Inversion-based Time Series Analysis of PS-InSAR Data: Uncovering the Origins of Subsidence and Annual Fluctuations in Southern Hesse, Germany

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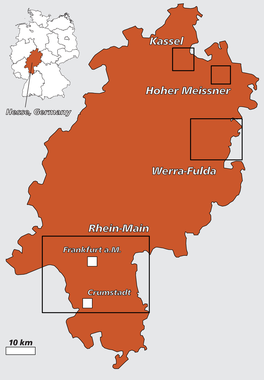
Motivation

Introduction

The uplift and subsidence of the earth's surface can be attributed to many different processes. In urban regions in particular, it is important to understand which ground movements occur, whether they pose a risk to infrastructure and whether countermeasures can be taken. While events such as earthquakes, sinkholes and landslides have abrupt and visible effects, slow ground movements such as slope instabilities and tectonic movements are difficult to detect and it can take decades for visible damage to occur. Remote sensing, especially InSAR and Persistent Scatterer InSAR, provides high spatial and temporal coverage for monitoring these processes. The state of Hesse in central Germany is confronted with various ground movements, including former open-cast lignite mines, active salt mining and landslide-prone geological units.



Areas of increased hazard

- Mining activity (Werra-Fulda)
- Abundance of landslide prone units (Hoher Meissner & Kassel)
- Ground water extraction (Rhein-Main & Kassel)

Sharing is encouraged

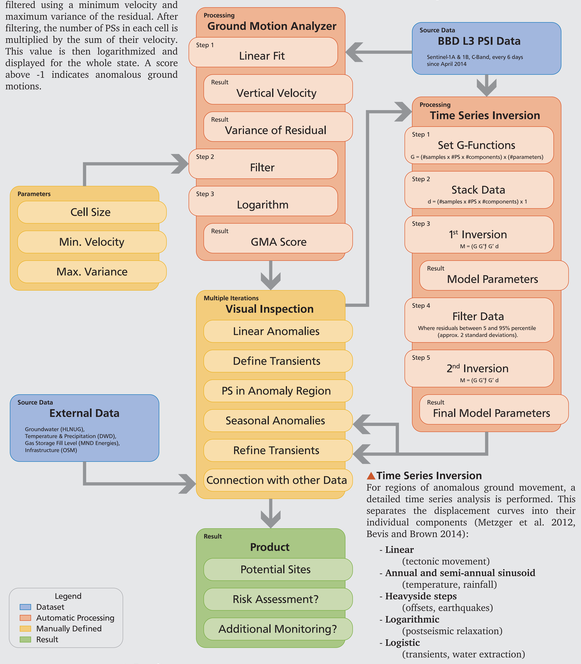
Methodology

Ground Motion Analyzer

The ground motion analyzer (GMA) assigns a ground motion score to a grid of defined resolution (Krzepek et al. 2023). The score is derived from the linear vertical velocity of each PS. This is filtered using a minimum velocity and maximum variance of the residual. After filtering, the number of PSs in each cell is multiplied by the sum of their velocity. This value is then logarithmized and displayed for the whole state. A score above -1 indicates anomalous ground motions.

Datasets

We use Persistent Scatterer Interferometry (PS-InSAR) data from the Ground Motion Service Germany (BBD) to analyse ground motion patterns.



Time Series Inversion

For regions of anomalous ground movement, a detailed time series analysis is performed. This separates the displacement curves into their individual components (Metzger et al. 2012, Bevis and Brown 2014):

- **Linear** (tectonic movement)
- **Annual and semi-annual sinusoid** (temperature, rainfall)
- **Heavyside steps** (offsets, earthquakes)
- **Logarithmic** (postseismic relaxation)
- **Logistic** (transients, water extraction)

Results

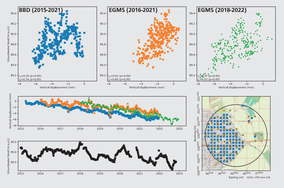
Several regions of anomalous ground motion were detected. Here we present:

- A **linear** displacement anomaly in the urban area of Frankfurt a.M.
- A **seasonal** anomaly in the more rural area of Crumstadt.

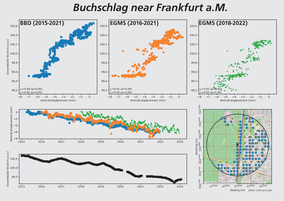
Using external data we search for possible causes of the anomaly and inform the responsible authorities.

Comparison PSI - Groundwater

Hähnlein near Crumstadt



Buchschlag near Frankfurt a.M.



Groundwater level and surface motion

In the Rhein-Main area the ground motion is strongly connected to the ground water level. To evaluate the applicability we compare the Boden-Bewegungsdienst Deutschland data (BBD, Kalia et al. 2017) with the European Ground Motion Service (Costantini et al. 2021) and correlate both datasets with selected ground water observation wells in the Rhein-Main area (based on the methodology in Boni, 2016).

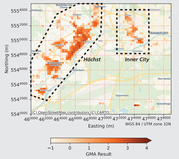
Results

Where data coverage is sufficient, the surface motion is strongly correlated with the ground water level, suggesting a good connection of the reservoir and surface. Therefore, we suggest that both - BBD and EGMS - datasets are valid targets to use for our study.

Caveats

While having a similar processing, BBD and both EGMS periods can strongly differ (Even et al. 2024). Furthermore, the groundwater reservoirs which are monitored might not be the one closest to the surface. A correlation with precipitation is thus not always expected.

Results - Urban Case Study Frankfurt a.M.

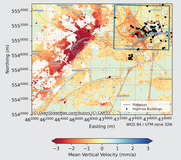


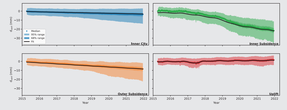
GMA

Two main regions of strong ground motion in Frankfurt a.M. are detected:

- Höchst
- Inner City

For the "Inner City" a detailed time series analysis is done because of the possible impact on infrastructure.





Components

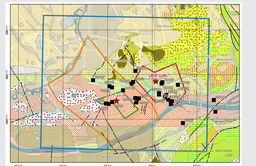
The components for the four subregions are:

Component	*Inner City*	*Outer Sub.*	*Inner Sub.*	*Uplift*
Linear trend (mm/a)	-0.43	-1.27	-2.91	0.22
Annual sine (mm)	0.03	0.05	0.35	0.25
Annual peak	30. June	25. Aug.	01. Sep.	06. Nov
Semiannual sine (mm)	0.03	0.04	0.03	0.08
Semiannual peak	30. April	26. April	03. Feb.	21. April
Transients	None	None	8.90	-3.57
			-4.80	1.90

Timeseries

On average the "Inner City" is stable, but several regions show subsidence or uplift. Additionally, the region of strongest subsidence and the region of uplift show transient events that lead to temporary or permanent change in surface height.

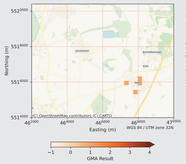
The region "Inner Subsidence" has the highest subsidence rates due to the extraction of groundwater due to construction. The transients coincide with the onset of construction of the U5 underground station. The "Uplift" region has fewer active construction in the recent years. Additionally, the reequilibration of swell-and-shrink layers below buildings that were finished before the start of the time series could lead to the uplift.



Geology of FFM

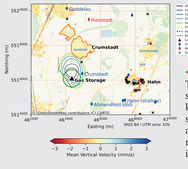
Besides less construction activity, the subsurface structure changes between the wester and eastern part of the inner city. The absence of Pliocene formations might be one of the factors leading to differences in subsidence and uplift.

Results - Rural Case Study Crumstadt



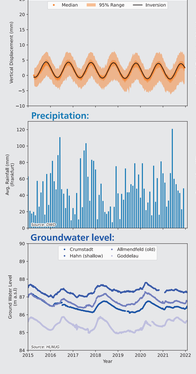
GMA

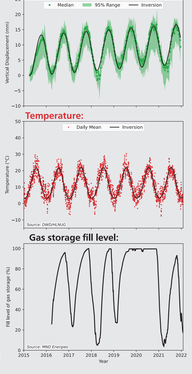
Due to the very small linear velocity, the Crumstadt area is not detected by the ground motion analyzer.



Known Issues

The vicinity to a gas storage site and known damaged structures, as well as a strong seasonality make Crumstadt an interesting case study.





Components

The components of the two regions are:

Component	*Crumstadt*	*Gas Storage (500 m radius)*
Linear trend (mm/a)	-0.09	0.58
Annual sine (mm)	2.69	6.52
Annual peak	21. Oct.	06. Oct.
Semiannual sine (mm)	0.04	0.17
Semiannual peak	07. April	22. May

To identify the possible reasons of the strong seasonal motion we correlated the PSI time series with several external datasets:

Precipitation:

- Strong correlation, time lag is too large (mid-July vs. October)

Temperature:

- No correlation

Groundwater level:

- No correlation

Gas storage fill level:

- No correlation, however periods of very low fill level coincide with strong subsidence (e.g., in 2018 and 2021).
- Seasonal motion despite constant fill level in 2020.

Conclusions

PSI Datasets

- Data shows good correlation with ground water level.
- Irregular deformation is not well represented by InSAR processing (linear+sinusoid in Germany, vs. piece-wise linear in other regions, see Even et al. 2024).

Ground Motion Analyzer

- Enables the identification of regions with significant ground movement at various spatial scales.
- Allows for quick assessment of datasets.
- Limited applicability for seasonal or transient signals
- No temporal correlation, in contrast to alternatives such as ADAfinder (Barra et al. 2017).

Timeseries Analysis

- More detailed information on active regions.
- Improved deduction of geological causes.
- Identification of transients and temporal correlation between regions.

Applicability

- The data can be used to monitor ground movements and identify risk areas to inform authorities and stakeholders.
- Integration of external data is required for the assignment of possible causes.
- Important for:
  - **> urban planning, risk assessment, monitoring**
  - **> impact of anthropogenic activity**
  - **> climate-induced changes in subsurface**

References

This Study:

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