REASSESS - Early Detection and Assessment of Railway Substructure Moisture Problems at National to Local Scale Using Spaceborne, Airborne and Train-based Remote Sensing Systems

Detection of railway track anomalies using interferometric time series of TerraSAR-X satellite radar data

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1 Introduction

- The Swiss railway network is among the most heavily used globally, which requires resource-intensive planning, construction, operation, and maintenance.
- **Substructure condition**, affected by moisture accumulation, influences service life and maintenance processes.
- **Early detection** of track anomalies is crucial to extend service life.
- **Current methods**: track geometry vehicles, ground-penetrating radar, and spatiotemporally sparse in-situ inspections.
- **Satellite-based remote sensing techniques** potentially offer a cost-effective means to monitor railway track infrastructure including all-day, all-weather imaging with large spatial coverage at high spatial resolution.

2 Methods

In this study, we investigated a new approach to detect track anomalies based on surface displacements retrieved from interferometric time-series of satellite radar data (TerraSAR-X). The performance of this new detection method is compared to the conventional chord-based measurement technique, which is presently used by SBB as a proxy-based indicator for track anomalies on a network-wide scale. Inspired by the chord-based method's use of vertical undulations of the track geometry, our proposed approach employs statistics derived from variations of surface displacements along the railway track retrieved with persistent scatterer interferometry as proxies for track anomalies.

Persistent Scatterer Interferometry (PSI)-based deformation estimation:

- We use time series of radar satellite observations to estimate surface deformations on the order of mm per year for pixels that contain a persistent scatterer.
- The PSI processing includes several steps: PS pixel selection, iterative estimation of linear deformation and height corrections using multiple linear regression, including temporal phase unwrapping, spatial filtering and unwrapping of the regression residuals to isolated the atmospheric phase contribution.
- For our data analysis we computed several quantities along a moving window including the standard deviation, number of PS showing large deformation rates, as well as the number of total PS and their quality.

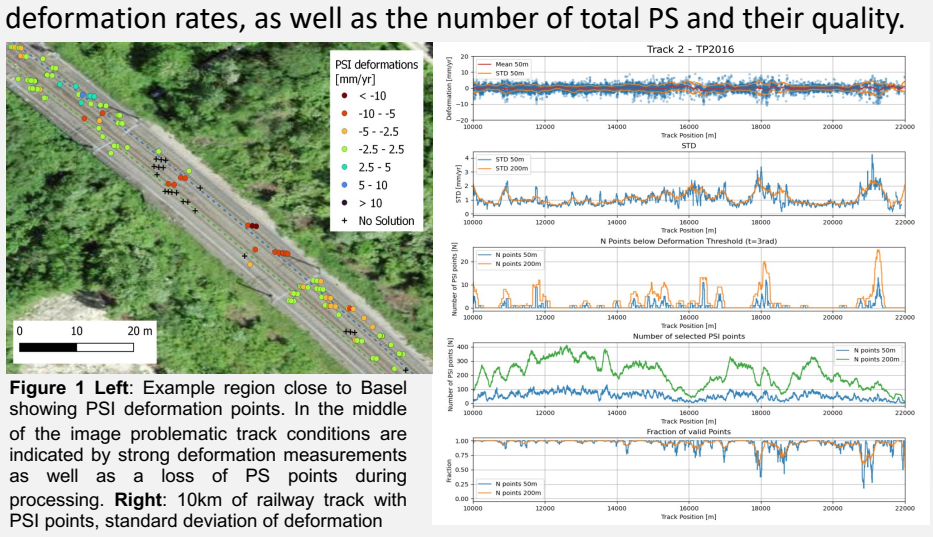

Figure 1 Left: Example region close to Basel showing PSI deformation points. In the middle of the image problematic track conditions are indicated by strong deformation measurements as well as a loss of PS points during processing. **Right**: 10km of railway track with PSI points, standard deviation of deformation velocity along a moving (STD), number of PSs with deformation rates above an adaptive threshold, number of selected PSs and fraction of points with a valid solution.

Chord-based measurements (D1 and D2 signal):

- Measures longitudinal height undulations as a proxy signal for track condition; evaluated at different spatial frequencies:
- Sliding standard deviation of longitudinal height undulations is used.

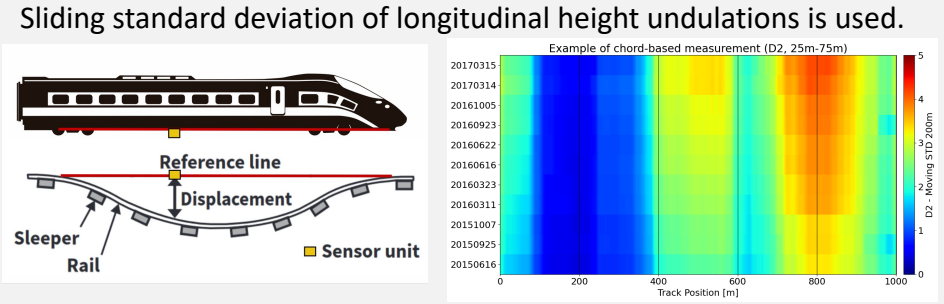

Figure 2 Left: Schematic of the chord-based measurement principle. **Right**: Example data along the railway track of the moving standard deviation (200m) of the D2 signal that includes variations at a longitudinal intervals from 25m to 75m. Around track position 500 and 800 a worsening of the track condition can be seen.

4 Results and Discussion

In our study, we investigated about 75 km of usable railway track (2 track lines) between Basel and Tecknau (BL), for which SBB provided chord-based measurement time-series from 2012 to 2023. TerraSAR-X time series observations are available from November 2015 to November 2016 and August 2021 to November 2022.
Currently, there is no automated method to extract problematic track parts from chord-based measurements, and we use the same approach as SBB internally, where potential problems are identified by visual inspection of the D1 and D2 time-series (Figure 1, right). To investigate if the PSI derived properties can be used to classify problematic track parts, we used the classification based on the chord-based measurements as a reference for comparison.

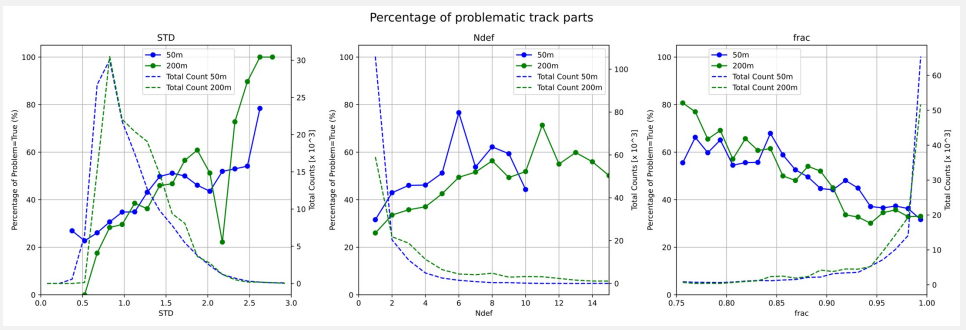

Figure 3 illustrates the relationship between three track features (STD, Ndef, and frac) and the chord-based classification of problematic and nonproblematic track parts. The secondary y-axis shows the total count in each bin. The blue line indicates the features based in the 50m moving window and green indicates the 200m moving window. A minimum threshold of 100 data points (corresponding to a track length of 50 m) per bin is applied. All features show an increase towards larger (STD, Ndef), respectively smaller (frac) values corresponding to an increasing percentage of problematic track parts using the chord-based classification as a reference.

- Problematic track sections, as identified from the chord-based measurement signal, show a correlation with the PSI-derived properties (Figure 3).
- The current state-of-the-art PSI measurements for identifying infrastructure problems primarily focus on substantial deformation measurements (change rates above a certain threshold).
- Incorporating STDs of PSI-derived deformation measurements along track as well as other PSI derived properties can enhances the identification of problematic track sections (Figure 4).

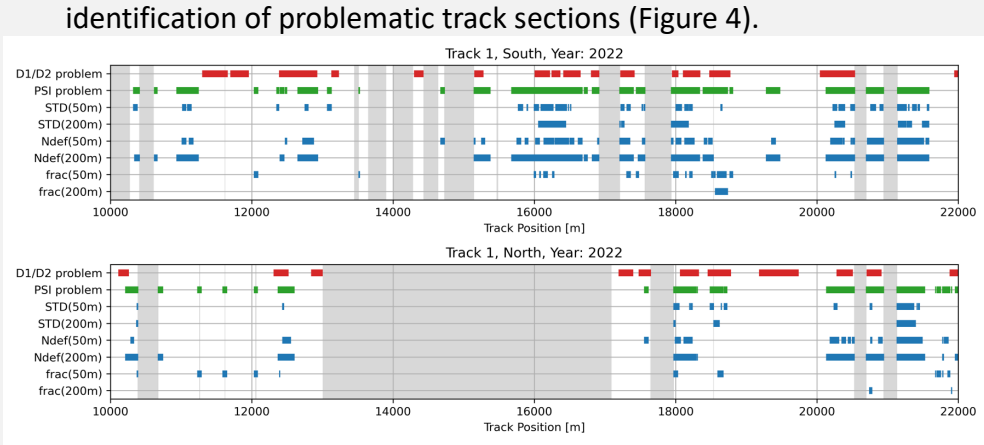

Figure 4: Classification using threshold values of the different classifiers obtained by a grid-search. The southern (top) and northern (bottom) track of Section 1 in TP2022 are shown (see paper for details). The red line shows the track sections identified to have anomalies by the chord-based proxies. The green line below represents the anomalous track sections as cumulatively obtained from all PSI-based proxies. The detections obtained for each individual PSI-based proxy are shown in blue, below. Grey areas indicate excluded sections (turnouts, tunnels etc).

5 Summary and Conclusions

- We proposed a method to detect railway track anomalies based on PS interferometry; demonstrated with TerraSAR-X satellite radar data.
- Our proxy-based approach is inspired by the chord-based method applied operationally, today.
- Both, the satellite-based and chord-based methods to detect track anomalies are proxy-based indicators.
- We found that both approaches lead to qualitatively similar but not always identical detection results. Validation remains challenging.
- Currently, we see our PSI-based detection approach as a useful additional source that complements state-of-the art techniques used for an expert-driven identification of anomalies in railway tracks.
- In the future, high-resolution wide-swath (HRWS) imaging radars will provide high spatial resolution *and* large spatial coverage at the same time, which is needed for a network-wide satellite-based detection.