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Citation for the original published paper (version of record):

Carlvik, F., Mirzanamadi, R., Torstensson, P. et al (2025). Remote sensing of track degradation using InSAR-a case study of the Iron ore line. Transportation Research Procedia, 86: 313-320.
http://dx.doi.org/10.1016/j.trpro.2025.04.040

(article starts on next page)

Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 86 (2025) 313–320

Transportation Research Procedia

www.elsevier.com/locate/procedia

26th Euro Working Group on Transportation Meeting (EWGT 2024)

Remote sensing of track degradation using InSAR – a case study of the Iron ore line

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Abstract

Track irregularities induce increased wheel-rail contact forces causing poor ride comfort, accelerated mechanical degradation of vehicle and track or even failures that may lead to speed restrictions or temporary track closure. Today's monitoring of railway tracks in Sweden using measurement vehicles consumes traffic capacity and means a restriction in data collection to a few occasions per year. Remote sensing such as Interferometric Synthetic Aperture Radar (InSAR) can be used to monitor ground deformation in the close vicinity of the track with potential impact on the track substructure. The importance of geotechnical properties of the track substructure on the development of track irregularities is well known from experience and literature and is demonstrated for example by the re-development of discrete track irregularities at the same locations after tamping. The Sentinel 1A and 1B satellites have collected data every 12th day resulting in roughly weekly observations between 2016 and 2021. This case study evaluates the relationship between ground deformation in the ascending and descending tracks, basic geological properties and track irregularity. The average negative ground movement rate measured using InSAR was higher for track segments that had experienced poor track geometry in the ascending path, especially for track built on clay, moraine or glaciofluvial deposits. A higher variance in ground motion was found in both the ascending and descending path near segments which had experienced track geometry alerts. Future work should further investigate these relationships by observing vertical and horizontal movement separately, incorporating a temporal dimension, and increasing spatial resolution, taking special consideration to variation of settlement surrounding and along the track.

Peer-review under responsibility of the scientific committee of the 26th Euro Working Group on Transportation Meeting

Keywords: track geometry; track settlement; maintenance; InSAR; remote sensing

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10.1016/j.trpro.2025.04.040

1. Introduction

Railways are a sustainable mode of transport but there is a need for efficient maintenance to enable a modal shift to railbound travel and to keep trains running safely and on time. Ultimately, a lack of maintenance can result in track failures and derailments with catastrophic consequences such as that afflicting the Iron ore line in 2021 (Nyström, 2023). In their maintenance plan for 2023-2026, the Swedish National Transportation Administration (Trafikverket) illustrate the condition of the railway system as affected by a long period of limited economic resources and prioritisation resulting in a maintenance deficit (Canaki and Honauer, 2023).

The maintenance plan (Canaki and Honauer, 2023) describes the strategy that encompasses a mix of corrective and preventive maintenance interventions, as well as reinvestment when proven economically beneficial as the track approaches the end of its technical lifespan or experiences recurrent resulting in traffic disruptions. Today, track geometry is measured in Sweden with a fleet of measurement vehicles. While the measurement vehicles give accurate data, they occupy traffic capacity and can hence only run sparsely. Track geometry on Trafikverket's network should be measured at least 1 to 6 times per year depending on the monitoring classification (Trafikverket, 2022). There is a need to understand the drivers for repeated discrete track geometry degradation at certain locations along the rail network. Remote sensors do not occupy the tracks and measure both near and around the track with high frequency. For example, the Sentinel 1A and 1B satellites orbited the Earth every 12^{th} day, resulting in new measurements every 6 days when both satellites were in orbit. While Sentinel 1A was launched in 2014 and Sentinel 1B was launched in 2016, the mission ended in 2022 for Sentinel 1B, while Sentinel 1A is still in orbit.

Interferometric Synthetic Aperture Radar (InSAR) is a technique that uses phase differences between two high-resolution SAR images (Bamler and Hartl, 1998). One use for InSAR is to observe changes in spatial properties over time, which has been used in earthquake, volcanic, and glacial monitoring from the technique's early stages. Recent research is emerging on the use of InSAR to observe railway infrastructure. In the Netherlands, Chang et al. (2014) demonstrated a method for monitoring vertical and horizontal deformation using InSAR for a segment of a freight railway track near the Rotterdam harbour. Similarly, Wang et al. (2018) observed differential settlements at the transition zones of railway bridges using InSAR. Both papers showed initial success but were conducted on a small spatial scale.

Empirical correlations have shown that repeated track deformation can be related to deformations in the soil layer (Roshan et al., 2022). By correlating track degradation and track stiffness on the iron ore line, Nielsen et al. (2020) found that track sections with low magnitude and high gradient substructure stiffness were more often affected by recurring track geometry irregularities on the 1-25m wavelength. In their review, Briggs et al. (2017) highlight risk factors due to design of older railway infrastructure that affect pore water pressure behaviour: poor compaction along and a permeable capping layer consisting of coarse granules. Heavy rainfall can further exacerbate the situation, increasing the risk of slope failure. The Swedish Accident Investigation Authority (Haverikomissionen) is currently examining a railway derailment from the summer of 2023 that occurred due to embankment failure during a period of intense rainfall (SVT, 2023).

While InSAR is not a new method, its potential as a source of track condition data has not been properly investigated on a larger geographical scale. This research aims to investigate the potential of InSAR data for understanding preconditions and risks associated with rapid and repeated track deterioration. This is done by correlating the ground deformations as derived by the InSAR process to track geometry measurements, soil layer type, and cross-sectional height profile for track segments along the Iron ore line. On an aggregated scale, hot spots regarding track geometry defects are detected and evaluated. Such knowledge can assist in prioritisation and timing of track maintenance beyond the physical track geometry, as well as be used for decision support for larger reinvestment in regions with poor surrounding conditions.

The Iron ore line (Malmbanan), which is the studied rail line, is located in the north of Sweden between Luleå port to the east and the Norwegian border, Riksgränsen, to the west. In Norway, the track continues to Narvik as Ofotbanen. The iron ore line is a single track construction primary trafficed by freight trains carrying iron ore with a maximum axle load of 32.5 tonnes.

The Iron ore line is divided into several sections of which some were found unsuitable with regard to the InSAR method and the scope of the study. These included for example bridges and tunnels, as well as parts of the alignment that extend toward mining areas or had complex layout with several secondary tracks and ring-lines. The lines which were excluded had a total length of about 12 km of compared to the approximately 400 km track which was included.

2. Methods

2.1. Data collection and pre-processing

Geospatial data are collected from several sources and are heterogenous both in their spatial resolution and data-types. Temporal data was collected between 2015 and 2021. To aggregate data into a cohesive system, the software Feature Manipulation Engine (FME) was used, where transformations are made on data through flow diagram-like programming. The data sources and their geographic references are given in Table 1.

Table 1. Data sources and description.

Data description	Source	Georeferencing
Track position	Trafikverket	SWEREF 99TM & Internal
Track alignment	Trafikverket	Internal
Ground deformation	InSAR Sweden (Sentinel 1A and 1B)	WSG 84
Soil type	Geological Survey of Sweden	SWEREF 99TM
Height above mean sea level	Geological Survey of Sweden	SWEREF 99TM

First, data were aggregated into the same georeferencing system. The coordinate system SWEREF 99TM was applied which agrees with that commonly used in infrastructure projects on a larger scale in Sweden. The reference system used by Trafikverket to describe their track network uses line number, track number, and distance in kilometers and meters (track-following coordinate) from a given origin station.

The soil type was obtained from the Geological Survey of Sweden as polygons with a minimum resolution of 1 km^2. While the resolution means that the dataset should be used with caution, it was chosen as it had full coverage of the chosen region. Better resolution is available at the expense of poor coverage of the region of interest. The soil type in this dataset regards soil 0.5 meters below the ground surface.

2.1.1. Positional and technical properties of the track

Data on track position and track properties were collected from a web-based interface provided by Trafikverket called Lastkajen. Two datasets were used, the first contained polylines describing the line and track number, starting and ending kilometer and meter value for each line segment, as well as other identifying information. The second dataset contained similar data regarding the line and track number, along with basic characteristics such as maximum speed restrictions, tunnels, bridges, and maintenance levels. Tunnels were removed as InSAR measures movements of the Earth's surface. Bridges were removed primarily because it was difficult to determine whether an InSAR measurement point belonged to the track and its surroundings or the water or waterfront. As parameters from both datasets would be used in the analysis, the values of the second dataset were added to the first using a spatial join function.

2.1.2. Track alignment

The data on track alignment used in this study were collected from Trafikverket's measurement system 'Optram' which is based on data from a fleet of measurement vehicles. Track position is evaluated based on several parameters; track gauge, vertical position, lateral position, cant, and twist, as well as the standard deviation of a few of these (Trafikverket, 2021). The Optram system supplies processed data of geometrical deviations above four threshold limits, alert, (low/high) intervention limit, and immediate action limit which describe the required maintenance action. Track irregularities are defined as differential positions along a given wavelength, in this case 1 to 25 m. For this study, vertical position and twist were considered. Vertical position is evaluated for the left and right rail respectively within three wavelength regions, see (Swedish Standards Institute, 2019).

Data on track irregularity were aggregated from several measurement vehicles that have run on the studied tracks between 2015 and 2021. Each data point regards a segment of the track where track geometry deviations were observed and consists of a starting and ending position for the affected track segment, current type of geometry parameter, and the deviation magnitude. The level of deviation is given both in millimeters and as a categorical label of either “PLAN”, “UH1”, “UH2”, and “KRIT” corresponding to recquired maintenance actions.

2.1.3. InSAR data processing

InSAR data from the Sentinel 1 mission were used. The data were pre-processed using persistent scatterer InSAR (PS-InSAR) technique (Ferretti et al., 2001) that gives the line of sight (LOS) displacement of the scatterer over time. The satellites acquired SAR data either in their ’ascending’ or ’descending’ orbit, resulting in observations of displacement from two different LOS directions. The ascending and descending data was analysed separately to account for differences.

The average velocity and acceleration from the InSAR data points were related to the railway track segments using an inverse distance weighting function (IDWF) as explained by (Mitas and Mitasova, 2005). The IDWF summarizes data from several data points within a certain distance from an unknown data point by weighting each known point based on their distance to the location of interest. In this case, the values from InSAR measurements are used to estimate the ground settlement along each railway segment. For each rail segment at position r, the weighted velocity was calculated according to Equation 1.

$$F(\mathbf{r}) = \sum_{i=1}^{m} w_i z(\mathbf{r_i}) = \frac{\displaystyle\sum_{i=1}^{m} \frac{z(\mathbf{r_i})}{|\mathbf{r}-\mathbf{r_i}|^p}}{\displaystyle\sum_{j=1}^{m} \frac{1}{|\mathbf{r}-\mathbf{r_j}|^p}} \tag{1}$$

Where $\mathbf{r_i}$ is the position of InSAR point i, m is the number of evaluated points, z is the observed value to be averaged (in this case the annual velocity of track settlement), and p is the power parameter. In this case, m is decided as all points within a chosen distance of the current track segment (see section 2.1.5) and $p = 2$. Rather than averaging to a point, the track segment is seen as a polyline, and the shortest distance from each InSAR point to the line is chosen as the distance $|\mathbf{r} - \mathbf{r_i}|$.

Using spatial averaging such as IDWF assumes that the variation of settlement is smooth, and does not take into account local maxima or minima between points. Highest negative movement (settlement) and highest positive movement (uplift) were recorded for each rail segment.

2.1.4. Limitations and Data Availability

The spatial resolution of InSAR data from Sentinel 1 is approximately 20x20 meters. Track geometry data used looks at the wavelengths 1-25 m. There are thus relatively few data points from InSAR to explain the small-wavelength geometry. However, there is a hypothesis that there is a relationship between long-wavelength settlement and the development of poor track geometry at a later stage; which can be observed indirectly using this method.

2.1.5. Parameter variations

When aggregating the different data sources, two parameters were variable with regard to the spatial resolution: the length of the track section and the search radius for finding InSAR points. The different cases are shown in Table 2. Reasonably, a larger track section and search radius increases the chance of their being InSAR data points within the chosen area; however this comes at the cost of a lower precision, especially with regard to the track irregularity wavelength as stated in section 2.1.4.

2.2. Statistical analysis

After the pre-processing, each track segment was attributed data. Note that since the InSAR data was collected as LOS, their related variables were collected once each for both ascending and descending orbits. The general aim of the analysis is to correlate ground movement as measured by InSAR data to track geometry exceeding maintenance

Table 2. Parameter variations used in the statistical analysis

Parameters	Scenarios
Length of track section	(a) 20 m with 0 m overlap (c) 40 m with 20 m overlap (d) 100 m with 80 m overlap
Search radius for InSAR points	(a) 5 m from track (b) 10 m from track (c) 20 m from track

thresholds. To further understand whether the relationship between track geometry and ground displacement holds for different soil layers, the same test is conducted by separating for the different soil layer types observed in the study. The basic statistical analysis was conducted on the mean of the average settlements in mm per year as well as the internal variation of settlement rate between the different InSAR points included in each observation. The means between the different test groups were compared and statistical significance was tested using a two-sample t-test assuming equal variance.

3. Results

The distribution of track geometry exceeding alert and intervention limits is shown in Figure 1 respectively. From Figure 1, it is observed that a higher number of alert limits are exceeded between latitude 66.5° and 67°, corresponding to line 117. However, the number of times when the intervention limit was exceeded is noticed to have a more even distribution with slight over-representation toward the southern part of the Iron ore line. A high number of track alerts can be observed near the Norwegian border, at Vassijaure.

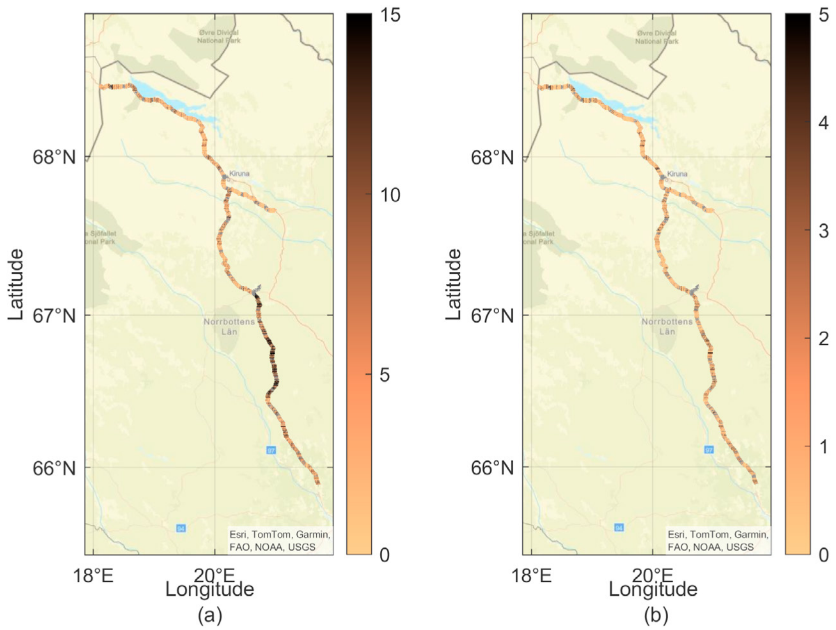

Fig. 1. Number of (a) track geometry alert limits (PLAN) and (b) track geometry intervention limits, low (UH1) per segment between 2015-2021

3.1. Relationship InSAR ground displacement and track irregularity alerts

In Tables 3-5 the mean value of InSAR ground displacement is shown for the different cases dictated in Table 2. The significance test is relative to no alerts, shown in the first column of each case. In the ascending orbit, it is observed that track segments that experienced some track irregularity at maintenance levels ”PLAN” or ”UH1” also have a higher negative ground deformation in the surrounding area. This is significant for all InSAR radius for track segments of 100 m and for the 40 m track segments with a 20 m search radius. The descending orbit shows no clear pattern and high p-values.

Table 3. Mean of average ground deformation in mm per year for track segments of 100 m and p-value according to a two sample t-test, *<0.05 and **<0.01

		Ascending				Descending			
Radius, InSAR		None	PLAN	UH1	UH2	None	PLAN	UH1	UH2
20 m	Mean	-1.26	-1.40	-1.48	-1.46	-1.00	-0.96	-0.97	-0.98
	p-value	-	0.004**	0.000**	0.092	-	0.384	0.596	0.838
10 m	Mean	-1.24	-1.36	-1.46	-1.46	-0.99	-0.93	-0.93	-0.93
	p-value	-	0.012*	0.000**	0.056	-	0.162	0.280	0.595
5 m	Mean	-1.20	-1.34	-1.45	1.43	-0.98	-0.91	-0.88	-0.76
	p-value	-	0.006**	0.000**	0.061	-	0.123	0.086	0.057

Table 4. Mean of average ground deformation in mm per year for track segments of 40 m and p-value according to a two sample t-test, *<0.05 and **<0.01

		Ascending				Descending			
Radius, InSAR		None	PLAN	UH1	UH2	None	PLAN	UH1	UH2
20 m	Mean	-1.29	-1.44	1.50	1.10	-0.97	-0.93	-0.98	-0.70
	p-value	-	0.010*	0.007**	0.270	-	0.371	0.828	0.068
10 m	Mean	-1.25	-1.34	-1.39	-1.09	-0.95	-0.89	-0.91	-0.60
	p-value	-	0.111	0.060	0.393	-	0.190	0.569	0.021*
5 m	Mean	-1.23	-1.29	-1.38	-1.11	-0.91	-0.83	-0.79	-0.06
	p-value	-	0.345	0.089	0.567	-	0.105	0.087	0.000**

Table 5. Mean of average ground deformation in mm per year for track segments of 20 m and p-value according to a two sample t-test, *<0.05 and **<0.01

		Ascending				Descending			
Radius, InSAR		None	PLAN	UH1	UH2	None	PLAN	UH1	UH2
20 m	Mean	-1.30	-1.38	-1.43	-1.00	-0.94	-0.93	-0.96	-0.50
	p-value	-	0.22	0.17	0.18	-	0.76	0.79	0.02*
10 m	Mean	-1.24	-1.23	-1.27	-0.73	-0.91	-0.84	-0.83	-0.43
	p-value	-	0.93	0.77	0.03*	-	0.190	0.40	0.02*
5 m	Mean	-1.22	-1.18	-1.27	-0.68	-0.88	-0.74	-0.67	0.022
	p-value	-	0.61	0.69	0.07	-	0.03*	0.04*	0.000**

For variation in measured displacement between InSAR points included in each track segment observation, a higher variation was found in both ascending and descending orbits, shown in Table 6. The increase in variation was statistically significant for all cases with 100 m track segments and for all cases with 40 m track segments except for the descending orbit when only including InSAR points within 5 meters from the track. The results were statistically significant for the 20 m track segments when including InSAR points within 20 m and 10 m from the track, while the null hypothesis could not be rejected when only including points withing 5 m from the track.

Table 6. Mean of ground deformation variance in mm per year for track segments of 100 m and p-value according to a two sample t-test, *<0,05 and **<0,01

Radius, InSAR		Ascending None	Ascending PLAN	Ascending UH1	Ascending UH2	Descending None	Descending PLAN	Descending UH1	Descending UH2
20 m	Mean	0.50	0.66	0.65	0.80	0.43	0.55	0.57	0.68
	p-value	-	0.000**	0.000**	0.000**	-	0.000**	0.000**	0.000**
10 m	Mean	0.57	0.77	0.80	0.98	0.49	0.63	0.65	0.82
	p-value	-	0.000**	0.000**	0.000**	-	0.000**	0.000**	0.000**
5 m	Mean	0.73	0.92	0.96	1.17	0.62	0.71	0.67	0.70
	p-value	-	0.000**	0.000**	0.000**	-	0.000**	0.009**	0.026*

3.2. *Overview of explanatory factors*

Within the observed area, six different types of primary soil types were observed, either primarily described by the grain size (e.g. clay, sand) or the processes from which it was developed (e.g. moraine, glaciofluvial deposits). The average ground deformation in mm per year depending on the primary soil type and maintenance level is shown in Table 7 for the ascending orbit. The explanatory factors were observed for track segmentation of 100 m and including InSAR points up to 10 m from the track, as this case showed highest statistical strength in the previous section. For track segments built primarily on glaciofluvial deposits, clay, and moraine, segments which experienced track irregularities also had an overall higher settlement rate. For bedrock, sand/gravel, and peat, such a correlation was not found.

Table 7. Mean ground deformation in mm per year for different soil types and maintenance levels observed, for track segments of 100 m and including InSAR data up to 10 m from the track

	None	PLAN	UH1	UH2
Bedrock	-1.15	-1.21	-1.24	-1.18
Sand/gravel	-1.06	-0.73	-0.91	-0.90
Clay	-1.44	-2.08	-1.86	-1.68
Glaciofluvial Deposits	-0.39	-1.30	-1.43	-2.35
Moraine	-1.40	-1.46	-1.55	-1.75
Peat	-1.31	-1.37	-1.52	-0.79

Similar to the results in Tables 3-5, the same observations were not found in the descending orbit, except for the case of glaciofluvial deposits.

4. Conclusion and future work

In this study, track geometry, ground deformation, and soil type were attributed to track segments along the Iron ore line, using data from 2015-2021. By comparing the mean value of the overall ground deformation as well as the variation between neighboring measurement points, it was found that track segments that at some point experienced track geometry above the alert or lower intervention limit had statistically larger settlement rates and higher variation in the region for ascending orbits but not for descending orbits. These observations were most clear when using track segments of 100 m, indicating that the surrounding ground deformation may be an indicator for changes in track geometry. When taking soil type into consideration, three types showed a higher increase in settlement rates in areas with track irregularities: clay, moraine, and glaciofluvial deposits. In future work, the LOS ground motion should be converted into vertical and horizontal ground motion; for the Sentinel 1 mission, this can either be done using the European Ground Motion Service (EGMS) processed data or by processing ascending and descending data from InSAR Sweden.

The data used in this study consisted of aggregated data and did not take into consideration the time domain; as such a level of detail was lost as to whether changes in the rate of ground deformation could correspond to a later occurrence of track irregularity. Further, the data was highly skewed toward track segments which did not experience any track geometry levels which exceeded any of the maintenance limits. Finally, the spatial resolution of the InSAR data was large compared to the wavelength used in track irregularity measurements - as such, it was not expected to have a high correlation between the measured values from Optram and the InSAR data.

This case study onto track geometry, ground deformations, and geological conditions show variations in ground deformation rates depending both on track condition and soil types. These results show that the use of InSAR, along with accompanying geological data can be used for understanding when a high negative ground deformation velocities are related to a high risk of track degradation. As such, one can make informed decisions regarding the timing of reparations as well as act as decision support for investments such as stabilization of the subsoil with piling. Future work toward this endeavor should take into account the time domain and a higher spatial resolution, taking care to not lose information when aggregating heterogeneous spatio-temporal data. To understand the implications of the local geology to track deformations, further research should be done where geological, geotechnical and hydrologic factors are included.

Acknowledgements

The work has been performed with support from Sweden's Innovation Agency (Vinnova), with the project number 2023-01253.

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