributed mainly to moisture change, surface roughness, or a long time elapsed between acquisitions. While a single CCD analysis can identify critical surface and subsurface features, processing individual pairs of images is inadequate for monitoring a region over an extended period. Using a large stack of SAR images, the timeline method creates image pairs for CCD analysis based on the chronological order of the SAR images. This approach ensures consistent results by using the same geometric property throughout the analysis, minimizing errors.

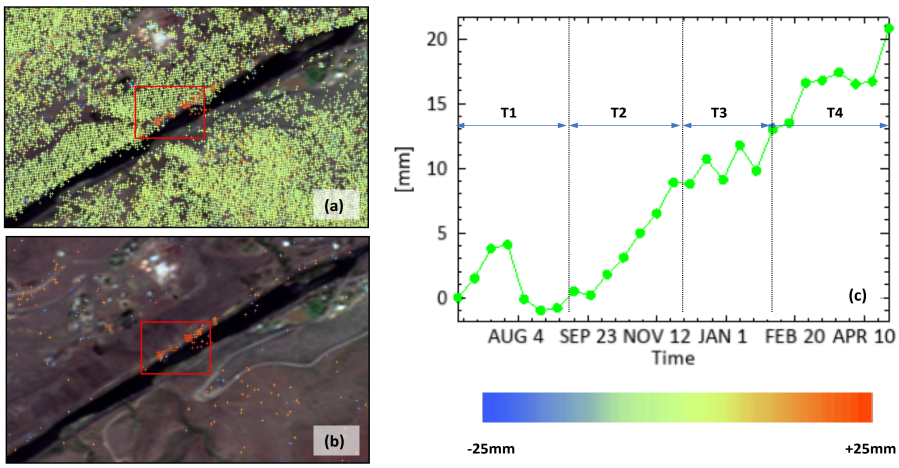


**Figure 2: (a) The PS displacement map superimposed on the optical image; (b) PS analysis results with displacement on railroad track (c) Time history of the displacement over time of one PS point.**

Figure 3 shows an example of CCD analysis and its correlation to soil water content.

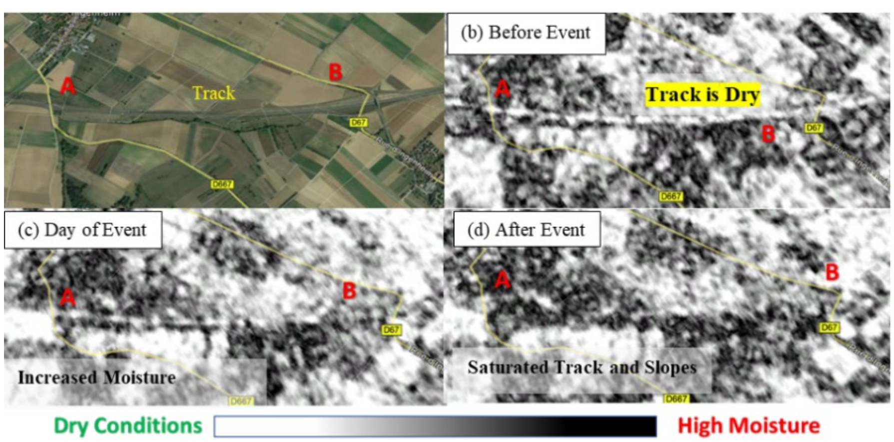


**Figure 3: Example of CCD image analysis and correlation with water content: (a) Visual image of site with a railroad track between point A and B; (b) A typical coherence image of the site showing high coherence along the track; (c) Coherence along the track is changing due to increasing soil moisture; (d) Coherence along the track is lost due to high soil moisture content.**

# 5 RESULTS

This section presents a case study that demonstrates the detection of track settlement at a known derailment location near Raymond, MN. Analysis results of other studies can be found in [21], [22].

## *5.1 Event*

On March 30th, 2023, a BNSF train carrying highly flammable ethanol derailed and caught fire in Raymond, Minnesota, causing concerns about safety and potential contamination. Out of the 22 derailed cars, four containing ethanol ruptured and ignited leading to a blaze, as shown in Figure 4 (a). Other cars carrying ethanol were also at risk of releasing the chemical.

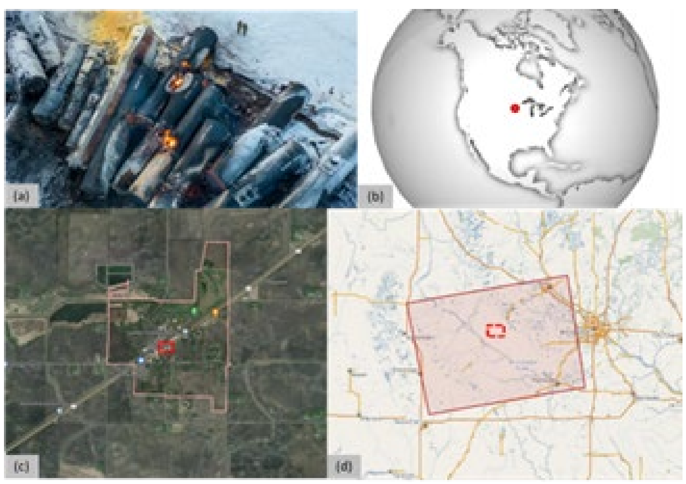


**Figure 4: (a) the train derailment. (b) the accident on the world map. (c) the location of the derailment in the town of Raymond, MN (d) the data path of Sentinel-1A covering the region with the accident highlighted.**

Figure 4 (b) and (c) show the location of the accident on the world map and the exact location of the derailment in the town of Raymond, Minnesota, respectively. The EPA report of the derailment suggests the cause is due to rupturing two denatured ethanol tanks, a highly flammable product [23]. This analysis was conducted before the report was public to see if the cause of the derailment was due to site mobilization or any other factors that are observable by InSAR analysis.

### *5.2 Site Description*

The region under investigation is located in Minnesota at latitude longitude (48.25, -101.46), about 100 miles from Minneapolis, MN. The region under observation is in a northern state with a mean annual precipitation of 24-37 inches with 140 to 180 frost-free days. The InSAR analysis can be divided into the urban area of Raymond, MN, and the rural farm area surrounding it, as seen in Figure 4 (d). The Urban area has a soil profile of clay loam in the top 0-16 inches of the soil layer, with the soil layer from 16-79 inches of loam soil. This region is classified as poorly drained, with the depth to the water table being 0 to 8 inches. The rural area has diverse soil classifications, with the largest having silt loam soil in the top layer of 28 inches of soil and loam from 28 to 79 inches below it. The water table in this region is about 47 to 59 inches, with a high capacity to transmit water (0.2 to 2in/hr). Both regions have never had problems with flooding and ponding. Soil profile map is shown in Figure 5 and complete information related to soil profile can be found in [24].

**Figure 5: The soil profile map of the region in Raymond, MN**

### *5.3 Data Availability*

The region under investigation is in Minnesota, at Latitude/longitude 45.01, -95.23. The radar satellite Sentinel-1A covers this region once every 12 days. The derailment occurred in the center of the town of Raymond, located in the urban areas with a large area exposed to radar backscatter. The town is surrounded by farmland which has a low radar backscatter. Since only one satellite covers this area, analysis of the region is restricted to the angle of incidence. The dataset for this study is obtained from the Sentinel constellation, and the satellite images are downloaded from the Sentinel-1 EU datahub (ESA, 2023) and Alaska Satellite Facility (ASF) (ASF, 2023). Figure 4 (d) shows the path taken by the Sentinel1-A satellite. The analysis employs PSInSAR techniques archived satellite radar images spanning 12 months (2/18/2022 to 03/09/2023). The analysis has an approximately 3 months gap period between May 2022 to Aug 2022. The results are overlayed on the optical image acquired by Sentinel-2 on March 11, 2023, for better visualization.

#### *5.3.1 PSInSAR analysis*

The PSInSAR analysis for site mobilization monitoring was conducted using a stack of 20 images, at a minimum. The deformation maps from the two orbits are superimposed on an optical image taken on March 11, 2023. The displacement observed is in mm and plotted on the color-coded PS images that show the total displacement over the entire analysis. The negative displacement (blue) indicates subsidence, and the positive displacement (red) denotes height gain about the line of sight of each satellite and orbit. The PSInSAR analysis uses single orbit data to produce the deformation results shown in Figure 6.  Figure 6 (a) shows that the rural area around Raymond, MN, has a low density of PS, while the highlighted region of Raymond has a high amount of PS.

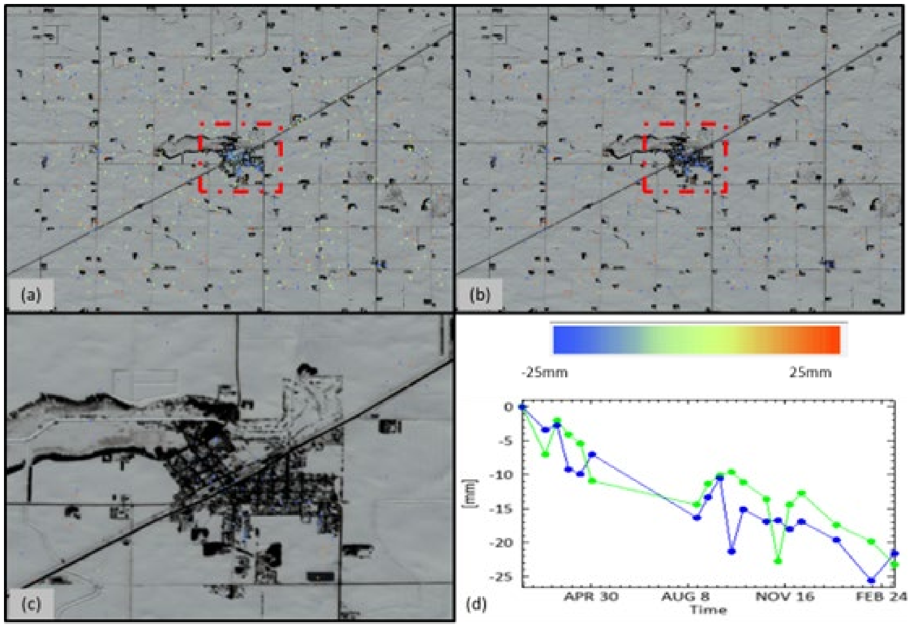


**Figure 6: (a) shows the total PS over the observation area; (b) Shows high displacement PS with stationary points removed; (c) Shows the area where the derailment took place; (d) Shows the average subsidence monitored in the region over time**

Figure 6 (b) shows the displacement in the range of -25 to -14 and 14 to 25 to show the largest deformation in the region without the stationary point. The town of Raymond, MN, is shown in Figure 6 (c) in a larger scale, with the average displacement of subsidence over time shown in Figure 6 (d).

### *5.3.2 Discussion*

PSInSAR analysis over the Raymond, MN, derailment analysis has shown a contrast in the density of PS from the urban environment of Raymond, MN, and the surrounding rural area. The analysis shows the rural regions of Raymond to have positive displacement while the urban region is experiencing subsidence. By comparing the displacement region with the soil reports, we can see that the water table is relatively high in the case of the urban region (0-8 inches). Similar conditions have been observed in cities where PSInSAR analyses have been conducted [18] [25].

## 6 CONCLUSIONS

This report presented the use of satellite-based radar data and other data sources for the identification and localization of track settlement. The proposed approach is developed based on

PSInSAR and CDC analysis. The feasibility to use satellite-based radar information to detect change along the railway right of way is demonstrated. The success of the highly accurate MTInSAR techniques depends on the detection of an adequate number of Persistent Scatterers in the region of interest for a given time period of observation.

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